The Benefits of Passive Haptics and Perceptual Manipulation for Extended Reality Interactions in Constrained Passenger Spaces

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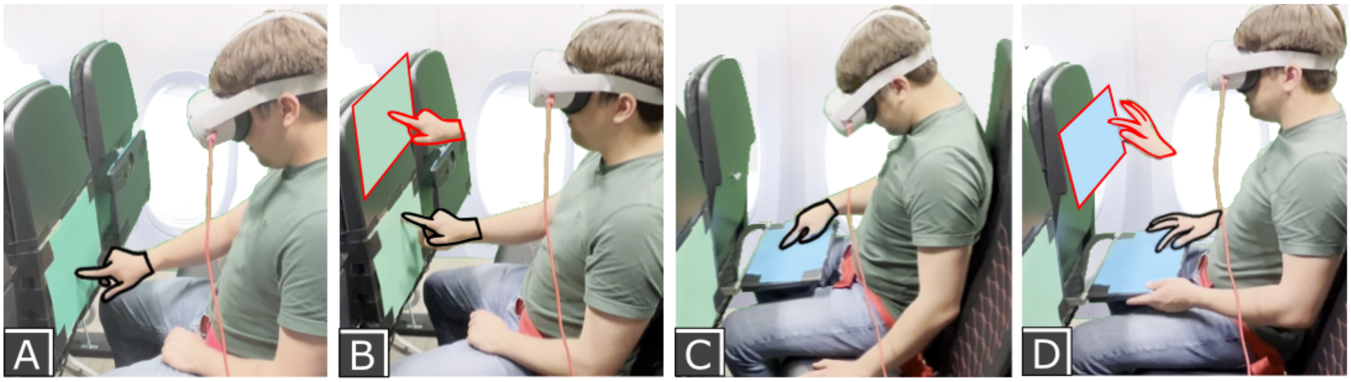

Figure 1: Using passive haptics surfaces in planes for interaction. (A) shows how the seat-back in front can be used as a passive haptic surface; (B) using translation remapping to create a more comfortable experience; (C) shows the use of a horizontal tray table for passive haptic input; and (D) using translational and rotational remapping for a more comfortable interaction.

ABSTRACT

Extended Reality (XR) technology brings exciting possibilities for aeroplane passengers, allowing them to escape their limited cabin space. Using nearby physical surfaces enables a connection with the real world while improving the XR experience through touch. However, available surfaces may be located at awkward positions, reducing comfort and input performance and thus limiting their long-term use. We explore the usability of passive haptic surfaces in different orientations, assessing their effects on input performance, user experience and comfort. We then overcome ergonomic issues caused by the confined space by using perceptual manipulation techniques that remap the position and rotation of physical surfaces and user movements, assessing their effects on task workload, comfort and presence. Our results show that the challenges posed by constrained seating environments can be overcome by a combination of passive haptics and remapping the workspace with moderate translation and rotation manipulations. These manipulations allow for good input performance, low workload and comfortable interaction, opening up XR use while in transit.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**.

KEYWORDS

Virtual Reality, confined spaces, passive haptics, 3D User Interfaces, airplane, aeroplane, selection

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1 INTRODUCTION

Recent advances in eXtended Reality (XR) have popularised Head-Mounted Displays (HMDs) for general use. These devices also

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bring exciting possibilities for passengers in transit to either augment (Augmented Reality) [51] or completely replace (Virtual Reality) [71] their constrained travel environments. In this paper, we investigate XR interaction in economy plane seating scenarios. Air passenger numbers are approaching pre-COVID levels[1] and are expected to fully recover by 2024[2], reaching 4 billion travellers globally per annum. However, passenger transport environments like planes are very different to most home or office XR interaction spaces, due to the close proximity of nearby seats, walls, bulkheads and other passengers. Economy plane seating, for example, may only have 50-80cm of open space for interaction [49, 51, 60, 63], much smaller than most home settings. Aeroplane (and car, bus and train) environments represent a space where the use of XR technology could improve the overall travel experience. It could enable travellers to escape their cramped long-haul surroundings to watch an IMAX movie [71], explore a larger VE, or create a work environment with multiple virtual monitors around them [49, 51]. However, interaction in such environments has had little focus in the HCI literature.

Interaction with rich 3D virtual content in such constrained spaces can be difficult. Our ability to move and extend our arms is limited by the seat belt, the seat-back in front, structural elements to either side and the close proximity of other passengers. This restricts the use of controllers or hands for the kinds of interactions typically used with XR. However, some of these restrictions could potentially be turned into advantages. There are several locations within easy reach that could be used for input, for example, the tray table and seat back offer horizontal and vertical surfaces that could be used to support interaction and provide passive haptic feedback, which could improve usability, presence and overall XR experience. [3, 42]. However, the reachable parts of these surfaces may require uncomfortable and awkward head/neck orientations due to the small space: staring directly down onto a tray table may hurt the neck; holding an arm up to make selections on the seat-back could be tiring and cause 'Gorilla arm' issues [28]. These problems are a significant challenge for practical XR use in flight [40]. In this paper, we look at how we can overcome these challenges to make rich and effective interactions in constrained spaces to open up XR use for travellers.

One way to overcome physical constraints is by using perception manipulation techniques [68], which rely on visual dominance to manipulate the surrounding virtual environment (VE) [39]. Commonly, such techniques are used to imperceptibly manipulate the VE to facilitate actions such as touching multiple virtual objects using a single prop [3], shifting interaction spaces [19] or enabling larger-scale walking in smaller-sized rooms [39]. Such imperceptible manipulations can improve interaction and maintain a high level of presence in the VE. However, physically-constrained spaces such as economy plane cabins would need more extreme perceptual manipulations to enable interactions, for example, displaying a horizontal tray table at head height to make it easier to see while still touching the physical surface in its original location may have negative effects on performance, presence and task workload [26].

Through two studies, we investigate and overcome these problems by (i) exploring different surfaces available in an economy plane seat environment and comparing passive haptics to mid-air interaction for object selection in VR; and (ii) overcoming physical constraints by using perception manipulation techniques to increase user comfort. The first study investigated selection performance, presence and embodiment for interaction using a Fitts' Law type task composed of 2D and 3D object selection and dragging operations. We used two different passive haptic surfaces: a *Horizontal* open tray table and a *Vertical* seat-back in front of the passenger and compared them to mid-air selection techniques.

