Augmented, Virtual and Mixed Reality Passenger Experiences

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Abstract Mixed Reality (MR) headsets enable the rendering of virtual content selectively intermixed with reality. These headsets have the capacity to allow passengers to break free from the restraints of physical displays placed in constrained environments such as cars, trains and planes. Moreover, they have the potential to allow passengers to make better use of their time by making travel more productive and enjoyable, supporting both privacy and immersion. This is of particular note given the predicted adoption of autonomous vehicles. This chapter explores both the applications of MR headsets in passenger transit scenarios, and the key barriers to headset usage by passengers, ranging from impediments that would entirely prevent safe usage and function (e.g. motion sickness, see Chap. 1.6) to those that might impair their adoption (e.g. social acceptability). We discuss the key challenges that need to be overcome and the necessary research required to facilitate adoption and realise the potential advantages of using MR headsets in transit.

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1 The Changing Reality of the Passenger Experience

Advances in transportation are such that there will be a significant conversion from drivers to passengers over the coming years. This is due both to the increasing use of public transport and the increasing adoption of autonomous vehicles. Given this, an important question is how to best support passengers to make the most of this expanded travel time, regardless of the mode of transportation. Observations of behaviours have revealed that modern passengers alternate between productive activities—reading, watching videos—and looking ahead, or out of a window [1]. Such behaviours are also observed in autonomous driving scenarios [2]. The conversion of drivers to passengers, fuelled in-part by autonomous car adoption, has the potential to enable passengers to perform more productive activities - if we can provide the technology to support them. In this chapter, we discuss the use of Virtual Reality (VR) and Augmented Reality (AR), together often referred to as Mixed Reality (MR) [3, 4], and how these novel technologies can be used to improve passenger experiences in cars.

1.1 The Existing Reality: In-Vehicle Displays

Phones, tablets and laptops are a common sight inside planes, trains, ships, buses and cars, offering passengers a distraction from the sights and sounds of their journey. This has long been a necessary feature of travel, with entertainment providing a *"diversion from speed and the risk of the catastrophic accident via screens"*, with in-flight entertainment being suggested to act as *"an intermediary, screening out the fact of flight and the events of travel... crucial to keeping passengers calm, occupied and content"* [5], significantly improving the perceived comfort of passengers [6, 7].

For the modern passenger, in addition to personal devices, many in-built displays are often available, e.g. dashboard displays for front seat passengers and seatback displays for those seated in the rear [8]. Recent advancements include projection-based AR heads-up displays [9] and windows [10–13], whilst technologies such as flexible OLED displays mean that every surface or window [14] could become a display, as demonstrated in some concept cars [15]. In effect, passengers can find themselves ensconced in a *"techno-cocoon"* with technology acting as a *"sensory filter... crucial for sensory privacy and exertion of control"* [16].

As Groening [16] notes, *"at least since the 1970s, passengers have sought more forms of separation between themselves and those other passengers perceived as 'undesirable'"*. However, all of the aforementioned displays fall short of this underlying aim of separation. This is because they are integrated into the physical environment and thus share common problems and drawbacks. They are often limited in terms of size, and thus immersion [17]. Privacy is rarely assured, with displays frequently gaze-accessible to other passengers. It has been noted in air travel for example that *"already there are too many screens in the plane with monitors on the seats and passengers bringing on their range of personal devices... When people are trying to rest it is already difficult with the glare of all these devices."* [18]. These displays are subject to glare and reflections from the changing lighting of the outside environment, and can require a gaze angle that can be sub-optimal in terms of comfort (e.g. staring downwards, or staring at one fixed place continually for long periods, noted to cause neck problems due to a lack of variety of head movement [19]). At worst, they are also more likely to induce motion sickness, termed *nauseogenic visual displays* [20]. Given passengers often require visual awareness of the motion of the car to avoid motion sickness [21, 22], some view of the outside world or the motion of the vehicle may be necessary, with any restrictions of the view having potentially negative consequences for motion sickness. Fundamentally, these displays have to work around, and within, their physical context, with passengers still perceiving themselves as being in the constrained and repetitive space of a car, plane, train or bus.

2 The New (Mixed) Reality: Immersion, Limitless Display Spaces, and Privacy

MR headsets can potentially overcome many of the problems highlighted above. They innately improve the usability and ergonomics of existing passenger activities by comfortably rendering both 2D (e.g. planar displays, 360° video) and fully 3D virtual content (e.g. 3D objects, avatars, immersive environments) with depth anywhere around the seated passenger [23]. The virtual content is personal and private by default, unless shared through software. The headsets themselves are low-power, with consumption similar to that of a smartphone and improving levels of graphical fidelity. Occlusion issues are no longer relevant as any view can be presented in the headset, whilst interactions can move with the user (given the headset is subject to the same oscillations as the body). New possibilities for interaction (e.g. via gaze [24] or direct touch [25]) and communication (e.g. telepresence where those you are addressing appear in your local environment [26, 27]) can be supported. VR headsets, in particular, also allow users to escape the confines of the vehicle and become present and immersed in a different, entirely virtual, environment (often referred to as "place illusion", a component of presence [17, 28]). Because MR headsets have the capability to track head orientation and render content on that basis, they also have complete control over how motion is visually perceived. This has significant implications for combating motion sickness [29] (see Chap. 1.6

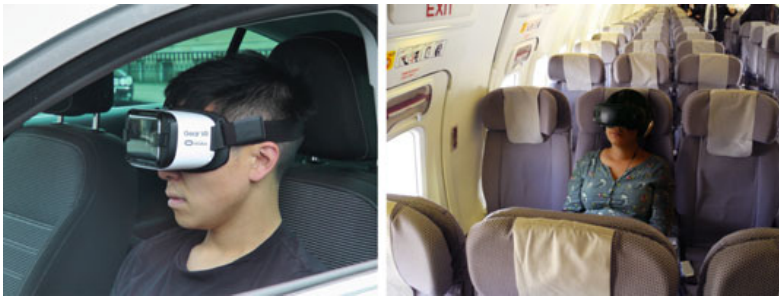

Fig. 1 Two use cases of MR displays in transit of particular note are (left) in-car [29] and (right) in-flight [41], as both use cases have the potential to feature private/secure surroundings with journeys of long durations

for theories behind), commonly resulting from a mismatch between how motion is physically (e.g. via the vestibular system) and visually perceived [30, 31] (Fig. 1).

The VR Hyperspace EU project, which finished prior to the advent of new, cheap, consumer VR headsets such as the Oculus Rift, noted the benefits of VR usage in transit, with their stated aim being to *"enhance the passenger comfort through... (the) adoption of Virtual and Mixed Reality technologies in the future air cabin"* [32]. More recently, airlines have also tested VR headsets for use in-flight [33, 34], with benefits even being shown for safety knowledge transfer regarding how to wear an aircraft life preserver [35]. There have also been a number of instances of industry explorations of VR headset usage in both planes [36–38] and autonomous cars, such as by Renault [39] and Apple [40]. As a blogger for The Economist noted: *"virtual reality headsets on planes mean we can isolate ourselves from irritating cabin-mates"* [36].

