A Lack of Restraint: Comparing Virtual Reality Interaction Techniques for Constrained Transport Seating

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Abstract— Standalone Virtual Reality (VR) headsets can be used when travelling in cars, trains and planes. However, the *constrained spaces* around transport seating can leave users with little physical space in which to interact using their hands or controllers, and can increase the risk of invading other passengers' personal space or hitting nearby objects and surfaces. This hinders transport VR users from using most commercial VR applications, which are designed for unobstructed 1-2m 360° home spaces. In this paper, we investigated whether three at-a-distance interaction techniques from the literature could be adapted to support common commercial VR movement inputs and so equalise the interaction capabilities of at-home and on-transport users: Linear Gain, Gaze-Supported Remote Hand, and AlphaCursor. First, we analysed commercial VR experiences to identify the most common movement inputs so that we could create gamified tasks based on them. We then investigated how well each technique could support these inputs from a constrained 50x50cm space (representative of an economy plane seat) through a user study (N=16), where participants played all three games with each technique. We measured task performance, unsafe movements (play boundary violations, total arm movement) and subjective experience and compared results to a control 'at-home' condition (with unconstrained movement) to determine how similar performance and experience were. Results showed that Linear Gain was the best technique, with similar performance and user experience to the 'at-home' condition, albeit at the expense of a high number of boundary violations and large arm movements. In contrast, AlphaCursor kept users within bounds and minimised arm movement, but suffered from poorer performance and experience. Based on the results, we provide eight guidelines for the use of, and research into, at-a-distance techniques and constrained spaces.

Index Terms—Virtual Reality, Interaction, Constrained Spaces, Transport

1 Introduction

With the mainstream adoption of standalone Virtual Reality (VR) headsets, users can take their devices on public and private transport such as cars, trains and planes, to make their journeys more enjoyable or productive [16,23,28,32]. However, these users are forced to interact in heavily *constrained spaces*: limiting the freedom of physical movement for traditional VR interaction compared to traditional 1-2m^2 home environments that commercial VR experiences are designed for. The size of the virtual space is greatly reduced by nearby seats, walls, tables and passengers, as well as the social acceptability of performing actions in public or where there's a risk of invading personal space [5, 60]. Therefore, alternative interaction techniques are needed to allow transport users to access larger virtual spaces from constrained physical ones. HCI research has proposed techniques for interacting beyond physical reach [9, 11, 21, 25, 33, 44, 48, 59, 62, 63], but these have not been tested under conditions of *constrained spaces* and limited arm movements that need to stay within small boundaries. Further, they have been designed for only selection [21, 25, 48, 59, 63] or selection and manipulation [44, 62] actions, and utilise controlled, abstract tasks that are not representative of commercial VR experiences.

In contrast, commercial VR applications - such as those on the Steam [55] and Oculus/Meta [39] stores - are designed to be used in open and unobstructed 1-2m^2 home spaces, where users can move freely within the 'guardian' safety boundaries [38]. They also involve a range of physical movements and actions that go beyond base reaching or selecting: many games involve swinging weapons, shooting guns, climbing and social gestures. While many of these actions are built on similar primitive components as existing research techniques (*e.g.*, pointing, direct grasping) they do so in ways that require large, fast and uncontrolled movements at unpredictable times. Such movements would be problematic in constrained transport settings, as they would be more likely to violate boundaries and result in hitting vehicle architecture or nearby passengers, or engage in socially unacceptable behaviour [5, 60]. Therefore, transport VR users are left unable to safely or acceptably make use of many available applications.

An additional limitation in a lot of at-a-distance VR interaction research is a lack of consideration for how the technique might affect key phenomena and benefits of VR such as presence [50] and embodiment [19]. The use of controlled selection/manipulation tasks (*e.g.*, [21, 48, 59]) and abstract/empty environments (*e.g.,* [25, 48, 59]) may not strongly induce presence (or plausibility) [50, 54], and the use of 'supernatural' abilities, non-humanoid controller models and a lack of a user avatar (*e.g.,* [23, 25, 59, 63]) may not strongly induce embodiment [19], though this may be task-dependent [26, 34]. While the task performance of research techniques has been established, at-a-distance research should also consider how wider user experience is affected.

The situation leads to three key challenges for in-vehicle VR experiences: 1) equalising the interaction capabilities of travelling and at-home users (as much as possible) and doing so in a way that 2) keeps users within the constrained interaction guardian boundaries and 3) maintains immersive illusions such as presence and embodiment. To start to address these challenges, this paper identified the most common motion-based VR input actions in commercial applications and implemented them in gamified experimental tasks intended to be representative of commercial VR experiences. We then ran a user study that adapted three at-a-distance research interaction techniques - identified as best-performing across common categories - to perform each action in the game: *Gaze-Supported Remote Hand* [62], *Input Gain* [21] and *AlphaCursor* [63]. We measured task performance, VR boundary-crossing behaviour, arm movement and subjective user experience, including presence and embodiment. By comparing metrics to an 'at-home' control condition involving traditional, unobstructed movement, we identified that Linear Gain is best able to equalise at-home and in-vehicle user ability and experience, but at the expense of more boundary violations and increased arm movement.

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2 Related Work

2.1 VR on Passenger Transport

The use of Virtual and Augmented Reality (collectively XR) in transport settings, such as autonomous vehicles [17,46,51], trains/buses [4,5,49] and aeroplanes [2, 36, 45, 60] is becoming an area of research and industrial focus. Early vehicular VR research instrumented cars with orientation, velocity and location sensors and used the data to drive immersive game [16] or media [29] experiences that followed the motion of the car. Similar functionality is used by Holoride [17], a commercial car-based VR entertainment company, and McGill *et al*. [31] have created an open-source any-car sensor platform for vehicular XR. Based on these principles, researchers have developed several applications, including driver interfaces [8, 12], rear-seat productivity [23], mindfulness experiences [40], AR games [56] and motion sickness mitigations [24, 29], a key challenge in vehicular XR [30]. More recently, research and industry has broadened the use of VR to planes [2, 36, 45, 60], trains [5, 49] and buses [4]. However, travel spaces are very different from traditional XR interaction spaces in homes and offices, and research is only beginning to explore how XR experiences should be designed to suit the physical and social constraints of transport seating.

2.2 XR Interaction Spaces

Both Oculus/Meta [35] and Steam [55] - the two biggest commercial VR application storefronts - categorise VR experiences based on the amount of physical space that is needed to use them: Seated, Standing and Roomscale. Oculus/Meta recommends 1m x 1m for Seated and Standing spaces (with standing spaces potentially requiring a step in any direction), and 2m x 2m for Roomscale spaces. Steam specify a minimum for Roomscale spaces of 2m x 1.5m. PlayStation VR [43] has only one set interactive space (3m x 2m) and does not support full Roomscale experiences. These minimum volumes are based on an assumption that the commercial experiences - predominantly games and media applications - will be used in homes (or potentially offices) where there is likely to be 1-2m^2 of open space to support a wide range of applications. The perimeter of the user's interactive space is typically indicated by a visible boundary, such as the grid-lines in Meta's "Guardian" or SteamVR's "Chaperone". These usually become more visible as the user's hands or head get closer to the boundary, to stop them leaving the space and potentially hitting nearby objects.

2.2.1 Transport XR Interaction Spaces

To characterise the interactive space in real-world transport seating for VR, Schmelter & Hildebrand [49] measured public train seats of different layouts and found that the typical open space was 60cm wide and 80cm deep and most seats had at least one neighbour (or an aisle) that could be inconvenienced by VR movements. SeatGuru [52] shows that the median pitch for economy airline seats is only ~80cm (31 inches) including the seat itself (~5-10cm) and the passenger (average chest depth is 21-30cm [41]), and with a width of ~45cm (17.5 inches). This leaves only ~40-55cm of open space in front. These values indicate how different the available space on transport can be compared to the 1-2m^2 required for commercial experiences (Fig. 1), particularly in terms of width and the risks posed by - and to - nearby passengers.