Results showed improved user performance and preference for the passive haptic surfaces, especially in horizontal configurations. However, neck fatigue had a significant effect on user comfort, especially for the horizontal surfaces where users had to look down at the tray table. To address this issue, in the second study, we employed position remapping for physical vertical surfaces and a combination of position and rotation remapping to transform horizontal surfaces to reduce neck fatigue but maintain good input performance. The use of a 3D component in our targeting task made the task different from pure indirect input [26, 27], which normally remaps the input from one surface or device to another, reaching for the mid-air sphere made necessary for the users to perform movements on all three axes, being representative of a 3D task.

Results showed improved target selection precision for the remapped conditions and increased neck comfort. Participants also strongly preferred the remapped conditions that relied on the horizontal surface.

Our work contributes:

- A detailed comparison of mid-air versus passive haptic interaction techniques for different surface orientations in constrained seating settings, showing that passive haptics significantly reduced the time taken for reaching and dragging, along with providing subjective benefits in terms of agency, self-location and workload;
- A detailed investigation of movement remapping to create more comfortable interactions in constrained spaces, showing that horizontal remappings between 45° and 60°could optimise user comfort and interaction performance;
- A novel set of guidelines to assist designers in making effective interactions for constrained plane seat settings.

2 RELATED WORK

This section covers literature regarding XR interaction in confined spaces, perception manipulation and Fitts' Law selection tasks.

2.1 Constrained Transport Seating and XR use

Cars, trains, buses and planes have fundamentally different spaces compared to the home or office where XR devices are typically used. Seats are fixed, there are walls, windows, armrests, and seat-backs in close proximity, limiting movement, and neighbouring passengers whose space could be invaded or who could be inadvertently hit. Regarding XR interaction, there is a limited body of work related to using XR headsets in transit, and most focus on providing reality awareness for VR wearers [71]. Further work shows that XR can

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[1] https://www.heathrow.com/company/investor-centre/reports/traffic-statistics

[2] https://www.iata.org/en/pressroom/2022-releases/2022-03-01-01/

be used as a replacement for display-based passenger workspaces on aeroplanes, trains, cars and subways [49, 51].

Schmelter & Hildebrand [60] measured seating layouts on public trains and found that there was only 60cm x 80cm of open space for XR interaction, and almost all seats had nearby objects, surfaces or people who could interrupt the user. The median seat pitch (distance from the back of one seat to the one in front) of economy airline seats is only 80cm (which also includes the passenger), with a median width of only 45cm [63]. Therefore, passenger locations and the position of surfaces are key for placing virtual content in selected passenger spaces. However, these papers only looked into content placement and physical space assessment in constrained spaces, not how the interaction is affected by these limitations. Further work is needed to understand the constrained spaces, especially in transport, and how to optimise these for interaction.

2.2 Selection and Fitts' Law in 3D User Interfaces

Object selection and manipulation are key tasks in Virtual Reality. These are often performed directly: an object is reached using a 1:1 mapping of user hand movements (or controllers) to the resulting movements in virtual space. 2D Fitts' Law has become the gold standard for measuring selection performance in HCI, with the introduction of ISO 9241-9 [65], and are used for different types of 2D input such as mice, keyboards and touchscreens. The standard uses a task in which circles are arranged equidistant from each other so that the same Index of Difficulty (ID) is required to select them. The ID is measured as a factor of distance and target width using the formula: ID = $log_2(2D/w)$, where D is the distance between targets and W is the width of a given target [45]. Selection on such devices includes single tapping on a target before moving to the next one [59]. However, beyond simple tapping input, previous work [59] showed that tapping followed by a drag movement is a good way to use more of the available touch surface.

Recently, Fitts' Law-type tasks have been extended for use in Virtual and Augmented Reality [5, 14]. These tasks can be done either by positioning 2D targets in a bi-dimensional plane, which could be either in mid-air or using a passive haptic surface [62] facing the user at a fixed depth, or by placing objects at varying depths, while still following the ISO 9241-9 target arrangement [6]. Another example is by placing targets using a spherical arrangement such as the one proposed by Lubos *et al.* [43]. For our study, we chose to combine the benefits of 2D and 3D selection using a Fitts' Law-type task, where we placed a 3D virtual sphere at a fixed distance from the user, in the centre of a 2D Fitts Law ISO 9241-9 circle [65]. The placement of the 3D sphere guarantees a 3D fixed starting point which is the same distance to access all targets located at the 2D physical surface.

2.3 Passive Haptics: Touching virtual elements using everyday objects

Research has shown that adding tactile feedback to mid-air hand-based interaction improves performance and user experience, particularly in terms of locating interface elements and the user's sense of agency and engagement [20]. Haptic feedback is also a common way to increase user presence in immersive virtual environments, by using haptic elements to represent the different objects represented in 3D space [40]. There are two main forms of haptic feedback: active and passive haptics, which differ in how the haptic feedback is provided [70].

Active haptics use devices, such as hand-held controllers or haptic gloves [22], to stimulate different body parts to provide tactile or force feedback, enabling users to feel they are physically touching virtual objects. Work by Lopes *et al.* [42] simulates physical walls in the 3D scene by placing electrodes to stimulate different muscle groups to enable haptic feedback in immersive virtual environments.

Passive haptics uses inert physical elements that are present in the real world to represent virtual objects or surfaces [1] with different sizes and shapes [46]. These physical elements are positioned at the same locations as the corresponding virtual elements in 3D space, so users feel they are touching a solid virtual element in the 3D scene [34]. The technique has been used for appropriating everyday objects, including knobs and surfaces [58] as proxies to virtual objects which can change in appearance when visualised in an AR headset. Passive haptics offers several benefits over active haptics, as complex and costly actuators are not needed, and existing objects and architecture can be leveraged for haptic input or feedback surfaces. Passive haptics has been shown to improve input and selection performance in VR [36], however, these results were limited to vertical surfaces positioned at eye level. Beyond task performance, passive haptics can also improve user experience in VR. In Snake Charmer [2], a robotic arm placed physical objects in different parts of the 3D scene wherever a surface was needed. Similar work by Hettiarachchi [33] proposed a system that adapts the virtual environment to the available surfaces, altering the appearance of physical objects by overlaying virtual models on top to reduce visual-haptic mismatch. Yixian *et al.* [73] used wheel-mounted wall surfaces that could be dynamically reconfigured to the users' 3D environment to enable a better spatial perception of the 3D space. Work by Cheng *el al.* [15] also showed that adding haptic feedback to complex 3D geometry is possible using a passive proxy. Henderson and Feiner [32], on the other hand, showed that it is possible to use indentations present in common surfaces as user interface elements, such as sliders and buttons as effective input in AR applications. Perception Manipulation has also been used as means to provide indirect input for symbolic input using physical keyboards, enabling users to render their hands in front of their faces to diminish the effort needed to locate physical keys [27]. This remapping had a small effect on performance but significantly affected overall preferences, where users preferred the remapped input over non-remapped for typing using a physical keyboard in VR. However, the task used was essentially 2D using a standard keyboard layout. Richer interactions in VR include selecting and manipulating 3D content, which could potentially impact user experience and performance for remapped input. We investigate this as part the the study in this paper