MR headsets currently provide immersive gaming and entertainment experiences [17], and will inevitably also support general productivity applications [23, 42]. VR headsets have been shown as favourable to existing displays for passengers consuming film media on simulated journeys [43]. However, they can also alter the passenger experience in more subtle ways. The VR Hyperspace project previously noted that such technology could change the perception of self and space, improving passenger experience and comfort through new virtual *"surroundings, real imagery and live flight data in addition to fantasy environments"* [18]. Indeed, it has been noted that:

> Virtual environments can fully or partially distract people from sources of discomfort, becoming more effective when they are interesting. They are also more effective at distracting people from discomfort caused by restricted space than noise disturbances [44]

Creating the perception of a more personal and private space, immune to invasion by others, is a significant benefit of MR headsets [45]. On this basis, we could envisage that an MR headset wearing passenger might, for example, retreat to their private, virtual workspace, with a similar display layout and interactions in the vehicle as in their physical office or workplace. Consequently, we might envisage the passenger experience improving in terms of:

Productivity The user sits down in their autonomous vehicle for the daily commute. Their AR headset renders a wide virtual workspace around them, allowing them to begin work immediately, and look forward to leaving work earlier as a result;

Entertainment Gazing at the real landscape in front of them, the train passenger's AR headset highlights landmarks of note, and generates new games and experiences out of the available landscape and location, e.g. rendering characters running alongside the vehicle in a high speed platformer game;

Isolation As the seat-belt sign turns off after takeoff, the passenger puts on their VR headset, entirely occluding the sights and sounds of the plane, finding themselves in a relaxing virtual home cinema, modelled on their own home for comfort.

3 Challenges and Impediments to Passenger MR Use in Vehicles

For the scenarios suggested above to be realised, a number of problems must be overcome. If we consider existing consumer MR headsets outside of their use in transit, they still have some notable limitations. In the case of VR headsets, use is limited with respect to field of view (typically ranging from $\sim$90° to $\sim$130° in current consumer models) and fidelity, comfort and weight, especially on-the-move where mobile headsets are often powered by smartphones. For AR headsets, some of these issues are more pressing, for example the Microsoft Hololens 2[1] currently supports only a $\sim$70° horizontal field of view. However, we can assume that lightweight and hi-fidelity headsets will become a consumer reality over the coming years, given the recent leaps made in terms of hardware, software and processing power. For example, consider the advances made between the release of the Oculus Rift DK1 in 2013 and the Oculus Quest[2] in 2019. Over the space of 6 years, there were significant leaps in resolution, refresh rate, positional tracking, mobile use, fidelity, tracked controller interaction and hand tracking.

Assuming that MR headsets reach the anticipated level of maturity and utility, consideration should be given towards potential impediments to their use in transit, so they can be dealt with in parallel with the development and mass adoption of these headsets. The VR Hyperspace project offered the most comprehensive discussion of use in transit thus far [18]. They suggested that the most problematic barriers to the use of VR in-flight were those of cost, a reluctance to be immersed in VR (e.g. due to mistrust, being unaware of safety related conditions), a lack of standardisation, and security/privacy concerns. However, these problems are not necessarily unique to passenger MR. McGill et al. broadly categorized the most pressing problems regarding MR headsets in transit specifically [46] into two categories:

[1] www.microsoft.com/en-gb/hololens.

[2] www.oculus.com/quest/.

Functional impediments to MR Usage In-Motion: Being fundamental problems that currently rule out safe and proper passenger usage of headsets, such as maintaining a forward bearing in a moving world; physical crash safety; and motion sickness.

Impediments to acceptance/adoption: where the technical platform exists to deliver passenger MR, yet there may remain compelling reasons why consumer uptake may not occur that need to be addressed e.g. for reasons of social acceptability, limited support for the kinds of interactivity or social experiences that may be expected of MR technology outside of transit contexts, or a lack of understanding as to how to exploit vehicle motion and context for immersive, entertaining experiences.

This chapter further explores these two aspects of passenger MR, looking at the functional and technological barriers to deployment, and how we might make passenger MR experiences palatable to consumers.

4 Functional Impediments to MR Usage In-Motion

By functional impediments, we refer to challenges and problems that would prevent or limit normal usage of MR headsets specifically in transit. We discuss three key functional impediments: how existing Inertial Measurement Unit (IMU)-based head orientation tracking, relying on a head-mounted accelerometer/gyroscope to sense head movements, is confounded by the presence of external vehicle motion; the unknown safety of MR headsets in the event of a crash/airbag impact; and how discrepancies between what motion is physically perceived (e.g. via the vestibular system) and visually perceived (e.g. being present in a stationary virtual room) will lead to the onset of motion-sickness. For each of these challenges, we discuss the state-of-the-art in terms of solutions, and what further research is necessary to overcome this problem. We also refer to transportation in terms of the motion experienced by the passenger, grouped into three common types:

Motion type 1 Stable/constant velocity, infrequent vehicle orientation changes, little-to-no oscillations, e.g. large commercial planes, autonomous car journeys along a straight motorway;

Motion type 2 Frequent orientation changes, e.g. autonomous car journeys on main roads, inter-city trains;

Motion type 3 Frequent vehicle velocity and orientation changes with oscillations, e.g. autonomous car journeys in cities, inner city trains/buses.

Note that we do not cover impediments to general purpose HMD usage by consumers, of which there are many. For example, the weight of existing headsets, their typical reliance on a fixed focal plane resulting in accommodation-vergence conflict and causing discomfort over long periods of viewing [47], and their low resolution and field of view [17], compared to what human vision is capable of perceiving, are all notable challenges that must be overcome for consumer MR headsets to reach wide adoption. However, we concentrate on the challenges in transferring such usage to transit contexts.

4.1 Maintaining a Forward Bearing in a Moving World

Most affected: Motion type 2/3 Transportation that involves frequent and/or significant changes in orientation and acceleration.