Li and colleagues have begun exploring the use of rear car seats for VR productivity tasks [22, 23]. They found that users were particularly concerned about hitting something in the car or invading a nearby passenger's space, and so recommended that a productivity interaction volume be confined to a small (undefined) space immediately in front of the user. A follow-up study in a stationary car [23] used an interaction space of 30cm width and 10cm depth with a guardian boundary either absent or always visible during pointing-based productivity tasks. Very few participants accidentally contacted the inside of the car, and having no guardian did not affect feelings of safety, presence or performance. However, the movements involved were relatively slow, small, controlled and not time-sensitive, unlike many commercial VR experiences - particularly games - and so the likelihood of violating boundaries may be more likely in other scenarios.

As can be seen, there are mismatches between the space requirements of mainstream VR applications and the reality of transport seating (Fig. 1). Transport VR users have much less space and are much closer to potential hazards than home users, and so alternative interaction techniques are needed to make larger virtual spaces accessible.

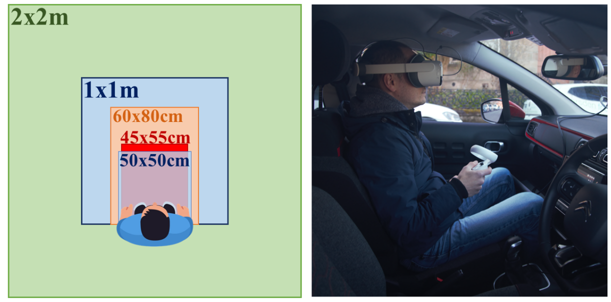

Fig. 1. Left: Space dimensions of commercial VR experiences (1x1m, 2x2m), constrained transport seating (60x80cm [49], 45x55cm [52]), and the spaces used in our study (1x1m virtual space, 50x50cm constrained space, in Blue). Right: VR user in constrained transport seating.

2.3 At-a-Distance VR Interaction

As VR offers potentially infinite interactive spaces, researchers have explored interaction techniques that allow users to select, translate and manipulate virtual objects at variable distances, to speed up interaction time or reduce the need for locomotion. As the mainstream use of VR is based on 1-2m^2 of unobstructed space - where users can already reach freely - most research has explored ways for users to access and control content far beyond reaching distance.

2.3.1 Movement Amplification

Many techniques use some form of *amplification*, or translational gain [61], where the movement of the virtual hand/controller that the user manipulates has a level of gain applied to it, so that it reaches further than the tracked physical hand. These techniques have the benefit of being general-purpose and applicable across experiences, in comparison to techniques that require knowledge of where a target object is (*e.g.*, [25, 48, 62]). Go-Go [44] applies a non-linear gain to the virtual hand once the physical hand is beyond ~2/3rds of the user's reach. However, as the level of gain increases with reaching distance, precise control becomes more challenging, and Li *et al*. [21] found that a linear level of gain led to better reaching performance than Go-Go for targets beyond 30cm. Wentzel *et al*. [59] developed a non-linear amplification mapping based on Hermite splines to improve control and increase reaching comfort, especially at maximum reaching distances.

2.3.2 Volumetric and Gaze-Based Techniques

While movement gain can be a suitable and general-purpose technique, the level of amplification may impact control precision, especially for distant targets [21] or environments with many targets in close proximity [25]. In the context of using VR on transport, the amplitude and variability of vehicle motion could compound this issue. Therefore, a number of techniques have been proposed to improve precision at-a-distance or to make crowded targeting easier. Lu *et al*. [25] designed a number of volumetric (*i.e*., using an interactor constituting a spatial volume) bubble-based techniques for target selection that used the known locations of available targets to either automatically activate the nearest one, or rearrange their locations for easier disambiguation.

Ninja Hands [48] places a volumetric arrangement of multiple virtual hands spread evenly throughout the virtual environment, with the real hand controlling the movement and rotation of all others. Any hand can be used to select a target object, with a queuing system used to disambiguate the currently 'active' target. When interacting within 2m^3 virtual spaces, task time and total physical movement decreased as the number of virtual hands increased, though task error rate also increased. Only target selection was tested, not manipulation, and no measurement was taken of whether the multiple floating hands would affect embodiment or presence.

Rather than solely relying on hand-based input, Yu *et al*. [62] compared four gaze-supported at-a-distance selection and manipulation techniques. All used gaze for indicating the intended target and a controller trigger for selection. They concluded that the addition of gaze may only be of benefit for far distances and large environments, and that their "Remote Hand" technique - where the real hand controls the object where it is located - generally performed well, though they recommend adding translational gain to reduce the amount of movement.

2.3.3 Raycasting Techniques

Raycasting, or pointing, techniques are common VR interaction methods: a visible (or invisible) line is drawn from the user's controller out into the environment to act as an indirect interaction pointer. They allow a user to indicate and interact with objects or interfaces from an arbitrary distance and with minimal arm movement. However, in busy virtual environments objects can become occluded, making raycasting difficult. PRECIOUS [33] combined pointing with temporary locomotion to disambiguate and select objects at far distances. Yu *et al*. [63] compared several techniques also to disambiguate and select targets of varying density. In low densities, where potential targets are placed more comparably to mainstream VR applications, their AlphaCursor technique performed well: a visible raycast where the depth of an interactive cursor on the ray is controlled via a joystick.

2.4 Limitations & Research Questions

There are three important limitations to the work described here: *constrained spaces, embodiment & presence,* and *limited input characteristics*. Few techniques have been evaluated in, or designed for, constrained spaces [23, 57]. Therefore, mappings, algorithms and inputs were not designed for limited arm movement; users and designers did not need to be wary of guardian boundary-crossing behaviour, or how the technique may influence this; and there was no consideration of how the limited space impacted the usability or utility of a technique. Therefore, it is unclear how these techniques will perform, or need to be adjusted, to be suitable for constrained spaces.

Many at-a-distance papers also do not measure how the interaction technique or visual representations of the user and environment affect the user's feelings of *presence* or *embodiment*. These illusions are two unique benefits of immersive devices that underpin the experience of commercial VR games in particular, and could greatly impact user preferences. Researchers need to identify how their techniques may affect them. Finally, research techniques support a *limited range of input characteristics*: almost all support target selection only, or selection and manipulation. While target selection is a core method for assessing interaction techniques, we discuss in the next section how commercial applications - particularly games - involve a range of movements, inputs and actions whose characteristics - *e.g*., the size, speed, control, or required user reactivity - are very different from controlled selection tasks. Therefore, it is unknown how different research techniques might also support these mainstream actions.

Based on the literature, we developed 4 research questions (RQs):

RQ1 *How do at-a-distance techniques perform in constrained space?*

RQ2 *How well do techniques support commercial input actions?*

RQ3 *How is VR boundary-crossing behaviour affected?*

RQ4 *How do different techniques affect presence and embodiment?*

In the following Sections, we identify the most common movement inputs in commercial VR experiences (Section 3), describe the tasks we designed based on these commercial inputs (Section 4), and the chosen at-a-distance interaction techniques (Section 5) to be used in our proposed user study (Section 6).

3 Identifying Movement Inputs in Commercial VR

3.1 Methodology

It is not feasible to perform an exhaustive catalogue of all actions in all commercial experiences (at time of writing Steam contains over 6700 titles supporting VR). Therefore, we analysed the top 25 most popular experiences on the Steam [55] and Oculus [39] stores to identify the most common movement input actions in commercial applications. We only included games that had at least 1000 reviews on Steam, or 500 reviews on Oculus, to ensure the games were sufficiently popular, as "top seller" lists also include recent releases. Most experiences found were common to both lists, and so we made efforts to include experiences exclusive to either platform.

For each VR experience, an author viewed ˜45 minutes of videos of the experience being used on YouTube [13], and looked for different sections of the experience (*e.g*., later parts of a game) to see if different mechanics were introduced. If the experience was available, an author also personally took part in it for ˜20-30 minutes to explore the mechanics more deeply. The full list of experiences that were analysed is provided in supplementary materials and includes 19 games, 2 social applications, 2 sports applications and 1 gambling application. There was a heavy bias towards games, however, many movements/actions identified were seen across application types.