Previous work shows that it is possible to use visual dominance to simulate virtual objects in different shapes with a single physical flat proxy object [38]. These perception manipulation techniques and their effect on the use of passive haptics proxies are explored in the next section. Oculus are implementing a feature for Quest headsets that can detect a user's work desk and bring it into virtuality [52], and it is feasible that such a system could be extended to detect and make use of smaller surfaces such as tray tables or seat-backs around the headset wearer.

The use of passive haptics is compelling in physically constrained XR spaces, as it can support more accurate and usable hand-based interactions, compared to the *de facto* mid-air interaction on headsets like the Oculus Quest. Recent advances in hand-tracking found on devices such as the Oculus Quest 2 mean that dedicated controllers are no longer needed, but this means the active haptic feedback they provide is lost. Passive haptics from surrounding surfaces could be used as an alternative. The use of dedicated controllers also diminishes the available space, as they can cause unwanted collisions with physical elements in real environments, such as surfaces or other people.

2.4 Perception Manipulation Techniques and Haptic Retargeting

2.4.1 Embodiment and User Representation. User representation is an important part of the feeling of presence in Virtual Reality [37, 48, 61]. Representing users digitally also gives people a feeling of connectedness with the virtual environment (VE) and provides a reference of size within the environment [35, 58], increasing one's sense of spatial awareness [16]. A common way to do this is by using a virtual representation of the user's body, an 'avatar', which is co-located with the user. A feeling of being connected to, or inhabiting, a virtual body is known as the "sense of embodiment" [37], which is composed of three sub-factors: the sense of agency, i.e. the feeling avatars' actions are your own; the sense of body-ownership, i.e. the feeling the virtual body belongs to you; and sense of self-location, the feeling of the virtual body being located at the same place as your own. The visibility and level of fidelity of the virtual representation/avatar (i.e. how similar it is to the real body) depend on what the user is doing. For instance, if performing a walking task, it is important to have a representation of the lower body. In selection tasks, it is more important to have a realistic depiction of the hands; however, in tasks that require more hand precision, a more abstract hand representation may be preferred [50]. Previous work also indicated that a realistic depiction of only the hands (without the rest of the arm) increased presence and embodiment compared to the depiction of whole arms, which also may be more susceptible to uncanny valley side-effects [67].

Previous studies showed that it is possible to manipulate the location of the virtual representation in such a way that users still feel connected to it. These are called virtual-body illusions [54] - based on the rubber-hand illusion [12] - and show that, due to visual sensory dominance in humans, users are still able to feel connected to artificial bodies when the stimuli provided are close enough to their real counterpart [12, 54]. In VR, a common use of this illusion is the use of third-person avatars, where the user can see their bodies from the outside [48].

Due to human visual dominance over other senses [56], it is also possible to use techniques that perceptually change the virtual representation of the environment without the need to alter the physical environment itself [3]. A recent example is Redirected Walking [66], which imperceptibly rotates the world around the user, giving them the illusion of walking in a straight line while walking on a curve. Previous work on Redirected-Walking [10, 39] suggested that users could further adapt to extreme rotation manipulations, indicating that people could use such manipulations when the physical space available is strictly limited. Wilson [72], for instance, showed that users can tolerate higher (up to 2x) translational gains - amplifying physical movement for greater virtual movement without compromising user experience in walking scenarios. Work by Azmandian *et al.* [3] showed that it is possible to apply a similar perception manipulation technique to rotate the virtual world, giving the impression people are interacting with multiple physical objects while only one real object is present.

2.4.2 Remapped Input. Perception manipulation techniques have also been employed in selection-type tasks, where users' hands are retargeted to manipulate position and rotation to enable distant-object selection or to make selection more comfortable [17, 19, 23–25, 55]. These techniques are especially important when users are located in constrained spaces such as plane seats, where larger reaching motions may not be possible. Differently from indirect input, that commonly remaps input in one surface/device to another and is commonly bidimensional [27], more complex perception manipulation techniques such as the redirected walking and haptic redirection [3] alter user's movements and/or the world around them. A common practice is using gain to enable users to reach far-away objects, such as the Go-Go technique, which applies non-linear gain to a virtual hand once the real hand is extended beyond 2/3rds of the arm's reach [57]. The detection threshold for reaching (where the user can tell a manipulation is being used) is below that of walking and can be perceived when more than 1.3x gain is applied [21]. These results can be improved when a more realistic hand representation is used, making retargeting less perceptible in larger mismatches [53]. Hand retargeting techniques are still limited to translational remapping [7, 29, 41, 69] and minimal hand rotations [74, 75]. These techniques can also be used to enable users to feel virtual objects with different shapes using a singular flat physical proxy [38]. Follow-up work shows that it is possible to remap users' hand positions to enable haptic touch [29], with remapping being limited to position retargeting.

In more constrained scenarios, such as planes and other modes of transport, surfaces may be located at uncomfortable positions for both hand and head movements, which make their use as haptic proxies to virtual elements (re-purposing) unfeasible for extended use. Such cases may require more extreme manipulation in position and rotation to support more comfortable long-term use. However, the effects on the performance and usability of such extreme manipulations are still not well known in the literature.