To understand the difficulties in performing head tracking in transit, first we must discuss how MR headsets typically support rotational and positional tracking. This is achieved through IMU-based sensor fusion of a gyroscope and accelerometer, captured at a high sampling rate ($\sim$1000 Hz in the latest headsets) and low-latency for dead reckoning [48]. To compensate for sensor drift over time, additional sensing is used for frequent corrections, so that what the user perceives as forward when they start using the headset remains in the same physical direction after prolonged use. For simple rotationally-tracked headsets (e.g. the Samsung Gear VR), the gyroscope is responsible for providing this correction factor, offering a constant bearing for magnetic north. For positionally-tracked headsets such as the Oculus Quest or HTC Vive[3] , optical tracking is used to provide the correction to the IMU. There are two common approaches to this end, referred to as "outside-in"' and 'inside-out" tracking. Outside-in tracking typically refers to tracking systems where the corrective sensing is embedded in the environment. Inside-out tracking refers to headset-based sensing for determining the position in the world. In the case of the HTC Vive and successors such as the Vive Focus,[4] "Lighthouse" beacons in the physical environment broadcast pulses of IR light which the headset detects [49]. However, recent consumer headsets such as the Oculus Quest now typically use SLAM-type [50] inside-out tracking enabled by integrated depth cameras, using computer vision to track the surrounding environment, and consequently the position of the headset within the environment. Beyond this, outside-in optical solutions are also relatively commonplace e.g. using Optitrack of Vicon cameras, and other systems such as magnetic tracking have also been used in the past. Regardless of the tracking technology used, positionally tracked headsets have the benefit of knowing their absolute position in 3D space and adapting their presentation accordingly, minimising the discrepancy between what is visually and physically perceived, and consequently minimising simulator sickness [51] whilst better facilitating presence [17].

Both rotationally and positionally tracked headsets share a common problem when in-motion: any in-built IMU sensing is no longer detecting head movement

[3] https://www.vive.com.

[4] https://enterprise.vive.com/uk/product/vive-focus/.

Fig. 2 The MR headset undergoes translations (indicated by the blue/green/red arrows indicating translations in x/y/z) and rotations (indicated by the blue/green/red circles) relative to the interior of the vehicle. However, the vehicle also undergoes translations and rotations relative to the world, which may also be detected/conflated by the headset sensing

alone.[5] Instead, it is now detecting a combination of user head movement and vehicle accelerations/rotations (see Fig. 2), and then applying this in periodic corrections. In the case of rotationally tracked headsets (e.g. Samsung GearVR), they will lose track of the forward bearing of the user, meaning the MR headset will not be able to maintain a stable focus on 360° content under motion, with the user's view turning with the vehicle. In the case of positionally tracked headsets that rely on additional optical tracking, external motion will lead to the user experiencing judder as the corrective optical sensing contradicts the IMU sensing. Future MR headsets are likely to exhibit the same problems so long as they rely on IMU-based sensor fusion with corrective tracking technology that has not been adapted for use in a moving vehicle.

4.1.1 Resolving This Challenge

Providing a general-purpose solution for enabling rotational and/or positional tracking for consumers across a variety of motion environments, from planes and trains to autonomous vehicles, represents a significant research problem, requiring additional sensing to either *correct the headset inertial sensors* and provide a stable forward bearing, or to *replace the reliance on IMU-based inertial sensing* for tracking headset orientation. Figure 3 details the potential sensing solutions we envisage.

Examples of correcting the inertial sensors can be seen in both [29] and [52], where a car-mounted gyroscope was used to allow car orientation changes to be subtracted from a rotationally-tracked headset's orientation. However, in this case, gyroscope drift still occurs, so any such sensing would still require periodic corrections itself, e.g. the user explicitly instructing the headset to re-orient when facing forward, or using additional sensing such as vehicle and head-mounted accelerom-

[5] For an example of this, see youtube.com/watch?v=eBs8biTWuEs.

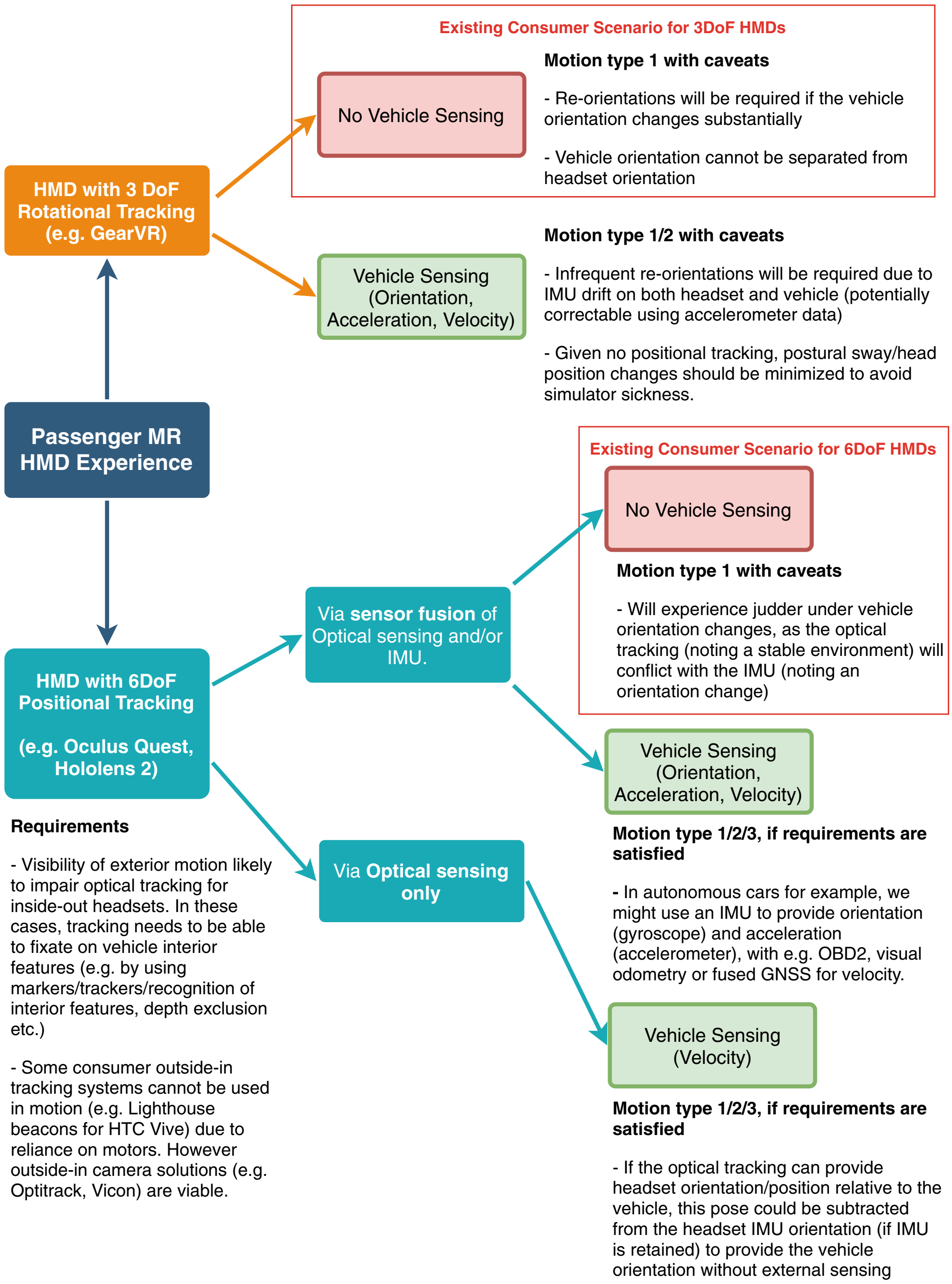

Fig. 3 Flow-chart describing both the challenges regarding usage of existing consumer headsets by passengers, and how we might arrive at 3DoF and 6DoF MR headsets that function correctly in a moving vehicle environment. We consider both the sensing required on/around the headset, and vehicle-specific sensing of orientation/motion, enabling passenger experiences where stable viewing of MR content is possible (i.e. vehicle motion can be selectively ignored or conveyed by the MR headset at will)

eters/magnetometers, GNSS/GPS or optical tracking as a means to correct for this drift and keep the “forward” of the HMD aligned with the “forward” of the vehicle.