We did not conduct a formal classification, but rather an iterative emergent coding process, where individual actions were given initial codes/categories and then iteratively grouped into higher-level codes/categories based on shared movement characteristics. Because our research is focused on spatial interaction, we only considered actions that required some degree of physical movement of one or more body part; we did not consider button presses or joystick inputs.

3.2 Results

We identified over 200 movement-based actions across the experiences, with many shared/duplicated across titles, and these are included in supplementary materials. These actions were initially characterised under 17 categories, covering the type of movement (e.g., open or closed loop), whether head/torso movement was required, the type of interaction (pointing, selection or manipulation), if it involved reaching or pointing, among others. These categories were then iterated and collapsed into 14 sub-categories under 5 characteristics:

Control Loop: *Open-loop* (ballistic movements with no adjustments) or *Closed-loop* (controlled movements that can be adjusted);

Engagement: *Direct* (virtual hand/head directly contacting the relevant artefact), *Indirect* (engaging an artefact from a distance) or *Freeform* (movement in space irrespective of a specific artefact);

Interactor: *Hand* (via controller or hand-tracking) or *Head* (via headset);

Interaction: *Pointing*, *Selection* or *Manipulation* (including rotation and translation);

Controlled Endpoints: *Start* (the user deliberately controls the start of the movement), *Termination* (the user deliberately controls the end of the movement), *Both* or *None*.

From these categories, and the frequency with which actions were noted across experiences, we identified 7 types of input action that were most common in the commercial applications we analysed, shown in Table 1. It is not practical to include all 7 types of movement in one task, nor have participants engage in 7 tasks with each of several interaction techniques. Therefore, for this first study, we included only 4 of the movement types - those we hypothesise will be most impacted or restricted by constrained interaction: *SwingArm, AimArm, DirectGrab* and *Manipulate* in Table 1. While constrained spaces have ramifications for any body movement in VR, this study focuses on arm-based interactions, and so the two headset-related categories (*MoveHead* and *Looking*) were not included at this time. *PointArm* - controlled 3D pointing movements for *e.g*., interacting with menus or pointing a torch - do not contain a depth component to them, and includes no reactive component, and so are less likely to be impacted or problematic in constrained spaces.

SwingArm corresponds to open-loop (*i.e*., uncontrolled) movements that directly engage with an artefact in VR as a means to manipulate it, and includes common actions like swinging weapons, punching or throwing objects. These actions are typically fast, reactive and do not have a controlled start or end-point, and so are potentially problematic for staying within constrained interaction boundaries. For the current study, we implemented this type of movement in a *Sword-Swinging* game.

AimArm relates to open-loop pointing movements with a controlled termination point, typically for the purpose of aiming a gun or a spell-casting hand at an enemy. It is imilar to standard 3D pointing in VR, however, like *SwingArm*, these movements are often fast and reactive (*e.g*., aiming at a suddenly visible enemy), although having a controlled

Name	Example Actions	Example Games	Control Loop	Engagement	Interactor	Interaction	Endpoints
SwingArm	Swing weapons, throw grenades	"Blade & Sorcery", "Onward"	Open-Loop	Direct	Hand	Manipulation	None
AimArm	Aiming guns or spells	"Robo Recall", "Zenith"	Open-Loop	Indirect	Hand	Pointing	Termination
PointArm	Aiming torch, social gestures	"Walking Dead: S&S", "VR Chat"	Closed-Loop	Indirect	Hand	Pointing	Both
DirectGrab	Grab objects, activate door	"Half-Life: Alyx", "Skyrim"	Closed-Loop	Direct	Hand	Selection	Both
Manipulate	Moving objects, climbing	"Boneworks", "Stormland"	Closed-Loop	Direct	Hand	Manipulation	Both
MoveHead	Ducking & avoiding	"Pavlov"	Open-Loop	Freeform	Head	Manipulation	None
Looking	Looking, investigating	"Walkabout Mini Golf"	Closed-Loop	Freeform	Head	Manipulation	Both

Table 1. Common types of movement input actions from popular commercial VR experiences, with examples. Those in blue were used in this study.

termination may make them less prone to boundary-related concerns. We implemented a *Shooting* game to test this type of movement.

DirectGrab and *Manipulate* often occur in sequence, and are like traditional 3D manipulation in VR. *DirectGrab* is a closed-loop - and so controlled - movement to directly engage an artefact for the purpose of selecting it, such as grabbing hold of an object, tapping a spatial menu, or opening a door by reaching for a UI prompt. *Manipulate* is then the closed-loop manipulation of a directly engaged artefact, such as moving an object, turning a door handle or climbing up a cliff. These involve spatial translation and rotation of the hand. While these two movements typically involve more controlled start and end points, commercial applications require freedom of arm movement to any point in space, including to the sides, above or below the user, as well as quick user reactivity, which could lead to constrained boundary violations. Time pressures in a game may also lead to less controlled reaching. We implemented a *Selection & Manipulation* game to analyse these two types of movement in one task. This deliberately goes against recommendations to analyse them separately [6], as we wanted more representative tasks to assess each technique's suitability for commercial VR applications. The next section describes the *Selection & Manipulation*, *Sword-Swinging* and *Shooting* experimental tasks.

4 Experimental Tasks

We developed 3 gamified tasks to test how well each at-a-distance interaction technique (Section 4) could support the four chosen commercial movement types. We chose gamified tasks for two reasons. Firstly, we wanted to test the techniques in scenarios that were more representative of the commercial games we want to provide support for. These involve more realistic, recognisable locations, events, artefacts *etc*., but also game elements like time pressure, penalties and achievement, which may increase immersion or engagement [47,53], and potentially reduce awareness of the boundary or external environment. Secondly, we were interested in measuring how each technique affects a user's experiences of presence and embodiment, and a highly controlled, abstract and empty virtual environment (VE) [6] would be less likely to strongly induce these illusions [19,50], leaving it harder to measure effects.

4.0.1 Constrained Interaction Space

We chose to use a *constrained interaction space* of 50cm (W) x 50cm (D) by 60cm (H), to provide a realistic constraint similar to economy airline seats [52] and slightly smaller than train seats [49]. The width/height consisted of 25cm/30cm on either side of the centre of the chest, and the full 50cm depth started at the headset. We chose to use a virtual space of 100cm x 100cm, the size recommended by Meta for Seated and Standing experiences, (by far the most numerous on the Steam/Meta app stores). We also used a 100cm x 100cm space for the at-home control condition. Therefore, participants were to interact with a virtual space twice the size of the constrained interaction space, and the same amount of virtual space as would be available at-home.

4.0.2 Game Setting & Conceit

The setting for all three tasks is a fairground mini-game stall: the player is in a booth where one might play games like fishing for ducks, throwing a ball at targets or firing a water-gun. The VE shows a fairground setting with rides, props and visitors [18] (Fig. 2). In each game, the player is standing inside a stall, facing into the fairground, to give them an immersive viewpoint. They are unable to move out of the stall (there is no locomotion) but they can rotate their virtual body left and right 45° using the joystick, and will need to do so as part of the tasks. An audio recording of a fairground [15] was played throughout each task to create additional atmosphere. The participant controlled plain white articulated virtual hands (fingers gripped inwards as the grip button was held) and had an un-tracked avatar with torso and legs.

In all games, the player gains points by completing tasks correctly and quickly, and the participant with the most points was awarded an additional £40 prize, as an incentive to play as well as they could. Points were only gained by correctly completing a trial, and the number of points decreased from 1000 as the time taken increased.

4.0.3 Challenging User Boundary Awareness

In commercial applications, particularly games, a user will frequently have to react to events occurring outside their current field of view (FOV), such as enemies moving to, or appearing by, their side. A player may feel compelled to respond quickly, such as turning to face the enemy and attacking with a sword or gun. When in unobstructed home spaces, a player can more easily do this. On public transport, they do not have this freedom, yet the same impulses may remain, leaving the user susceptible to unintentionally violating their boundary. To recreate such a situation, and determine whether different techniques may be better able to avoid such violations, we deliberately spawned target objects 45° to the left and right sides of the participant. This enemy arrival was visible in the periphery of the FOV and the participant could, in error, move/point their arm towards it to interact, violating the boundary. Instead, the participant had to rotate their own view (and with it the interaction boundary) the same 45° using the controller joystick to be able to reach the target without violating the boundary.