Previous work in the literature about interaction in constrained spaces is minimal. Given the physical nature of the environment, nearby surfaces may be small in size and be in different orientations to the user. Previous work has used varied haptic surfaces for interaction [3, 32, 33], which are known to improve user satisfaction while interacting with augmented content. However, the additional specifications of surfaces in passenger contexts may influence user preferences, performance and presence as the available surfaces may cause unwanted comfort-related side-effects related to their position in relation to the user, such as neck and arm fatigue. To address this, we designed a user study which evaluated vertical and horizontal surfaces around the user. We used these for passive haptics and compared them to mid-air interaction in the same orientations to understand the benefits of haptics in constrained seating settings. From our results, we identified a series of preferences and ergonomic guidelines that may impair XR use over longer periods of time. We addressed these in a follow-up study by using perception manipulation remapping techniques for re-appropriating physical surfaces. Our work aims to combine passive haptics with perception manipulation techniques such as movement remapping to overcome the physical constraints of limited passenger spaces.

3 STUDY 1: PASSIVE HAPTICS FOR VR TARGET SELECTION IN PHYSICALLY CONSTRAINED SPACES

Little research has investigated XR interaction in the constrained spaces of passenger environments. The physical environment around transport seating may hinder people's interaction due to the risk of collisions with nearby objects or invading a neighbour's personal space. However, these physical surfaces could be used to improve interaction by representing physical boundaries [71] and creating the possibility to re-appropriate those surfaces. Although passive haptic surfaces have been previously used in the literature, many of the surfaces available for interaction in transport settings, including seat-backs and tray tables, come in different positions and orientations relative to the user, and so it is important to assess the influence of passive haptics and investigate how position and orientation affect input performance and user experience. In this study, we chose economy airline seats as the interaction scenario, as they represent a particularly constrained space, and compared the presence/absence of passive haptics when performing object selection in VR with vertical and horizontal surfaces.

To enable a more comfortable experience and to enable comparing the surfaces equally in terms of arm fatigue, we chose the tray table as the interaction surface. In its open position, it provides a horizontal surface, and when stowed it can be a vertical surface.We are particularly interested in the effects of the presence/absence of a haptic surface and the orientation of surfaces on task performance, user preferences, comfort, sense of presence, and sense of embodiment. Therefore, we arrived at the following research questions:

RQ1 - How does passive haptics influence VR selection performance and subjective experiences in a physically constrained space?

RQ2 - How does surface orientation influence VR selection performance and subjective experiences in a physically constrained space?

3.1 Setup and Apparatus

The Oculus/Meta Quest 2[3], an off-the-shelf VR headset with a 90° of field of view and a resolution of 1920 x 1832 per eye was used to present the visual scene. This device has four depth cameras that enable positional inside-out tracking along with hand-tracking, which we utilized in our study. To give ecological validity to our results, we used two rows of AirAsia-branded Hawk economy aircraft seats from Mirus. Participants interacted with the tray table attached to the seat in front of them: it was stowed for the vertical surface and opened on the horizontal one. Due to indentations (e.g. cup-holders) found in the tray table, we added stiff cardboard to both the top and bottom sides to provide a flat surface for interaction. We also added tape to the corners of the surfaces to make the calibration procedure easier. The seats were 120 cm in height, and we used a seat pitch (measured from the very top of the two seats) of 74 cm (or 29 inches), similar to the average seat pitch across airline Economy classes [63].

Figure 2: From Left to Right: Plane Seats and the surfaces used in the experiment; Horizontal Tray table (Red); Vertical Surface (Green) (the purple surface was not used in this study).

3.1.1 Surfaces Selected. All surfaces measured 16 cm horizontally and 9 cm vertically, the size of the tray table. We selected two different surfaces commonly present in an economy plane seat:

Vertical Surface: We used the tray table in an upright position, forming a 90-degree angle with the ground reference (the green rectangle in Figure 2). The centre of this surface was located 82 cm from the ground, with the lower border at 77.5 cm and the upper border at 86.5 cm.

Horizontal Surface: We used the open tray table, which was 69 cm above the ground (the red rectangle in Figure 2).

Mid-air selection: To understand the influence of passive haptic surfaces in our interaction scenario, we included two Mid-air variants where there was no physical surface present. Participants sat in the front row of seats and interacted in open air, in a vertical or horizontal orientation, in the same positions as the physical surfaces.

Precise mid-air interaction can be challenging due to a lack of feedback, reducing input precision [20]. Since we included a dragging component between 2D targets in our experimental task, we added a *Snap* component to one Mid-air condition [8, 9] to provide additional control in the absence of tactile feedback. This led to two Mid-air conditions: *Mid-air Snap* and *Mid-air No-Snap*. The *Mid-Air Snap* condition allowed the system to re-align the movement of the user's dominant index finger to the virtual surface if it deviated slightly. We chose the threshold of +/-1 cm based on the average error of mid-air selection [43] to maintain a fair comparison between the *Mid-Air Snap* and Mid-Air No-snap conditions and to allow for a more smooth movement.

These surfaces were calibrated before the start of each of the conditions. For this procedure, we asked participants to touch the top-left, top-right and bottom-right corners, using their hands with the tape serving as a guide (Figure 2). After this, we calculated the normal of the surface and positioned the surface according to the corner positions. To avoid imprecision and expedite the calibration

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[3] https://store.facebook.com/gb/en/quest/products/quest-2/

process, we used a fixed size (width=16cm height=9cm), using the corners only to control the orientation and estimate the centre of the virtual surface based on the touch points. We then asked participants to place their finger in the surface's physical centre, to fine-tune the position of the virtual surface, making it match the centre of the physical surface.

3.2 Experimental Design

We used a within-subjects design with two Independent Variables: *Surface Orientation* (Vertical, Horizontal) and *Surface Type* (Passive Haptics, Mid-air Snap, Mid-air No-Snap). This gave a total of 6 conditions: (Vertical, Horizontal) x (Passive, Mid-air Snap, Mid-air No-snap). The order of conditions was counterbalanced to avoid ordering effects using a Balanced Latin-Square. We included both qualitative and quantitative measures to evaluate subjective user experience and task performance. The study was approved by the University ethics committee.

3.3 Experimental Task

We designed a task based on the ISO 9241-9 standard used for 2D selection using Fitts' Law [45, 65]. This task places targets in a ring, where all opposing pairs of targets are located at the same distance from each other, guaranteeing the same Index of Difficulty for each target.

For our task, eleven 2cm targets were arranged in a ring with an 11 cm radius aligned with the 2D surface.As we were interested in 3D object selection in VR, we included an additional 3D sphere object, 2cm in diameter, positioned aligned with the centre of the 2D plane, but located 11 cm above the surface, closer to the participant (Figure 3). We included this extra object to guarantee that all movements included a selection and a drag for all targets located at a distance of approximately 15.5cm from all the targets on the surface to guarantee the same index of difficulty to reach the 3D sphere. This was used as the start and end points of each interaction.