Ideally, we might perform such corrections on positionally tracked headsets, given the necessity of positional tracking for avoiding simulator sickness. As Fig. 3 details, there are a number of possible permutations of sensing that can provide support for all three of the motion types discussed, and it is not clear what the optimal solution might be for any given transportation type. This is because positionally tracked headsets face additional challenges in-motion. For outside-in headsets, cameras or sensors need to be mounted in the vehicle environment, and need to be compatible for use in-motion. For example, HTC Vive Lighthouse beacons (both V1 and V2) cannot yet be used in-motion, relying on a hard drive motor [53] that shuts down to prevent damage when external motion is detected—a solid state equivalent would be required. Passenger seating and movement may pose additional challenges in terms of occlusion and lighting; while such solutions would only be viable for a subset of vehicles where such technology could be pre-installed or quickly deployed.

Inside-out headsets might appear preferable, requiring no hardware additions to the external environment. However, depth camera-based optical tracking solutions come with their own technical challenges. They are well suited to enclosed and stable environments with little-to-no outside visibility, such as in planes. This is in contrast to environments such as car interiors that feature a large proportion of refractive and translucent surfaces such as windows (problematic for any IR-based depth camera), and a constantly shifting visual environment (problematic for binocular depth imaging and tracking features in the world). In effect, any visible external motion (e.g. moving landscape through windows) could impair tracking, requiring such headsets to be able to fixate on known, stable interior features for tracking (e.g. excluding point cloud data based on depth).

Nonetheless, we could envisage a peripheral which combined a single optical tracking camera or optically trackable marker and an IMU, which could be temporarily mounted on the vehicle within visibility of the MR-headset wearing passenger. Such a device could facilitate positional tracking in a range of environments and provide corrective data regarding vehicle orientation.

At the extreme, we could envisage future tracking solutions that *no longer rely on IMUs*. For example, instead of optical tracking providing corrective pose updates, it could be used to provide the headset orientation data. However, on top of the previously discussed problems with using optical tracking in-motion, removing the reliance on IMUs poses significant technical challenges regarding latency, accuracy and processing requirements for generating the headset pose, particularly when considering Timewarp-type solutions that require high frequency/low latency sensor data to function [54].

Much as with the variety of tracking technology in current consumer MR headsets, there are research problems with the possible solutions, each potentially better suited to different forms of transport and different use cases. For example, if we consider autonomous vehicles, research collaborations will likely be required between headset manufacturers and the automotive industry to arrive at car designs which provide adequate support for this use case. This may be in the form of designing standards for sharing car bearing telemetry at low-latency, integrating IMU or positional tracking sensors or creating car interiors that are conducive to being optically tracked by passenger headsets (e.g. integrated IR LEDs, markers or other discrete optically trackable features). Conversely, for usage in planes, given plane bearing changes are relatively infrequent and head movement is largely restricted to rotations only, it may be that software-only solutions (such as periodic user-driven re-calibration/zeroing) or initial versions of consumer inside-out tracking (capable of tracking the plane interior) may be sufficient to enable widespread usage with little-to-no disruption.

4.2 Physical Crash Safety

Most affected: Transportation where recoverable crashes can occur without warning (e.g. cars), as opposed to where incidents may be forewarned and the headset removed (e.g. planes).

In the event of a crash, the seat belt restrains the passenger's body whilst, in cars at least, the airbag is deployed to slow down the change in momentum of the head. However, use of an MR headset during a crash may impact the effectiveness of these safety measures. Firstly, MR headsets increase the mass of the wearer's head (e.g. VR headsets typically weight around 0.5 kg [55]), with the average human head weighing approximately 5 kg [56], meaning a ∼10% increase), and consequently will increase the force exerted on the neck during a crash. The consequences of this are yet to be established. Secondly, the user may be denied any warning cues or anticipatory information regarding there being a crash imminent, and thus will be unlikely to brace themselves. Thirdly, in cases where an airbag is present, the airbag will inevitably make contact with the protruding headset. At this point, the headset could break, resulting in broken glass from the lenses and display, plastic debris, and ruptured batteries. Alternatively, it could remain intact, applying the impact force from the crash onto a smaller surface area where the headset makes contact with the wearer's face.

4.2.1 Resolving This Challenge

There is no information available about the crash resilience of current consumer headsets, although they have all passed basic safety checks required for safety certification (e.g. receiving a CE mark in Europe). The consequences of such an impact remain as-yet unknown. Whilst this situation is understandable, this point will need to be addressed by regulators to allow for safe, legal usage of MR headsets by passengers. There is a body of research examining the risks of eyewear being worn during such events. Notably, whilst the additional risk encountered was small [57, 58], the severity of individual cases [59] combined with the dimensions, materials and form factors of current MR headsets suggests that crash safety should be evaluated for any headset where usage in transit is likely. Users should be made aware of any discovered risks. In time, consideration should be given to crash-worthiness at the design stage of headsets, acknowledging their potential usage in transit and safeguarding against being worn during a crash. There is also the perception of safety to be considered (overlapping with impediments to acceptance and adoption)—users must ultimately have trust that such devices will not pose any additional danger in their use in-transit.

4.3 Motion Sickness

> **Most affected: Motion Type 2/3 in VR** Transportation that involves frequent and/or significant changes in orientation, acceleration or oscillation (e.g. cars, buses, ships).

As summarised earlier in this book, in Chap. 1.6, the problem of motion sickness has remained ever-present in transportation. Regarding the prevailing theory of motion sickness being a result of a sensory mis-match, MR headsets have the potential to contribute to new forms of sensory mismatch, particularly in the case of VR headsets where reality is entirely occluded [29]. Consider playing a VR game where the player controls their virtual movement independent of that of the vehicle. This could result in conveying no motion visually when the vehicle is moving, conveying motion visually that is entirely different to what is physically perceived (e.g. the car turns right but in the VR scene the view turns left) or even conveying motion which matches the physically perceived motion but at a different magnitude. The effects of such circumstances are largely unknown, but it would seem likely that they will create new opportunities to cause motion sickness.