4.1 Task 1: Selection & Manipulation

In this game, the player has to feed a big biscuit to a cartoon dog, by grabbing it from a source position, moving it to the dog's mouth and rotating it to match the orientation/tilt of the dog's head (Fig. 2, A). It incorporates the *DirectGrab* and *Manipulate* movement types from Table 1. For each trial, a biscuit [7] appeared at one of two source locations in the middle of the VE at chest height: 24cm and 47.5cm away from the user in the 50cm x 50cm constrained space, corresponding to 48cm and 95cm away in the 1m x 1m virtual space. A dog [37] appears at one of 18 target positions in the participant's FOV with its head rotated to one of 3 angles: 0° (un-rotated), 30° or 60°. Target dog positions were at depths of 24cm, 36cm, 47.5cm, placed laterally at centre and ±23.5cm of centre, and vertically at chest height as well as ±25.5cm. For the 1m x 1m at-home control condition, positions were twice these values. To add gamification, we include sound effects and repercussions for good or bad performance. If the biscuit is placed in the mouth at the correct orientation and position (within 10° and 10cm, where the biscuit turns green to confirm) the dog barks happily and the controller vibrates; if the orientation or position is incorrect (more than 10°/10cm difference), the dog whimpers, and no points are awarded. The dog then disappears, and the next trial began after 2 seconds. The dog also whimpers and disappears if the trial is not completed within 6s, to add time pressure. All 18 dog positions were moved to from both source biscuit locations, resulting in 36 trials per task (each head angle was repeated 12 times at random).

4.2 Task 2: Sword-Swinging

In this game (Fig. 2, B) - created to incorporate the *SwingArm* movement type - an Invader enemy character [3] appears in one of 15 loca-

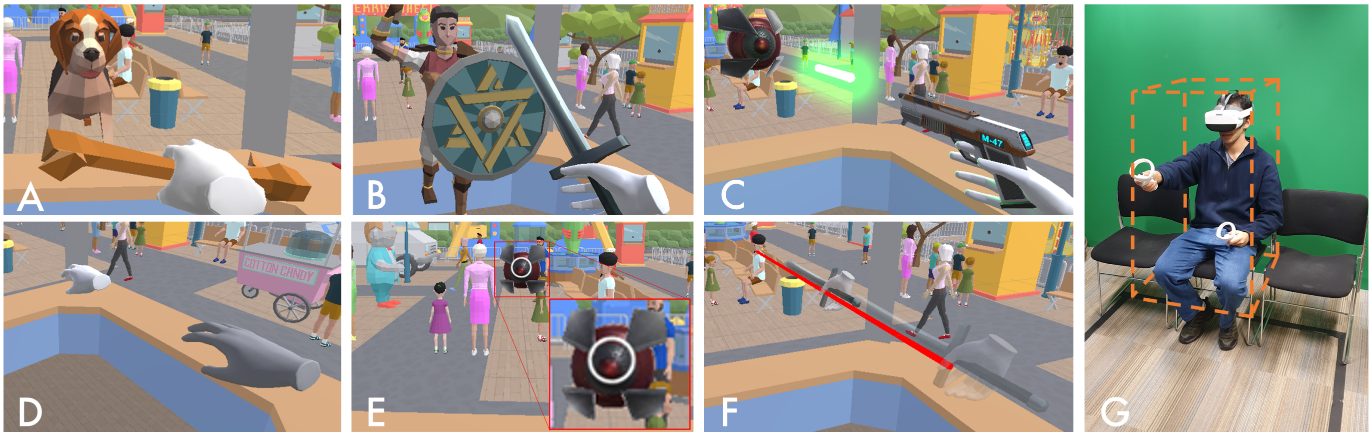

Fig. 2. Screenshots from the three gamified tasks (A-C) and three Constrained interaction techniques (D-F). A: *Selection & Manipulation* (feeding a dog a biscuit); B: *Sword-Swinging* against invaders; C: *Shooting* robot drones with a laser. D: Linear Gain (real hand shown in grey here, but invisible in VR). E: Gaze-Supported Remote Hand. F: AlphaCursor. G: experimental space, with outline illustrating the constrained interaction volume.

tions within the participant's FOV (depths of 24cm, 36cm and 47.5cm; centred and ±23.5cm of centre), and is equipped with either a shield (and no helmet) or a helmet (and no shield). The participant holds a virtual sword [27] and must defeat the enemies as fast as possible by swinging it in the correct direction/orientation: enemies with helmets must be swiped side-to-side; enemies with shields must be swiped from top-to-bottom. When an enemy is defeated, they give a dying grunt and disappear in a puff of smoke and the controller vibrates. We did not want to implement a health system, as each participant was to complete the same number of trials. However, to add time pressure and penalty for poor performance the enemy laughs and disappears after 3 seconds if not defeated and no points are gained. They also laugh and shake if hit in the wrong direction. To add some dynamism and challenge to the game, the Invaders move short distances side-to-side and back-to-front. The next trial begins after 2 seconds and each enemy location was attacked twice (once per enemy type) resulting in 30 trials per task.

4.3 Task 3: Shooting

This game (Fig. 2, C) had a similar structure to the *Sword-Swinging* game but is used to incorporate the *AimArm* movement type. Robot drones [1] appeared in one of 33 locations in the participant's FOV (depths of 27cm, 47.5cm and 68cm; centred and ±23.5cm of centre; chest height and ±25.5cm) and, like the Invaders, move left/right/back/forward to increase the challenge. A laser gun is held by the virtual hand [58] and participants are tasked with shooting the drone as fast as possible (with controller vibrations for each shot fired), while the drones fire back every 300-500ms, subtracting 10 points for each hit. Successfully shot drones audibly and visibly explode and if the drone is not shot within 3 seconds it makes a robotic noise and disappears. There were 33 trials per condition: 1 for each enemy location.

5 Interaction Techniques

This section explains the at-a-distance interaction techniques that we used in the experiment, with our choices based on our analysis of the previous literature. Because existing research techniques are mostly designed for only selection and/or manipulation, we describe how a given technique was adapted to support the *Sword-Swinging* and *Shooting* input actions. For all techniques a black boundary grid was placed at the left, right, front and top sides of the interaction space. All were invisible but a given side/grid became increasingly opaque as the controller moved closer to it, starting from 15cm away.

5.1 At-Home

This technique represents traditional VR interaction, which we used as a control/baseline technique. A key aim of this research is to identify if any interaction technique - or components thereof - is able to equalise the interactive capabilities of at-home and on-transport VR users. Therefore, we included this control condition/technique for comparison, where the user engages in typical unobstructed 1:1 input mapping between real and virtual hand within an open 1m x 1m space.

5.2 Linear Gain [21]

Amplification of hand movements [44, 59], or translational gain [61], could be a suitable general-purpose approach for *constrained spaces*, by mapping the maximum available physical space to the maximum required virtual space. We chose to use Linear Gain as it was the best-performing amplification method for selecting objects in previous work [21]. As discussed in 4.0.1, most commercial VR experiences require 1m x 1m of physical space to play, and so we used the same interactable space. We also chose a 50cm x 50cm (x 60cm) constrained transport space based on economy airline seats, to assess performance in a challenging environment. Therefore, we applied a fixed gain of 2x to hand translations on all axes but not to rotations (see Fig. 2, D). This gain multiplier enables users to reach the borders of the virtual environment (1m x 1m) from our confined interaction space. We did not amplify rotations as our primary concern was with spatial translation and maintaining interaction within boundaries, which rotations are less likely to affect. As gain simply amplifies existing VR controller movements, we did not need to adapt this technique to support any of the three tasks. The user grabs and releases objects using the controller Grip button during the *Selection & Manipulation* task, swings the sword with the controller in the *Sword-Swinging* task and aims with the controller and fires with the Trigger button during the *Shooting* task.