The task comprised two different sub-tasks: the *Reaching Task*, where the user would first select the 3D sphere with the tip of the index finger of their dominant hand and then reach for a target highlighted in red on the 2D plane in front of them (Figure 3). This task was deliberately designed to force participants to lift their fingers from the surface and reach for a 3D object, which had the same euclidean distance from all of the targets on the 2D plane. The use of this 3D component allowed the task to be different from pure indirect input [26, 27], as it needed users to perform movements on all three axes for the sphere, being representative of 3D tasks.

After selecting this, again by touching it with the index finger, the target would turn green and then the next target would be highlighted in red (Figure 4). This would start the *Dragging Task*, where the user would drag the selected target to the red one and confirm the selection by lifting their finger off the target. The next trial would then begin (Figure 4). For the passive haptic conditions described above, the 2D interaction surface was aligned with the physical one so that touching a target in the 2D ring coincided with the physical surface.

We used the default Unity3D hand model, which was a realistic depiction of users' hands in the virtual environment using the Oculus Quest 2 hand-tracking capabilities. A hands-only representation was chosen as, according to previous work [67], it elicits a higher sense of embodiment and presence than a full-hand model.

Figure 3: Reaching Task : (A) 3D Sphere is highlighted red, indicating the start of the interaction. (B) After the initial selection, the user moves to select the highlighted red target in the 2D plane. (C) After selecting that, the target colour changes to green and a new target is highlighted in red. The user then drags to that.

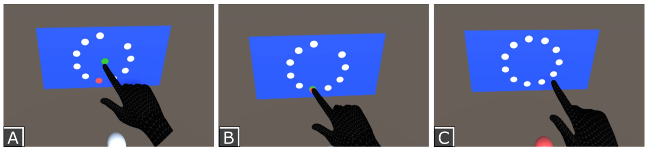

Figure 4: Dragging Task : (A) The user drags the selected target to the target highlighted in red. (B) The user places the green target on top of the red target. (C) The user confirms by releasing the finger from the 2D target.

3.3.1 *Measures.*

Qualitative Measures. User subjective ratings were evaluated through questionnaires using 7-point Likert scales for Presence and Embodiment. We used the questions about each sub-component of *Embodiment* [37]: Agency, Body-Ownership and Self-Location. We used 9-point Likert scale questions for NASA TLX Task Workload [30] to measure subjective workload. We measured *Arm Exertion* using the Borg CR10 scale [11] (0-10) to investigate the fatigue of interaction in the different orientations. Finally, we conducted a *semi-structured interview* at the end of the study where we asked participants: to rank their preferred surfaces for interaction; whether they preferred passive haptics or mid-air conditions; and their preference between the Mid-Air and Snap conditions.

Quantitative measures. We measured the performance of the Reaching (3D) and Dragging (2D) tasks independently. *Reaching Time* was calculated from when the user touched the 3D Sphere until the time they touched the highlighted target on the 2D plane. *Dragging Time* was calculated from the moment when the highlighted target was first selected until the user released the finger from the 2D plane after dragging to the next target. *Reaching Precision* was the Euclidean distance between the position of the fingertip and the centre of the initial target when the finger contacted the 2D plane (Figure 3). *Target Confirmation Precision* was the Euclidean distance between the fingertip position and the centre of the target when the fingertip was released from the 2D plane (red highlighted target 4-A). Additionally to the precision metrics, we also derived the *Path Length* metric for the dragging task, which was the total movement made between targets. Differently from the precision metrics that deal with selection precision, the path length is intended to capture the precision of the whole movement, meaning the lower the path length, the more precise the movement was. Path length was sampled at 90Hz, summing the change in distance of the fingertip over the targeting task. Because of this sample rate, the reported distance is exaggerated compared to actual path distance due to accumulated fingertip movement jitter from the XR tracking, however, relative comparisons remain valid.

3.4 Participants

We recruited 19 participants aged 23 to 50 years, with an average of 30 years. These participants were recruited through university mailing lists and paid £10 for participating. Of these participants, only three had not used a VR headset before, nine rarely, and 7 used them at least once a week. Users' heights varied from 1.65cm to 1.91cm, with an average of 1.75 cm.

3.5 Procedure

Participants were presented with a brief explanation of the study and were allowed to ask any questions before signing a consent form. Users then performed a software calibration procedure where they touched the corners of the physical surface to create the coincident virtual 2D target plane. Afterwards, participants performed a training session where they performed both *Reaching* and *Dragging* sub-tasks to all 11 targets present in the virtual environment. Users did training for each condition before they undertook it to ensure they understood the task and could perform it well.

At the end of each condition, participants completed a questionnaire regarding their overall preferences, a NASA-TLX workload assessment, Embodiment, Presence, arm exertion and overall subjective preference. Finally, at the end of the study, we conducted a semi-structured interview to gather further insights into their subjective preferences.

3.6 Results

3.6.1 *User Performance:*

First, we performed a Shapiro-Wilk test to investigate if the data had a normal distribution. Since all our variables did not follow a normal distribution, we performed an Aligned Rank Transformation (ART) [18] to transform the data and then a two-way repeated measures ANOVA on *Surface Type* (PassiveHaptics, Mid-Air No-Snap and Mid-Air Snap) and Surface Orientation (Vertical and Horizontal).

Reaching Time: There was a significant main effect of *Surface Type* (F(2,36) = 73.940 p<0.001)), no effect of *Surface Orientation* and no interaction (see Figure 5 for the data). *Post hoc* tests showed a significantly shorter Reaching Time for the Passive Haptics compared to the Mid-Air No-Snap conditions (both p<0.001) Mid-Air Snap had a significantly shorter Reaching Time than Mid-Air No-Snap (p=0.025).

Dragging Time: There was a significant main effect of *Surface Type* (F(2,36)=77.729 p<0.001), *Surface Orientation* (F(1,18)=4.093 p=0.044) and a significant interaction (F(2,36)=8.907 p<0.001), with the vertical surface performing lowest in the passive haptics condition but higher in the mid-air snap. See Figure 5. *Post hoc* tests showed a significantly shorter dragging time for the Passive Haptics condition than both Mid-Air No-Snap (p<0.001) and Mid-Air Snap (p<0.001). The Vertical Orientation led to a significantly shorter dragging time than the Horizontal (p=0.044).