4.3.1 Resolving This Challenge

MR headsets can contribute towards both understanding the causes of motion sickness, and fixing the sensory mismatches that result from it. As McGill et al. demonstrated [29], if the motion that is visually conveyed via the headset is congruent with what is physically perceived, motion sickness will be minimized. It may also be possible to blend visual motion cues with other stable content allowing for a general purpose presentation of motion for any content type, as initially shown by McGill et al. by peripherally blending motion cues with content in VR, and Meschtscherjakov et al. by blending motion cues at the edge of a tablet display [60]. Headsets can also visualize unseen motions, for example showing orientation changes when below decks on ships [61, 62].

If the vehicle is moving uniformly (e.g. no orientation changes, constant velocity), such as in a passenger aircraft after takeoff, motion sickness may not arise [63]. Provoking anticipatory responses to motion through the vection illusion has also shown some promise [64]. Soyka et al. incorporated motion into VR in the form of a magic carpet ride, finding that *"brief exposure to turbulent motions [does] not get participants sick"*, suggesting that VR use in-flight may not pose the same motion sickness risks as in other modes of transport [65]. VR has even been used to reduce seasickness [66] by providing passengers below decks with a visual awareness of the orientation changes of the ship.

MR headsets also offer new possibilities for deploying vestibular counter-stimulation or desensitisation, for example through wearable neurostimulation devices (such as directional Galvanic Vestibular Stimulation (GVS) [67]), in conjunction with visual manipulations, to compensate motion perception to reduce motion sickness. Entirely virtual displays can be presented anywhere around the user, potentially minimising car sickness, given that positioning in-car displays at eye-height has been shown to have a significantly beneficial effect to motion sickness [68]. At a higher level, Iskander et al. [69] suggested that to provide resilience against motion sickness, efforts need to be made toward a framework that would encompass a "passenger-centric component" for measuring onset through physiological state; a "vehicle-centric component" for tracking the vehicle state and adjusting the environment of the vehicle; and an "infotainment system with smart AV apps which are motion resilient" (e.g. through counter-measures identified by the likes of McGill [29] or Meschtscherjakov [60]. There are a number of questions around the counter-measures to be considered:

Visual motion cues What motions need to be conveyed (orientation, acceleration, velocity etc.)? What are the design parameters (e.g. perceived magnitude of motion [70], portraying accelerations versus velocity, the necessary perception of optic flow [71, 72])? How can visual motion cues be presented in virtual experiences, either interleaved with content or shown in a content-agnostic manner (e.g. as with the peripheral motion cue examined in [29])?

Motion cue timing When should motions cues be presented? For example, based on user preferences or motion thresholds in an attempt to minimise the visual disruption or distraction the cues might cause;

The importance of rest frames Having previously been shown to be important for simulator sickness [52, 73] (see Fig. 5.4 for examples of usage for immersion), what role should rest frames play in perceiving real-world motion? Is it disconcerting or motion sickness inducing to experience motion without some form of rest frame?

Anticipatory motion cues/Compensatory neurostimulation Displaying impending motion can help but more needs to be done to fully understand this [74]. We could, for example, trick the MR passenger into mimicking anticipatory motion actions as performed by drivers. Neurostimulation is one viable approach here, with techniques such as directional GVS [75] or galvanic cutaneous stimulation (GCS) [76] able to compensate for the absence of actual physical movement by stimulating the head through a small amount (< 2 mA) of direct electric current or low-frequency ($<$10Hz) alternating current. The induced movement includes head rotation and body sway. The perception of these movements can be real or illusory depending on if users are standing or sitting [77]. Although the number of stimulation electrodes used can be as many as four to induce movement about all three axes (pitch, raw and roll), the principle behind directional GVS or GCS techniques is that the user will turn or sway from the direction of cathodal to the direction of anodal electrode(s) [78].

Inhibitory neurostimulation By employing techniques such as high-frequency GVS [79] or cathodal transcranial direct current stimulation (tDCS) [80], motion sickness can be inhibited. This type of inhibitory technique is the opposite of the compensatory ones, instead inspired by the fact that individuals with no vestibular system (such as deaf people or individuals with damage to the inner ear) are not susceptible to motion sickness [81]. Specifically, inhibitory GVS techniques usually adopt a fixed (e.g., 40 Hz) or randomized ($<$100 Hz) high-frequency noisy current (zero-mean amplitude) to reduce the signal certainty of vestibular sensory organs [79, 82], while cathodal tDCS aims to reduce the signal reliability of vestibular cortical area [80]. These have been shown to delay the onset of motion sickness by resolving visual-vestibular conflict.

5 Impediments to Acceptance and Adoption

At this point, we assume that MR headsets can discriminate between user and vehicle motion, have been certified to be safe in the event of a crash, and provide effective measures for preventing the onset of motion sickness. The next challenge is to provide acceptable and compelling MR experiences that would justify their adoption and use. We focus on four challenges that we consider most pressing: understanding and designing for acceptable use in shared transit; supporting interaction in constrained or confined spaces; supporting bi-directional social at-a-distance experiences (e.g. holoportation-style telepresence [27]); and exploiting vehicle motion and context for entertainment.

5.1 Acceptable Use in Shared Transit

Most affected: Transportation shared with members of public (e.g. planes, trains, carpooling).

Our use of MR headsets in shared transit is challenged by a multitude of factors: the social and cultural norms regarding our fellow (known and unknown) passengers, the context of our travel environment, and the practical challenges introduced by occluding reality (particularly focusing on VR headset usage). Regarding social acceptability, consider a VR game that uses grabbing gestures in mid-air. Whilst likely acceptable at home or in private, on a public bus such behaviour could be extremely unacceptable and even disruptive to other passengers. When interacting with technology that is highly visible to others, such as a headset occluding the face, the sustained spectatorship of other passengers creates a potentially uncomfortable situation for both users and passengers alike [83].

Our travel context may affect our willingness to wear an MR headset or engage in an MR experience. For example, travelling with close knit groups, such as friends or family, could bring with it social pressures to converse or engage in shared activities to pass the time. Passengers might exhibit very different attitudes toward MR headset use when sharing a flight with collocated strangers (where the VR headset might even be provided by the airline [33, 34]), during a daily commute when carpooling or on the train, or on a late-night bus journey. There are a multitude of contextual factors at play, from the nature of the physical environment and proximity/relationship to other passengers, the duration of travel, to perceived personal safety within the mode of transport. There will be cultural effects, with research noting that different cultures often have different attitudes and expectations when it comes to socialising with other passengers in-transit [84–86]. Will the person you are seated next to on your long haul flight resent your immediate escape into the solitude and isolation of an immersive VR experience?