5.3 Gaze-Supported Remote Hand [62]

Using gaze can make target selection/indication easier and more precise, especially at-a-distance [62]. Based on the results of Yu *et al*. [62] we adapted their *Remote Hand* technique, where the user indicates which object they want to interact with using gaze, before manipulating the object from where it is located. Our headset is a consumer-grade device (~€400 Pico Neo 3) and so does not support eye-tracking, which is typically a feature of enterprise (€1000+) headsets. Therefore, we use head pose - the direction the headset is facing - as an alternative. In all tasks, a white circular reticle is shown in the centre of the display where the raycast is sent, and is used to aim at targets. Targets are selected using the Grip button and the virtual hand is then manipulated using 2x amplified translational movements, as recommended by Yu *et al*. [62] to avoid repeated clutching.

For the *Selection & Manipulation* task, hand movement begins at 1:1 until the user looks at the target biscuit (which turns green) and holds the Grip button to teleport the virtual hand to grab it. Hand movement is then amplified by 2x until the task is completed, at which point the virtual hand returns to the real hand position. During the *Sword-Swinging* task, the user similarly looks at the enemy to attack and holds the Grip button to teleport the hand+sword to a position in front of it. The sword is then swung at 2x translational gain, before returning to the real hand position after the trial. When *Shooting*, the user aims the circle at the robot and pulls the controller Trigger button to fire at it (see Fig. 2, E).

5.4 AlphaCursor [63]

As discussed in the literature review, Yu *et al*. [63] compared a number of techniques specifically designed for disambiguating and selecting densely-packed - and so visually occluded - targets. Alongside being specific to these actions, many of the techniques require knowledge of, and also dynamically alter, target positions and so are not suitable general-purpose techniques. However, the *AlphaCursor* technique often outperformed the volumetric methods and is a variant of common raycast-based VR interactions that are more generalisable across applications. AlphaCursor sends a visible ray out from the controller, and the user can move a cursor along it using the joystick. In each Task, the user can control the depth of the virtual hand (including sword or gun) along a 1.5m visible red ray cast from the end of the controller by pressing up/down on the joystick on the right controller (see Fig. 2, F). Virtual hand movement is 1:1 in all tasks and controls are otherwise the same: Grip button to grab objects, Trigger button to fire the gun and swing the arm to swing the sword.

6 Design & Procedure

6.1 Experimental Design

The study used a within-subjects design, with all participants taking part in all conditions, and was approved by our University ethics committee. The Independent Variables were: *Interaction Technique* (Linear Gain, Gaze-Supported Remote Hand, AlphaCursor, At-Home) and *Task* (*Selection & Manipulation*, *Sword-Swinging*, *Shooting*). All 4 *Interaction Techniques* were performed in a counterbalanced order and all 3 Tasks were performed in a random order within each *Technique*.

The Dependent Variables were largely the same across tasks, with some exceptions. For objective measures, *Accuracy* was measured differently in each task: In *Selection & Manipulation*, Position and Rotation error (the distance from the target location/orientation) were recorded separately and an Error was recorded if outside of the positioning range (10cm, ±10°); in *Sword-Swinging* we recorded the number and percentage of incorrect swing directions per trial; in *Shooting* we recorded the number and percentage of missed shots. *Total Points* were summed for each task. *Total Time* was measured for each trial of all tasks, from the moment a target object (or biscuit) appeared until the trial was completed or failed. *Time-Outs* were recorded for all tasks when a trial was not completed in time. *Reaching Time* and *Manipulation Time* were also recorded individually during the *Selection & Manipulation* trials. *Total Arm Movement* was the amount by which the interacting arm moved during a trial, by summing the Euclidean distance travelled. *Boundary Violations* were recorded when the controller passed through any of the guardian boundary walls.

Subjective questionnaires included the NASA-TLX workload [14], Igroup Presence Questionnaire [50] and sense of embodiment [20]. We also included 6 custom 7-point Likert questions, scored from 1 (low) to 7 (high) to get subjective opinions about using the techniques on transport: *"Please rate your physical comfort during the last technique"* (COMFORT); *"How physically easy was the last technique to use?"* (EASE); *"How safe do you think the technique would be to use on public transport seats (e.g., train, bus, plane)?"* (SAFETY); *"How concerned would you be that your arms would leave the boundary when on public transport seats?"* (CONCERN); *"How would you describe the amount of arm movement you performed during this technique?"* (MOVEMENT); *"Do you think you left the boundary during the tasks?"* (BOUNDARY). Finally, participants were asked to rank the techniques in order of preference, explaining their choices.

6.2 Participants & Procedure

There were 16 participants (6 female, 9 male, 1 non-binary), aged 18-41 (mean 25.5, SD = 6.74), and all were right-handed. Only one participant owned a VR headset, and when asked how often they had used VR, one had used it "many times", three "several times", eight "a few times", three "once or twice" and one "never". Six participants "regularly" play games, four "sometimes" play, two "rarely" play, three "used to" play and one "never" plays. Participants were paid a £10 voucher, and the highest total points won a further £40.

After reading an information sheet and signing the consent form, participants were fitted with a Pico Neo 3 Pro [42] standalone VR headset (Qualcomm XR2 processor, 6GB RAM), which is broadly equivalent to the popular Meta Quest 2, and has been recommended for vehicular XR research [31]. The procedure for the 4 *Interaction Techniques* was the same, except that participants were sat in the middle of 3 non-rotating office chairs for the at-a-distance techniques (Linear Gain, Remote Hand and AlphaCursor) to give the impression of being on transport seating, and give participants a sense of how close other people and architecture would be, and so how small the interaction space is. Participants were instructed to stay within the play boundaries as much as they can. The three tasks were performed in a random order, and each was preceded by a training environment where participants performed at least 2 minutes of practice and until they expressed confidence in using the technique. This was repeated for each task and then participants removed the headset, completed the subjective questionnaires and had a 5-minute break before the next *Interaction Technique*. Participants ranked the techniques at the end of the ˜60-minute study.

7 Results

For task Accuracy, Time and subjective responses, we only compare the four *Interaction Techniques* within each task due to the different measurements taken, and participants only completing subjective questionnaires after performing all *Tasks*. For Total Arm Movement and Boundary Violations, we analyse both *Interaction Technique* and *Task* factors together to understand how each influences participant safety-related behaviour. Objective measures were analysed using One-Way Repeated-Measures ANOVAs followed by *post hoc* tests unless otherwise stated; for subjective ratings, we use non-parametric Friedman tests followed by Bonferroni-corrected pairwise Wilcoxon tests. Effect size is shown via partial eta-squared (η_p^2). For brevity, we shorten "Linear Gain" to "Gain" and "Gaze-Supported Remote Hand" to "RemoteHand". A summary of the results is shown in Table 2.

7.1 Selection & Manipulation Task Performance

Accuracy There was a significant main effect of Technique on both the Position ($F(3,45) = 7.394$, $p < 0.001$, $\eta_p^2 = 0.33$) and Rotation error ($F(3,45) = 7.012$, $p < 0.001$, $\eta_p^2 = 0.32$) when correctly placing the dog biscuit. For Distance, both Gain (4.62cm) and At-Home (4.54cm) led to significantly lower error than RemoteHand (8.01cm; p = 0.002, p = 0.011, respectively). AlphaCursor had a mean Distance of 8.67cm. For Rotation, AlphaCursor had a significantly lower error (6.88°) than RemoteHand (11.85°, p = 0.015). The At-Home mean was 6.72°, while Gain mean was 6.56°.

In terms of Errors (*i.e*., the biscuit was not placed within the correct bounds) we did not find a significant effect of Technique ($F(3,45) = 1.648$, $p = 0.192$, $\eta_p^2 = 0.10$). Mean errors were 10.9% for Gain, 11.5% for At-Home, 12.3% for RemoteHand and 16.0% for AlphaCursor.