Reaching Precision: There were significant main effects of both *Surface Type* (F(2,36)=6.129 p=0.002) and *Surface Orientation* (F(1,18)= 19.660 p<0.001). No interaction effects were found. *Post hoc* tests between Surface Types showed significantly worse precision for Passive Haptics than Mid-Air No-Snap (p<0.001) The Vertical Orientation led to significantly lower precision than the Horizontal (p<0.001).

Target Confirmation Precision: We found significant main effects of both *Surface Type* (F(2,36)=27.548 p<0.001) and *Surface Orientation* (F(1,18)=138.323 p<0.001). We also found an interaction effect between Surface and Orientation (F(2,36)=19.673 p<0.001). *Post hoc* tests for *Surface Type* showed that participants were less precise in the Passive Haptics condition than in the Mid-Air Snap (p<0.001) and Mid-Air No-Snap conditions (p<0.001). In terms of Orientation, the results showed that participants were significantly more precise on Horizontal surfaces than on Vertical (p<0.001).

Throughput: The throughput was calculated for the different surface types and orientations (see Figure 5), following the formula proposed by Mackenzie *et al.* [44]. Since the data did not follow a normal distribution, we performed an Aligned Rank Transformation followed by a two-way ANOVA with Surface Type and Orientation as factors. There was a significant main effect for Surface Type (F(2,36)=20.906 p<0.001) but not for Orientation. There was a significant interaction between variables (F(2,36)=9.764 p=0.001), with the vertical surface performing best with passive haptics, but worse with mid-air snap. *Post hoc* tests for *Surface Type* showed significantly higher throughput with Passive Haptics than both Mid-air conditions (both p<0.001). The best performing condition was passive haptics on the vertical surface, with a throughput of 1.74 bits/s, with 1.49 bits/s on the horizontal. Mid-air Snap on the vertical orientation was the lowest performing with 0.58 bits/s.

Path Length: There was a significant main effect for the *Surface Type* (F(2,36)=5.964 p=0.003), but not for *Orientation* (F(1,18)=0 p=0.99). There was a significant interaction effect (F(2,36)=10.310 p<0.001) due to the vertical condition having the lowest performance for passive haptics but highest for Mid-Air Snap. For *Surface Types*, Passive Haptics had significantly shorter path lengths than the Mid-Air Snap condition (p=0.008). Mid-Air Snap had shorter path lengths than Mid-Air No-Snap (p=0.018).

3.6.2 *Subjective Results.*

Since the subjective ratings are non-continuous data, we performed an Aligned Rank Transform [18] to transform the qualitative data gathered from the questionnaires into a form suitable for parametric analysis. A two-way repeated measures ANOVA was conducted with *Surface Type* and *Surface Orientation* as factors. Data can be seen in Table 1

Presence: There were no significant effects for Presence, for neither Surface type (F(2,36)=1.86 p=0.16), Orientation (F(1,18)=0.01 p=0.89) and no significant interaction effects (F(2,36)=1.8 p=0.17).

Agency: For Agency [37], a significant main effect of *Surface Type* was found (F(2,36)=4.78 p=0.014) as well as an interaction effect between variables F(2,36)=7.38 p=0.002), due to the performance of

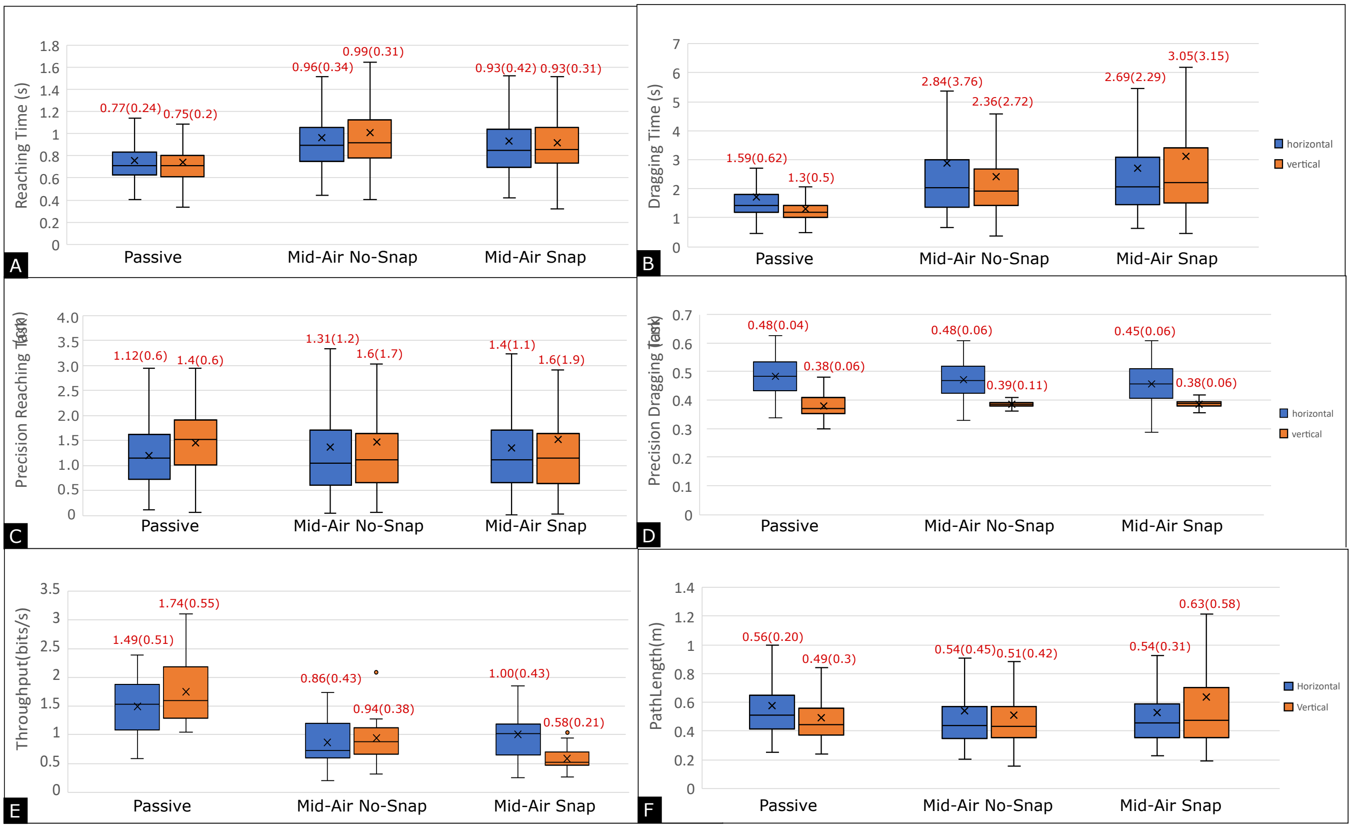

Figure 5: Boxplot of the Times and Precision split by Task. (A) and (C) show the Time and Precision of the Reaching Task; (B) and (D) Time and Precision of the Dragging Task; (E) Throughput; (F) Path Length (m). Numbers in red are in the format: Average (Standard Deviation).

the mid-air no-snap condition. There was no significant effect of *Surface Orientation*. The sense of agency was significantly higher in the Passive Haptics condition in comparison with both Mid-Air Snap (p=0.04) and Mid-Air No-Snap (p=0.023).