Occluding reality while in transit could even result in issues that could make headset use unacceptable or even unsafe. Loss of awareness of other passengers means that VR/AR users may accidentally disrupt others or physically invade their space [41]. Fellow passengers may not know if they are visible to a headset user and be unsure how or if they can interact with that person (e.g. needing to squeeze past them to stand up). Emergent situations more generally - turbulence on a plane, the entry of drunk passengers to the bus - might change the acceptability of MR activities, if the user is even aware that such situations are occurring. As a blogger noted of their VR in-flight experience:

> Once it becomes clear that you can see someone through the hardware, even though they can't see your eyes, people don't seem to know how to react. I turned on the camera once or twice just to look around, and a few people were openly gawking at me... It also felt way too strange to play any game that forces you to look around in an active way. It seemed almost weird to be sitting in tight space, whipping my head around to look at things only I could see. [38]

Interaction with other passengers and staff is often unavoidable, for example to ask for directions or to move out of the way. In this anecdotal experience [38], the flight attendant reacted to the VR user by *"pass[ing] by without asking if I wanted anything"*, given there was no obvious/acceptable way of interrupting them. Safety becomes an issue if headset wearing passengers are unaware of safety announcements and cannot react quickly to dangerous situations. There are also practical reasons to need awareness of immediate surroundings, for example to protect your belongings or to know when to get off of a bus. The fact that users would actively choose to occlude reality may also be unacceptable [18], leading to tensions between passengers.

5.1.1 Resolving This Challenge

Aspects of this challenge may be resolved in time, given changing attitudes and exposure to MR headsets would be likely to influence passenger acceptance and adoption. However, research can make it easier for users to conceive of using these headsets in shared spaces. For example, social acceptability can be approached through more discreet, wearable and even fashionable form factors [87], and the design of interactions that are equally nondescript to carry out (see Challenge 5). We could imagine that a reliance on head-orientation/gaze-based selection might not be appropriate if it gives rise to the appearance that the user is staring at another passenger, perhaps requiring a different input modality better suited to the plane environment.

Social and cultural norms will evolve, and we would expect that new norms would arise. But tensions here could be eased, particularly for VR usage, if we could appropriately tackle the issues of occlusion, and awareness [88], of reality. The integration of cameras into VR headsets, particularly aiming at inside-out tracking, would could lead to headsets that can provide mediated awareness of reality, potentially improving social acceptability. For example, co-located people can be visualised in a virtual scene using depth sensing for a mixed reality experience [42, 89]. Cameras incorporated into headsets can also be used for mixed reality, for example the "Pass Through" views on the Oculus Quest or Gear VR which use a front facing camera to provide a view to the real world in virtual reality. Some travel contexts may be better suited for early adoption of VR/AR, for example air travel [34, 41], where passengers must spend extended periods of time in an enclosed and monitored space where other passengers have been security screened.

Of particular note are solutions initially proposed by Williamson et al. for in-flight VR [41]. They identified key mechanisms by which the acceptance of in-flight VR usage could be improved, by both facilitating easier transitions between virtual and physical environments by utilizing mixed reality, and supporting interruptions from co-located "outsiders" such as other passengers or staff. Supporting awareness of the real world, and providing mechanisms by which the real world can acceptably encroach upon the VR experience would appear key to the adoption of VR passenger experiences. Further research will be required to understand how acceptability varies by passenger context. It is likely that more can also be done to utilise the available headset sensing, and design more discreet interactions, to make these experiences more acceptable. There are significant open research questions regarding:

- **Providing awareness of proximate persons** How should MR headset wearers be informed of the actions, attention and proximity of other passengers or staff?

- **Providing external awareness** More broadly, how can passengers be kept aware of external events occurring within the vehicle in ways that do not break presence/immersion, e.g. if public announcements are being made on the train?
- **Facilitating interaction between passengers and proximate persons** How can other passengers or staff gain the attention of, or communicate with, the headset wearer? How should necessary interruptions be facilitated?

5.2 Interaction in Constrained Spaces

Most affected: Transportation with restricted seating in close proximity to others (e.g. economy airline seating).

MR users in homes and offices will be accustomed to rich support for interacting with virtual content. Currently, it is standard for VR headsets to support either on-headset buttons and touch sensitive surfaces, or hand-based interactions using controllers, providing haptic feedback as well as capacitive touch input. Further work is ongoing to incorporate necessary elements of reality into VR experiences, e.g. physical keyboards [42, 90, 91]. Conversely, AR headsets such as Hololens have demonstrated peripheral-free, touchless interactions using hand tracking technology. However, existing interaction paradigms for VR and AR headsets do not take into account:

- The physical constraints of a seated MR passenger (e.g. [92])
- The capabilities and affordances of a given instrumented, connected, interactive vehicle environment (e.g. a car dashboard or plane cabin with seat-back display)

With reference to the constraints, the most obvious is that of the physical seating. Regardless of if the user sees it as socially acceptable to perform body-based gestures [93] or use tracked handheld peripherals or controllers, the physical environment, seat belts and the proximity of those seated nearby will dictate that more discreet gestures or interactions be performed. Regarding existing capabilities and affordances of a given passenger vehicle, the way drivers and passengers use in-vehicle infotainment systems is ever-changing. For example, physical buttons and dials for the control of in-vehicle systems have been substantially reduced with the introduction of touchscreens and touch-sensitive surfaces (e.g. the Tesla Model 3.[6] This is already a common sight in long-haul plane journeys.

[6] www.tesla.com/model3.

5.2.1 Resolving This Challenge

Research will be required to explore the suitability of existing MR interactions transposed to constrained, in-motion contexts [94]. For example, hand-based gesturing may be impaired by the physical constraints of the environment, social acceptability and limitations regarding headset-based sensing. More unobtrusive, eyes-free interactions could bridge this gap, for example the NotifyEye eyes-free rub pad [24]. Supporting such interactions could require integration of sensing (e.g. Leap Motion [95], Soli [96]) and feedback (e.g. ultrasound haptics [95]) into the vehicle. These constraints will also impact how MR (with an emphasis on VR) content is viewed, given that physical limitations regarding neck and head movement would necessitate that either the content be restricted to a narrower field of view, or some other means of scrolling/changing orientation be provided (e.g. rotational gain [97]), to prevent users from being unable to fully attend to the virtual 360° space.