Time We found a significant main effect of Technique on Total Time ($F(3,45) = 50.525$, $p < 0.001$, $\eta_p^2 = 0.771$) as well as Reach Time ($F(3,45) = 24.64$, $p < 0.001$, $\eta_p^2 = 0.622$) and Move Time ($F(3,45) = 43.97$, $p < 0.001$, $\eta_p^2 = 0.746$). In all three cases, both Gain and At-Home led to significantly shorter times than RemoteHand and AlphaCursor (all $p < 0.001$). Mean Total Times were 2.79s (Gain), 2.95s (At-Home), 3.96s (AlphaCursor) and 4.14s (RemoteHand). Mean Reach/Move times were 1.20s/1.59s (Gain), 1.38s/1.57s (At-Home), 1.81s/2.15s (AlphaCursor) and 1.85s/2.28s (RemoteHand).

Finally, we analysed the average number of Time-Out trials, where participant ran out of time, and found a significant effect of Technique ($\chi^2(3) = 26.52$, $p < 0.001$). *Post hoc* tests showed Gain (2.2%), and At-Home (5.1%) led to significantly fewer Time-Outs than RemoteHand (18.1%) (both $p < 0.001$). Gain was also significantly lower than AlphaCursor (11.9%, p = 0.005).

	AlphaCursor	Linear Gain	RemoteHand	At-Home	Test Result
Selection Distance Error	8.70cm	4.60cm	8.00cm	4.50cm	*F(3,45) = 7.394, p < 0.001,* η_p^2 *= 0.33*
Selection Rotation Error	6.90°	6.60°	11.80°	6.70°	*F(3,45) = 7.012, p < 0.001,* η_p^2 *= 0.32*
Selection TotalTime	3.96s	2.79s	4.14s	2.95s	*F(3,45) = 50.525, p < 0.001,* η_p^2 *= 0.771*
Selection Time-Out	11.90%	2.20%	18.10%	5.10%	$\chi^2(3) = 26.52, p < 0.001$
Sword-Swing Error, % of trials	5.40%	6.00%	6.20%	2.10%	$\chi^2(3) = 10.991, p = 0.012$
Sword TotalTime	1.57s	1.37s	1.74s	1.53s	*F(3,45) = 6.18, p = 0.001,* η_p^2 *= 0.292*
Sword Time-Out	8.10%	5.30%	14.10%	9.00%	$\chi^2(3) = 12.105, p = 0.007$
Shooting Missed Shots per trial	1.21	1.26	2.08	1.23	*F(3,45) = 6.558, p = 0.013,* η_p^2 *= 0.304*
Shooting TotalTime	1.04s	1.08s	1.54s	1.00s	*F(3,45) = 26.46, p < 0.001,* η_p^2 *= 0.638*
Shooting Time-Out	3.60%	3.70%	10.30%	1.80%	$\chi^2(3) = 13.70, p = 0.003$
Boundary Violations, % of trials	10.50%	22.20%	24.70%	31.00%	*F(3,180) = 10.535, p < 0.001*
Total Arm Movement	44.30cm	75.60cm	68.50cm	148.00cm	*(F(3,45) = 132.76, p < 0.001,* η_p^2 *= 0.9*
Safety on Transport (1 low - 7 high)	5.19	4.19	4.43	2.56	$\chi^2(3) = 15.244, p = 0.002$
Concern on Transport (1 low - 7 high)	3.69	4.94	4.25	5.37	$\chi^2(3) = 9.5, p = 0.023$
Presence	4.19	4.47	4.29	4.64	$\chi^2(3) = 13.5, p = 0.004$
Embodiment	3.98	5.25	4.29	6.02	$\chi^2(3) = 18.4, p < 0.001$
NASA TLX Workload	23.81	21.75	26.19	22.06	$\chi^2(3) = 10.3, p = 0.016$

Table 2. Results from main task-related metrics and subjective responses. Coloured highlighting ranges from 0 (white) to max (blue) per-row. Subjective measures, and one-factor analyses that were not normally-distributed, were analysed using Friedman tests. All others used one-way or two-way repeated measures ANOVA, with Boundary Violations going through an initial Aligned Rank Transform, due to non-normality.

7.2 Sword-Swinging Task Performance

Accuracy The data for swing direction and number of Time-Outs were not normally distributed, and so we analysed them using non-parametric Friedman tests. We found a significant effect of Technique on incorrect swing directions ($\chi^2(3) = 10.991$, p = 0.012). Wilcoxon pairwise comparisons showed that At-Home had significantly fewer incorrect swings per trial (0.021) than AlphaCursor (0.054; p = 0.008) and RemoteHand (0.062, p = 0.007). Gain had a mean of 0.06.

Time There was a significant effect of Technique on Total Time (F(3,45) = 6.18, p = 0.001, $\eta_p^2 = 0.292$). Gain led to significantly shorter times (1.37s) than RemoteHand (1.74s, p = 0.001). AlphaCursor had a mean of 1.57s, while At-Home was 1.53s. There was also a significant effect of Technique on the average number of Time-Outs ($\chi^2(3) = 12.105$, p = 0.007). However, no Wilcoxon comparisons reached the required p-value of 0.008. Means were 8.1% (AlphaCursor), 5.3% (Gain), 14.1% (RemoteHand) and 9.0% (At-Home).

7.3 Shooting Task Performance

Accuracy We analysed the number of missed shots and found a significant main effect of Technique (F(3,45) = 6.558, p = 0.013, $\eta_p^2 = 0.304$), however, no pairwise comparisons reached the required level of significance. The mean number of missed shots was 1.21 (AlphaCursor), 1.26 (Gain), 2.08 (RemoteHand) and 1.23 (At-Home).

Time There was a significant main effect of Technique on Total Time (F(3,45) = 26.46, p < 0.001, $\eta_p^2 = 0.638$). RemoteHand led to significantly longer times (1.54s) than AlphaCursor (1.04s), Gain (1.08) and At-Home (1.00s, all p < 0.001). There was also a significant effect of Technique on average number of Time-Outs ($\chi^2(3) = 13.70$, p = 0.003). Both At-Home (1.8%) and Gain (3.7%) had significantly fewer Time-Outs than RemoteHand (10.3%; p = 0.003, p = 0.006, respectively). AlphaCursor had a mean of 3.6%.

7.4 Boundaries, Safety and Use on Transport

Boundary Violations The data for the number of boundary violations were not normally distributed, so we performed an Aligned Rank Transform (ART) using ARTool 2 for Windows [10], to be able to conduct two-way Repeated-Measures ANOVA on both Task and Technique. We conducted the analysis on the average number of violations, but we also report the equivalent total per ˜2-3 minute game.

There was a significant main effect of Task on the number of Boundary Violations (F(2,180) = 38.397, p < 0.001): *Shooting* led to significantly fewer Violations per trial (0.03, equivalent to ˜1 Violation per game) than both *Selection & Manipulation* (0.23, or ˜8 per game, p < 0.001) and *Sword-Swinging* (0.40, or ˜14 per game, p = 0.01). There was also a significant main effect of Technique on Violations (F(3,180) = 10.535, p < 0.001): AlphaCursor led to fewer Violations per trial (0.10, ˜3 Violations per game) than both RemoteHand (0.25, ˜8 per game, p = 0.017) and At-Home (0.31, ˜10 per game, p < 0.001). Gain had 0.22 per trial (˜7 per game). We also found an interaction effect between Task and Technique (F(6,180) = 6.085, P < 0.001), where RemoteHand and At-Home led to far fewer Violations than other Techniques during the *Shooting* Task, but to similar or more Violations in the *Selection & Manipulation* and *Sword-Swinging* Tasks.