Body-ownership: For the Sense of Body-Ownership sub-component of the sense of embodiment [37], we found a significant main effect of *Surface Type* (F(2,36)=4.85 p=0.013) , but not for *Orientation*. There were no interaction effects. *Post hoc* tests showed a lower score for Mid-Air No-Snap compared to Mid-Air Snap (p=0.01) .

Self-Location: For the Self-Location sub-component of Embodiment, there was a significant main effect of *Surface Type* (F(2,36)=13.721 p<0.001): users had significantly lower scores in the Mid-Air Snap condition in comparison to both Mid-Air No-Snap (p=0.0124) and Passive Haptics conditions (p<0.001). There was a significant interaction effect between *Surface Type* and *Surface Orientation* (F(2,36)=13.495 p<0.001).

Overall NASA-TLX Overall Workload - Reaching Task: There were no significant main effects for *Surface Type* (F(2,36)=2.62 p=0.08) or *Orientation* F(1,18)=0.89762 p=0.35 and no significant interaction effects (F(2,36)=0.82 p=0.44) (Figure 6-A).

Overall NASA-TLX Overall Workload - Dragging Task: There was a significant main effect of *Surface Type* (F(2,36)=9.91 p<0.001), but not for *Orientation* (F(1,18)=0.95). There was a significant interaction between the factors (F(2,36)=4.01 p=0.03). Participants had overall lower task workload scores for Passive Haptics conditions in comparison with both Mid-Air conditions: Mid-Air No-Snap (p<0.001) and Mid-Air Snap (p=0.039) (Figure 6-B).

Arm Exertion Results showed a significant main effect of *Surface Type* (F(2,36)=9.437 p=0.007) but not *Orientation*. There was no significant interaction between the factors (F(2,36)=0.92 p=0.912) (Figure 6-C). *Post hoc* tests showed a lower score for Arm Exertion in the Passive Haptics condition when compared to Mid-Air No-Snap (p=0.021).

3.7 Discussion

3.7.1 RQ1 - How do passive haptics influence VR selection performance and subjective experiences in a physically constrained space?

Passive haptics significantly reduced reaching and dragging times and had the highest throughput and the shortest path length (precision was higher for the mid-air conditions, but in all conditions, participants had to select the target correctly before continuing). This shows that passive haptics gives a major benefit to interaction in the plane seating environment.

In terms of the qualitative results, passive haptics gave a greater sense of agency, self-location, reduced workload when dragging,

User Preferences	Passive Haptics		Mid-Air Snap		Mid-Air No-Snap	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Presence	6.00 (1)	6.00 (2)	6.00 (2)	6.00 (2)	5.00 (1)	6.00 (2)
Agency*	6.00 (2)	6.00 (1)	6.00 (2)	6.00 (2)	5.00 (1)	6.00 (1)
Body-ownership*	6.00 (2)	6.00 (1)	6.00 (1)	6.00 (1)	5.00 (1)	6.00 (2)
Self-location*	6.00 (2)	6.00 (1)	6.00 (2)	6.00 (2)	6.00 (1)	6.00 (1)

Table 1: Results of the user preferences questionnaires comprised of 7-Point Likert scale statements. Results are in the format: Median (Interquartile Range) and * indicates statistical significance. Cells are shaded, ranging from white (lowest) to purple (highest).