Where available, touchscreens and touch-sensitive surfaces on centre consoles and arm-rests areas could provide an additional, richer input modality for users during MR interactions, and give designers the opportunity to develop new input techniques for passengers that are perhaps suitable for MR experiences in the future. However, this will require further advancement regarding how we incorporate necessary elements of reality into MR (and particularly VR) experiences [42], and necessitates the interactive environment of the vehicle be tailored or made accessible to the MR headset. Related work has investigated the how well drivers and passengers point [98] and perform common gestures such as swiping [99] on touchscreens in moving vehicles, as precise input can be difficult. The use of pressure input is becoming more popular with touchscreen smartphones, so researchers have also begun to explore in-car touchscreens and surfaces with force-sensing capabilities to look for alternative input modalities that could be more effective and safer to use in vehicles [100, 101]. New technologies such as printed sensors and actuators could be added to many more vehicle surfaces to provide users with multiple inputs with haptic feedback to interact with AR and VR applications [102].

There are open research questions to be answered. Firstly, how to design new MR peripherals suited to constrained spaces; from new positionally tracked peripherals that can function in-motion, to appropriating existing peripherals such as smart watches/phones/rings. Secondly, how to bring tangibility to virtual displays and interactions. For example, direct hand-based mid-air interactions with virtual displays or UI elements could be made tangible by appropriating existing surfaces (including existing interactive elements such as touchscreens) and appropriating existing and new feedback modalities (e.g. mid-air ultrasonic haptics has been repeatedly suggested for non-MR passenger use). This latter point in particular is one with much wider applications to VR/AR usage across a variety of contexts. The passenger MR use case suggests that appropriating existing surfaces is particularly worth exploring, given these physical surfaces (e.g. seatbacks, tray tables, doors, arm rests, etc.) are within easy reach. Finally, how should the multiple possible displays in MR be arranged for seated travelling environments. When multiple displays or applications are open at the same time in MR, we need to ensure the user can view and input on each display in comfort and with minimal head movement, especially when other passengers are nearby. To switch between displays, we suggest device-based commands, for example, left or right swipes on a touchscreen, rather than using head tracking-based techniques, for ergonomic reasons. How to optimally arrange multiple displays in confined spaces is still an open research area.

5.3 Supporting Shared Experiences

Most affected: Transportation that features a degree of privacy to allow for speech (e.g. autonomous cars).

Social VR has been suggested as a significant driver of adoption of MR headsets, precipitating events such as Facebook's $3 billion purchase of Oculus in 2014 [103]. MR headsets have the capability to change how we communicate at-a-distance. Prior to such headsets, communication was limited to voice and video. However, MR headsets have the capability to render virtual content with depth and real-life scale and thus support embodied telepresence, where those the user is communicating with at-a-distance are seen to be sharing the same virtual (e.g. [26, 104]) or physical (e.g. [27, 105]) space. This application could be suited to transportation where social acceptability is less of a concern, for example use in private autonomous cars.

5.3.1 Resolving This Challenge

Firstly, there is the question of how the passenger should be captured and portrayed at-a-distance. Currently, shared at-a-distance VR applications typically display an avatar conveying head movements and voice [103]. However, advances in depth

Fig. 4 Examples of embodied virtual social experiences. Left: VRChat, a VR social platform with voice chat and customized avatars for lower fidelity, but more broadly accessible, embodied telepresence [104]. Middle: A VR-based mixed reality experience where users could see each other captured in real-time and view a synchronised 360° experience [26]; Right: An AR-based mixed reality experience, 'Holoportation', where users could see each other captured in real-time [105]. Each brings with it different logistical challenges in terms of capture of users and presentation whilst in-transit

camera technology can allow for body tracking and embodied telepresence (e.g. [26, 27, 105], see Fig. 4) where the remote user is captured and rendered in 3D. To capture passengers in-car would require the integration of depth camera technology, thus it is likely that more cost-effective approaches will need to be investigated, e.g. portraying avatars on the basis only of what sensing is available on the headset [106]. Secondly, it is also unclear how best to render others at-a-distance in such environments, especially for AR headsets that have to incorporate reality in the presentation. Telepresence literature has often concentrated on room scale spaces, where a mapping between two disparate physical places could be constructed, essentially allowing direct interaction with virtual avatars [26, 27, 105, 107]. However, when using an AR headset in the constrained environment of a car or plane, such interactions are no longer feasible, as the existing physical space needs to be taken into consideration in the presentation. In such cases, should those at-a-distance be incorporated into the car or plane as other virtual passengers taking up empty seats, or rendered world-in-miniature for viewing by all passengers? It may even be the case that existing video communications enacted over AR [108] are the most appropriate for such constrained spaces. We suggest there are open research questions regarding:

How to capture and convey passengers? Different forms of transportation will likely be suited toward different sensing technologies for capture, depending on whether sensing can be integrated or must be carried in by the passenger;

How to render at-a-distance participants? This is of a particular challenge for AR headsets, as any telepresent portrayal would be constrained by the physical environment.

5.4 Exploiting Vehicle Motion and Context for Presence and Immersive Experiences

Most affected: *All forms of transportation.*

The motion, location and context of the vehicle itself can be instrumented and utilized to create more novel, engaging, immersive experiences. This point notably extends the discussion on motion sickness: where previously motion was being integrated to alleviate sensory mismatch for generic MR content, here the intention is to both alleviate the sensory mismatch whilst more deeply integrating the experience of motion into the virtual experience, taking advantage of sensory alignment [109]. The outcome of this could, for example, be turning your ordinary car journey into an exciting 100 KPH space battle, providing a more affective experience by using the vehicle as a motion platform.

Kodoma et al. [110] categorized the use of cars as motion platforms for VR content as being either (a) an active virtual drive system, meaning that the VR user controlled the car, with the experience in VR reflecting that of reality (effectively substitutional reality [111]); (b) a passive virtual drive system, meaning that the motion of the car was integrated into the VR experience, with content limited by the driving route, but the VR user exhibited no control over this (e.g. in autonomous cars/the passenger use case); (c) A content player system, whereby the motion of the car was synchronized with the VR environment.

They examined a content player system, where users had limited control over the car (controlling acceleration over a 7m track) and the content was synchronised with the motion along one axis (acceleration forward). The VR content was effectively a rollercoaster, and it was noted that, due to the congruent visual and physical motion cues regarding the forward motion, the additional visual cues of the rollercoaster going downhill induced a significant sensation of falling, despite there being no physical vertical motion experienced. This concept of having VR users control their vehicle was extended by Goedicke et al.. They adopted a ‘fused reality’ approach where passenger driving actions could be simulated by a real driver as a Wizard-of-OZ prototype [112], as a means to creating VR driving simulations which retained the “immediacy and rich sensations of on-road driving”. These papers help to illustrate the breadth of ways in which the relationship between the MR-wearing passenger and vehicle can be exploited.