Total Arm Movement A two-way Repeated-Measures ANOVA found a significant main effect of Task on the amount of arm movement (F(2,30) = 65.06, p < 0.001, $\eta_p^2 = 0.81$). Pairwise comparisons showed that *Shooting* led to less total movement (27.5cm) than both *Selection & Manipulation* (110cm) and *Sword-Swinging* (1.15m, both p < 0.001). There was also a significant effect of Technique (F(3,45) = 132.99, p < 0.001, $\eta_p^2 = 0.9$), where all were significantly different from each other (p < 0.001), except Gain vs. RemoteHand, with means of 44.3cm (AlphaCursor), 75.6cm (Gain), 68.5cm (RemoteHand) and 148cm (At-Home). There was a significant interaction effect (F(6,90) = 28.78, p < 0.001, $\eta_p^2 = 0.66$), potentially because RemoteHand led to lower movement when *Shooting* than in other Tasks.

Awareness of Own Movement In order to explore how aware participants were of their own behaviour, we analysed the correlation (Spearman's rho) between the participants' perceived amount of arm movement ("MOVEMENT" Likert question) and the actual amount of arm movement for each Technique, and each found no correlation. AlphaCursor: r(14) = 0.385, p = 0.14; Gain: r(14) = 0.379, p = 0.15; RemoteHand: r(14) = 0.441, p = 0.087; and At-Home r(14) = 0.051, p = 0.85. We also analysed the correlation between the participants' perceived boundary-violating frequency ("BOUNDARY" question) and the actual number of violations. There was a positive correlation between the perceived and actual violating behaviour for the AlphaCursor technique r(14) = 0.568, p = 0.02, but no correlation for any other technique. Gain: r(14) = 0.203, p = 0.45; RemoteHand: r(14) = 0.073, p = 0.788; and At-Home r(14) = 0.401, p = 0.12.

Use on Transport A Friedman test found a significant effect of Technique on how safe it was perceived to be ("SAFETY" question) for use on transport ($\chi^2(3) = 15.244$, p = 0.002). The At-Home Technique was considered significantly less safe (2.56) than the AlphaCursor (5.19) and Gain (4.19) Techniques (both p = 0.003) RemoteHand mean was 4.43. No other differences between at-a-distance techniques reached the required p-value of 0.008. Similarly, we analysed how concerned participants would be about leaving the interaction boundary when using a technique ("CONCERN" question) and found a significant effect of Technique ($\chi^2(3) = 9.5$, p = 0.023), however, no pairwise comparison met the required level of significance. Mean levels of concern were 3.69 (AlphaCursor), 4.94 (Gain), 4.25 (RemoteHand) and 5.37 (At-Home).

7.5 Presence, Embodiment & Comfort

Presence & Embodiment There was a significant effect of Technique on Presence ($\chi^2(3) = 13.5$, p = 0.004): AlphaCursor had significantly lower presence (4.19) than At-Home (4.64, p = 0.003). No other comparisons were significant, with means of 4.47 for Gain, 4.29 for RemoteHand. Technique also significantly affected Embodiment ($\chi^2(3) = 18.4$, $p < 0.001$), as AlphaCursor (3.98) and RemoteHand (4.29) produced lower Embodiment than At-Home (6.02; p = 0.002, p = 0.008, respectively). Gain had a mean of 5.25.

NASA TLX There was a significant effect of Technique on total workload ($\chi^2(3) = 10.3$, p = 0.016), but no pairwise comparison met the required significance (0.0083). Mean workloads were 23.81 (AlphaCursor), 21.75 (Gain), 26.19 (RemoteHand) and 22.06 (At-Home).

Comfort & Ease Participants rated the subjective comfort of each Technique ("COMFORT"), and there was a significant effect ($\chi^2(3) = 11.36$, p = 0.01). RemoteHand (4.62) was significantly less comfortable than At-Home (5.81, p = 0.005). Other means were 5.37 for AlphaCursor and 5.69 for Gain. They also rated how easy Techniques were to perform ("EASE") and Technique had a significant effect ($\chi^2(3) = 10.71$, p = 0.013). RemoteHand was significantly less easy (4.25) than At-Home (5.75, p = 0.004), with means of 5.12 for AlphaCursor and 5.25 for Gain.

7.6 User Preferences

Participants were asked to rate the 4 Techniques from most preferred to least preferred. Four participants finished the main study but were unable to give their preferences due to time constraints. Of the remaining 12 participants, six said Linear Gain was their most preferred, five said At-Home, and one said AlphaCursor. Linear Gain and At-Home were generally preferred for being easy to use, for feeling more in control and being closer to real movements, and At-Home also felt most immersive. AlphaCursor was preferred for requiring little movement, and so avoiding boundary violations.

In terms of the least preferred techniques, seven said RemoteHand, four said AlphaCursor, while one did not have a specific answer. Most participants commented that RemoteHand was difficult to use because both the head and hand had to be controlled, and the amount of head movement was sometimes tiring. Some found AlphaCursor difficult to control, and the joystick introduced a barrier between real and virtual movement, so it felt too dissimilar to the real hand movement.

8 Discussion & Guidelines

We reflect on the implications our results had for our RQs, and provide **guidelines (highlighted)** for practitioners.

8.1 Research Techniques in Constrained Spaces (RQ1)

Traditional 1-2m^2 unobstructed VR input is currently the standard in terms of interaction, and our At-Home control condition also often led to significantly better performance in terms of accuracy, time and subjective measures. By comparing to the At-Home condition, we can judge how well the at-a-distance techniques can equalise constrained performance with at-home users.

The Linear Gain condition was never significantly worse in task performance, boundary-related behaviour or workload than At-Home. It led to significantly less arm movement than At-Home, and it was also the most often preferred technique (even more so than At-Home), which suggests that it is highly effective for *constrained spaces*, and may allow for similar interaction capabilities. In contrast, the RemoteHand technique often performed significantly worse than the At-Home condition, resulting in less accurate manipulation, more trials where participants ran out of time, as well as longer successful task times. It was also frequently rated as the least preferred technique. AlphaCursor was somewhere in the middle: compared to At-Home it resulted in similar accuracy and led to significantly less movement and boundary violations, however, it was significantly slower in the *Selection & Manipulation* and *Sword-Swinging* tasks.

While Linear Gain appears to be a promising general-purpose technique to attain similar capabilities to traditional unobstructed VR input, both RemoteHand and AlphaCursor had unique benefits for specific aspects of interaction, which we discuss in more detail next. Also, in the context of interaction on transport, some vehicles (cars, buses) have unpredictable and rapid accelerations from vehicle movement which may make amplified input more difficult to control, in which case more stable techniques like AlphaCursor may lead to better performance and reduced boundary violations.

(1) Linear Gain Best Equalises Interaction: Linear Gain led to high accuracy, low task time, good user experience and was most preferred by participants, even more so than traditional At-Home interaction. Overall, it is recommended as the most effective technique for equalising *at-home* and *constrained* VR interaction.

8.2 Performing Commercial VR Inputs (RQ2)

To answer RQ2 "How well do research techniques support commercial VR input actions?", we compare the three at-a-distance techniques in terms of task performance and individual task actions/components, to establish which is able to support the common mainstream VR movement inputs that we identified.

(2) Linear Gain Best Supports Object Manipulation: The *Selection & Manipulation* task was implemented to represent commercial *DirectGrab* and *Manipulate* movements (in Table 1): closed-loop direct selection and manipulation of objects. We found that Linear Gain was able to support significantly more accurate interaction (object positioning) and a lower number of Time-Outs than RemoteHand. Linear Gain was also significantly faster in Total time (as well as Reach and Move time individually) than RemoteHand and AlphaCursor. From these results, we conclude that Linear Gain supports these commercial actions better than RemoteHand and AlphaCursor. However, AlphaCursor may provide a good level of support for rotation actions.

(3) All Our Techniques Support Weapon-Swinging Input: Commercial *SwingArm* movements (Table 1) involved open-loop arm-swinging for direct engagement, such as the weapon-swinging we implemented in the *Sword-Swinging* task. As the at-a-distance techniques from the literature had not been designed for these inputs, we had to adapt them to be suitable. We found that there were no significant differences between our adapted techniques in terms of attacking enemies in the wrong direction (though AlphaCursor was worse than At-Home), and no pairs were significantly different in terms of Time-Out trials (despite a significant main effect). Therefore, purely in terms of accuracy, none of the techniques were more or less able to support *SwingArm* movement types. Linear Gain was significantly faster than RemoteHand, which may suggest it is slightly better suited to these actions, though we discuss in the next section how the techniques lead to different boundary behaviour. These results may have been influenced by the simplicity of the game: more complex enemy behaviour or task requirements may lead to different findings.

(4) Linear Gain and AlphaCursor Best Support Gun-Aiming: *AimArm* movements (Table 1) involved open-loop indirect pointing with the hand, such as shooting a gun in our *Shooting* task. No technique pairs differed significantly in terms of shooting accuracy. Linear Gain led to significantly fewer Time-Out trials than RemoteHand, and AlphaCursor had similar low number of Time-Outs to Linear Gain. Linear Gain and AlphaCursor were also significantly faster than RemoteHand during completed trials, suggesting that participants are better able to engage in *AimArm* movements when using Linear Gain, and AlphaCursor to a lesser extent. RemoteHand performance may have been affected by the extra physical and mental effort required to aim with the headset.

(5) At-a-Distance Techniques Support Commercial Inputs: As well as being a suitable general technique for constrained spaces, Linear Gain also supported the 4 commercial VR movement actions best overall. However, our adapted AlphaCursor was also well-suited to the *Sword-Swinging* and *Shooting* tasks, and had the benefit of also reducing movement and boundary violations, making it a good candidate for playing these types of games with minimal movement. We also call for interaction designers to test new techniques in a range of representative actions, to determine the wider suitability of their techniques.

8.3 Boundaries & Safety on Transport (RQ3)

On transport, it is important that a user stays within the interaction boundary to avoid invading other passengers' space or hitting nearby architecture. Therefore, RQ3 asked "How is VR boundary-crossing behaviour affected (by different techniques)?".

(6) AlphaCursor Best Keeps Users Within Play Boundaries: We found that AlphaCursor led to significantly fewer boundary violations (10% of trials) than RemoteHand (25% of trials) and At-Home (31% of trials). Linear Gain led to violations on 22% of trials. AlphaCursor also led to the smallest amount of arm movement, with an average total of 44.3cm, followed by 68.5cm for RemoteHand and 75.6cm for Linear Gain. Therefore, we can say that, although AlphaCursor did not often lead to better task performance than other techniques, it was best at keeping users safely within the interaction boundaries, and requires much less movement. Other techniques led to fairly frequent violations, particularly in the *Selection & Manipulation* and *Sword-Swinging* tasks.

The *Shooting* task led to significantly fewer boundary violations than other tasks, despite our hypothesis that such a game might lead to users quickly pointing through the boundary at an enemy. This may have been due to the relatively narrow angle within which enemies appeared (*e.g.*, none appeared behind or directly to the sides), or our choice to not have full bi-directional combat (Invader's attacking the player), and our future work will explore if different enemy behaviour, or the addition of virtual locomotion, may influence boundary violations.

(7) Identify Ways to Reduce Boundary Violations: In contrast to AlphaCursor, Linear Gain leads to better task performance but also to many more boundary violations as well as more overall movement. This makes it potentially more problematic for safe use on transport, especially because we did not find significant correlations between participants' perceived amount of arm movement/boundary-crossing and their actual amount, other than for AlphaCursor. This suggests that they may not have been aware of how they were moving within the interaction space, and may be why they were only moderately concerned about leaving the interaction boundary when using the technique. Therefore, research needs to be done on how to maintain the benefits of Linear Gain while reducing overall movement and violations. Increasing the level of gain may help, so that less movement is needed, but it could lead to less controlled input (especially in moving vehicles). Visualising the real hand position alongside the virtual may increase a user's awareness of their movements, but could reduce embodiment [11].

8.4 At-a-Distance Techniques & User Experience (RQ4)

Many papers that propose and evaluate at-a-distance techniques do not also measure how the experimental setup or technique affects the immersive experience, and so RQ4 asked "How do different techniques affect presence and embodiment?". We found that AlphaCursor led to significantly lower presence than the At-Home condition, and both AlphaCursor and RemoteHand led to significantly lower embodiment than At-Home, with Linear Gain somewhere in between. These results suggest that the input technique can affect both of these phenomena. While the At-Home condition had participants standing up and AlphaCursor/RemoteHand were done sat down, this cannot be the only source of difference in presence/embodiment ratings, as Linear Gain was also done sat down and it did not have significantly lower values than At-Home. As several participants remarked, this may be because AlphaCursor and RemoteHand require additional actions/controls to move the virtual hand, introducing a disconnect between physical and virtual body movement.

(8) Holistic Evaluations of At-a-Distance Techniques: Our results showed that presence and embodiment were affected by the nature of the interaction technique, and these core VR phenomena are often not considered in at-a-distance research, despite involving potentially unusual 'supernatural' abilities [11, 44, 48], rapid user/environment movements [33,63] or UI elements like rays, bubbles and cones [25,63]. While the benefits of immersion will vary across different use cases or tasks, we recommend that research includes measures of immersive phenomena when proposing VR interaction techniques, to understand how wider user experience is affected.

8.5 Limitations

There are some limitations of the work presented in this paper. Firstly, although we designed our tasks to be more representative of commercial VR applications than many previous at-a-distance papers, they are still not fully comparable to real games, being simpler and with fewer pressures (*e.g.*, small number of enemies, not having health or resources). Also, the movement types and tasks were separated in our study, when in real experiences they are mixed and are required at unpredictable moments. Therefore, ours represent more ideal results and need further exploration with more complex game designs. Secondly, and related, there was no locomotion, nor an openly explorable space, which is common in commercial applications. This was intentional, as we wanted to isolate input for this study and investigate locomotion separately. Nevertheless, locomotion is a key component of many applications, and it will likely have an impact on at-a-distance techniques and boundary behaviour due to cognitive demands, spatial awareness/orienting and less predictable enemy/event locations.

Due to the technical limitations of our consumer-grade headset, we did not use real eye-tracking for the Gaze-Supported Remote Hand. This likely made the technique slower and more difficult to use, reducing its potential utility. However, our results remain indicative of performance on current consumer headsets, as eye-tracking remains a feature of enterprise-grade devices, and we will conduct a follow-up study to measure the impact of eye-tracking. Finally, most of the commercial actions in Table 1 came from games, and so we also tested the interaction techniques through games. We found that many actions were shared across application types, however, it is still necessary to test the use of techniques in other types of experience, such as productivity, media, social or creativity. Because of these limitations, our results and guidelines represent a first step towards our goals of supporting commercial VR experiences in constrained transport seating.

9 Conclusions

In this research, we investigated the use of Virtual Reality interactions in constrained spaces, in the context of passenger transport seating. Neighbouring passengers, walls, seatbacks, tables and other vehicle architecture physically (and socially [5]) restrict movements, and risk collisions [60]. As this paper shows, commercial VR applications - games in particular - often involve a number of large and/or fast movements that may not be fully controlled (*e.g.*, open-loop). A number of techniques have been proposed in the literature to allow VR users to interact with content beyond their physical reach, but they had not been designed for, or tested in, constrained spaces and the challenges specific to them: equalising interaction capabilities with unconstrained users, minimising movement and avoiding boundary violations.

Therefore, this paper adapted three at-a-distance techniques from the research literature to perform four common types of VR input movement found in commercial VR games. These were performed from constrained transport seating boundaries of 50cm x 50cm: direct selection and manipulation of objects, swinging weapons at nearby enemies, and firing guns at distant enemies. We compared their performance in terms of successfully playing the games, staying within the boundaries, and the effects on immersive user experience. Linear Gain (2x) [21] was the best overall technique, allowing for similar game performance and subjective experience as traditional unobstructed 'at-home' VR interaction. However, it also led to large amounts of arm movement and high levels of boundary violations. AlphaCursor [63] did not perform so well, but had other advantages in that it could minimise movement and keep users within bounds, at the expense of enjoyment. Based on the results, we provide eight guidelines for the design of at-a-distance interactions in constrained transport seating to enable travellers to engage in the same VR experiences that they would in the home or office.

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