5.4.1 Resolving This Challenge

There are eight factors to consider when using the vehicle to positively affect immersion:

Control over motion Control can range from active (full MR user control) to passive (no control, MR user is passenger). As noted by [110], this is perhaps the most problematic factor, as there are clear safety concerns regarding how much control the user is given over the experience. However, envisioning a fully autonomous car where the virtual experience or user has some measure of control over acceleration (e.g. varying between 80 and 120 km/h on a motorway), could be feasible in certain circumstances (e.g. a clear road), as demonstrated by [112];

Foreknowledge/Synchrony Foreknowledge can be both of the route and the impending vehicle actions, building upon the previously discussed benefits of anticipatory movements and actions [64] toward increased presence, e.g. seeing and feeling your virtual experience follow the same path [112]. Used particularly by Paredes et al. to create a calming, mindful VR experience in-car [113];

Context Context can encompass knowledge/sensing of the specific real-world location, e.g. rendering overlays on other cars in AR experiences[39], integrating elements of the real world such as landmarks into the passenger experience [114], or reacting to detected events [40] such as a red light being conveyed as a temporary virtual wall;

Motion Profile Different vehicles can have very different motion profiles. Compare a cross-country train with long periods of relatively constant velocity followed by long, steady changes in acceleration, versus autonomous vehicles driving around city streets;

Conveyance of Motion Movements could be conveyed in terms of changes in acceleration, or absolute velocity. Each would have implications for the kind of MR experience being presented, e.g. 'on the rails' virtual journeys versus seemingly stationary experiences with additional visual cues of motion (e.g. particles moving around the user, displays moving back and forth based on accelerations [115]).

Magnitude of Motion The transfer function between real-world motion and MR rendered motion has been shown to be able to be varied significantly in room-scale VR [116] without impacting simulator sickness. Translational and rotational gain could be manipulated to enable more exciting (e.g. conveying 30 km/h in reality as 100 km/h in VR, or conveying a modest acceleration as a significant one) or calming (conveying accelerations as if gentle movements of a rocking chair) virtual motion experiences;

Environmental Control Consider concept cars where temperature, air flow, and even odour [39] can be controlled by the virtual experience to increase the user's sense of presence in a virtual experience;

Anchors/Rest Frames Rest frames have been noted to be helpful in preventing motion sickness onset [52, 73], and such visual anchors could be exploited to convey very different environments, e.g. the cockpit of a spaceship, exploiting substitutional reality to render virtual elements that are physically congruent with the vehicle interior [111]. There have been few other concrete examples of exploiting motion for immersion thus far. With respect to VR headsets, Soyka et al. simulated a flight experience on a virtual magic carpet ride, with the intention that airline passengers would experience their journey across a virtual landscape with unrestricted views [65]. Hock et al. presented the movements of a car in a virtual cockpit of a helicopter flying over a pre-generated virtual landscape based on a pre-determined route for the car [52]. In effect, the car journey was gamified and turned into a first-person virtual helicopter shooter, with passengers flying around a new and different landscape during their journey. Hock et al. found that the kinesthetic forces perceived by users increased enjoyment and immersion, whilst reducing simulator sickness. Similarly, there exists a number of consumer rollercoaster rides where the virtual experience is tightly linked to the physical motion perceived, to varying degrees of success [117]. This congruence of visual and physical perception of motion delays or prevents the onset of motion sickness. Moreover, Hock et al. noted that the virtual portrayal of car motion resulted in some participants completely losing awareness of where they were, as well as distorting their awareness of the passage of time. This suggests that occluding reality can in-part aid the passing of time in transit, a notable potential benefit for long-haul flights, for example. Commercially, Apple has submitted a patent regarding congruent in-car experiences [40] whilst former Audi spin-off Holoride

[118], as well as Renault and Ubisoft ('Symbioz'), have demonstrated VR concept cars that exploit route foreknowledge and context to render motion:

> A minute ago I was on a real road, but now I'm rolling down a fake forested highway in a simulation created by Ubisoft. Meanwhile, Renault's Level 4 autonomous system has taken the piloting chores... It's a bizarre experience, but I don't feel sick, because the Symbioz is transmitting real road motion to the headset... I even see simulated versions of the cars and trucks on the road fed in by LiDAR and other sensors. [39]

Whilst there are a number of discussions regarding AR use in-car for aiding driving and navigation, there are few examples of AR headset usage by passengers. However, discussions of AR windscreen and windows [10–13] hint at potential applications, for example augmented annotations of locations and landmarks [114, 119] and identifying points of interest for tourism. Moreover, video-passthrough approaches mean that VR-oriented headsets may be the first to provide truely MR experiences for passengers, as particularly demonstrated by Volvo.[7]

Broadly, what these prototypes demonstrate is that the motion and location of a vehicle can be integrated into MR experiences in a variety of potentially engaging and affective ways. Virtual gamification of vehicle motion, and using AR as a virtual tour guide are two examples that have the potential to fuel adoption of MR headset usage in vehicles, whilst retaining a direct link between what is visually and physically perceived. This is the most immediately accessible use case of MR headsets in transit when considering motion sickness. Moreover, such experiences are unique to transit because they require some congruent element of reality to be incorporated, providing additional value to MR headset use beyond standard entertainment and productivity. However, a breadth of further research will be required to understand the design parameters for each of the factors identified.

6 The Potential Impacts of Passenger MR

Adoption of MR headsets in the home and office will lead to user expectations that such usage will continue when travelling. Accordingly, users should be provided with as close to the same capabilities when in transit as possible, such that they might perform the same actions, view the same content and communicate in the same way at-a-distance. The challenges and impediments discussed here are those we would consider key in establishing this parity.

It is important to note that the need to address these challenges is predicated on MR headsets falling into favour with consumers. VR headset adoption has recently stumbled, with the suggestion being that the cost, limitations in terms of fidelity, and a lack of compelling experiences and use cases has led to some consumer apathy, with suggestions that VR is in the "disappointment phase" of the consumer hype cycle [120]. Microsoft have suggested that immersive VR headsets "did not meet, in general, the high expectations that were set for them" [121]. AR headset adoption

[7] https://group.volvocars.com/news/future-mobility/2019/varjo-collaboration.

is not yet even a feasible possibility, with no compelling consumer-level headsets available in 2020, although this will inevitably change. Over time, it would seem reasonable to suggest that passenger adoption of VR headsets would be likely in long duration journeys in uncomfortable environments such as economy seating on long haul flights. The likelihood of AR headset adoption would appear stronger over the coming years, particularly if AR headsets reach a point where they become standard, everyday consumer devices. For both AR and VR, compelling use cases, such as productivity and entertainment will help to drive headset adoption only once headsets reach an inflection point across cost, fidelity, sensing capability, interaction, social acceptability and fashion, amongst others. If such a point is reached, it could be expected that demand for passenger usage would soon follow.

As recognised by both car manufacturers such as Renault [39], technology companies such as Apple [40], and commercial airlines [33, 34], the reward for facilitating such usage could be significant. MR headsets have the potential to provide new and varied ways by which travellers can make use of their time in transit, and could provide an additional motivator toward the adoption of transportation such as autonomous cars.

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