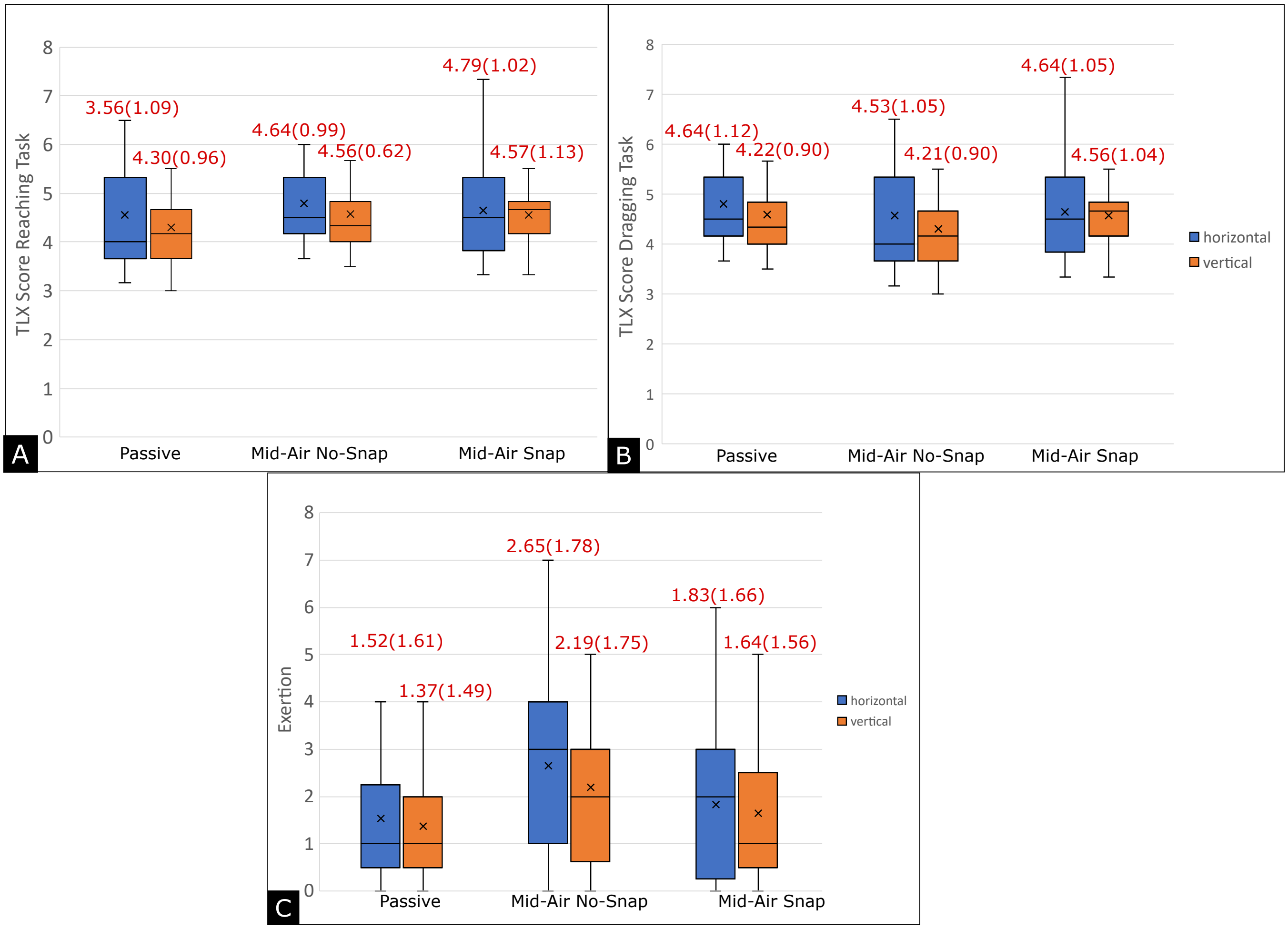

Figure 6: TLX Scores for (A) Reaching Task (B) Dragging Task, and (C) Arm Exertion Score. Numbers in red are in the format : Average (Standard Deviation)

and reduced arm fatigue. This again suggests that it is very beneficial.

There was a significant negative effect on both Body-Ownership and Self-Location in the Mid-Air Snap condition. Based on previous work, we chose a 1cm Mid-Air Snap threshold, but users felt less in control of their movements while interacting with targets. When asked about this issue in the post-questionnaire interview, most pointed to the target release being the main factor of disconnect between their virtual and real hand positions. The target release, which confirmed the selection and ended the dragging task, led them to make more exaggerated hand movements towards themselves, thus causing this issue.

3.7.2 RQ2 - How does the surface orientation influence user performance and subjective experiences in a physically constrained space? The quantitative orientation data were less definite than for surface type. The Vertical condition had a shorter dragging time than the horizontal, but Vertical had lower precision. There were no significant effects in the qualitative data for orientation.

In our post-test interview, we asked about preferences for the influence of surface orientation and surface type, and their potential impact for use over longer periods of time. 15 out of 19 participants preferred the horizontal surface. One of the participants (P12), explained this preference due to familiarity of interacting with touch surfaces in this orientation: "So the horizontal, it's comfortable for me... It's like a tablet. If you imagine yourself touching the screen of your laptop or a tablet that is horizontal". Participants pointed out that they could completely rest the weight of their hands on the horizontal surface for passive haptics conditions. Participants also stated that the Vertical surface put their hands at a "weird angle" (P12). 13 out of 19 said they would prefer horizontal surfaces for short journeys because of the effect of neck fatigue on long-term use. Participants commented that the position of the horizontal tray table required them to look at it from an uncomfortable angle, which was affected by the headset's weight, as pointed out by three participants in the post-test interview. This issue made these users prefer Vertical Surfaces for longer-term use. Participants mentioned that a possible solution was to physically raise the tray table or virtually manipulate its position to overcome neck comfort issues.

3.7.3 Impact of Social Acceptability on Overall User Preferences. In the post-test interview, we asked people to justify their preferences between surfaces according to how they would use the tested conditions in a real public setting, with the presence of other people. Horizontal was suggested as being the most socially acceptable for users as they kept interaction within their personal space. This would prevent them from staring at people inadvertently or poking people in front of them. Another interesting factor mentioned by P15 is that the possibility of front-row passengers reclining the seats would change how they interact, possibly needing them to recalibrate the surface for interaction: "Because usually people just recline the chair towards you, so the vertical ones are really hard then to see in a way."

Two participants also mentioned that horizontal surfaces were more common and that they would prefer to see people interact with them if they were sitting next to a person experiencing VR in a plane. P6, for example, mentioned that not using a surface would make the other users' actions feel unpredictable, as they could start staring at or colliding with them at any given moment.

Other aspects that might be considered are improving the feedback for selection, as a more realistic hand model, as used in our study, may make the fingers partially occlude the targets. Future work may investigate the different forms of feedback (such as using sound or colour glow) and using more abstract hand models (as seen in [26]).

3.8 Summary

Our results showed a significant performance benefit in all quantitative measures and preferences for using passive haptic surfaces for XR in constrained spaces. There was less consensus for surface orientation, but the qualitative data suggested several interesting issues to be further investigated. Neck fatigue concerns were raised in the post-test interview, with users pointing out that they would not use XR HMDs for longer periods because of the uncomfortable angle necessary to interact directly with targets. Such issues made people prefer vertical surfaces for longer journeys, but long-term use may still be limited due to the low height of the vertical surface, even though this is would reduce arm fatigue [28]. The issues raised regarding long-term comfort are especially important for use in plane contexts, as people are more interested in using XR for longer journeys [4]. To address this problem, we argue that perception manipulation remapping techniques are a cost-effective solution to improve user comfort [19]. The nature of the space, though, would require more extreme translations and rotations than are commonly employed [3, 39] due to the tight constraints and the position of available surfaces. We hypothesise these manipulations will increase user comfort while maintaining an effective and enjoyable XR experience. We address these issues in a follow-up user study that analyses the impacts of translational and rotational surface remapping in constrained spaces, using the same task in this study that combines both 2D and 3D movements.

4 STUDY 2: ADDRESSING COMFORT ISSUES WITH MOVEMENT REMAPPING

Our first study showed some qualitative benefits of interacting on a horizontal passive haptic surface. However, the position of this surface led to issues and concerns around comfort and long-term usage in the confined space of plane seating. Users reported having increased neck fatigue because of their need to look down to interact while wearing the HMD. People pointed out that this issue would hinder their long term use. Participants also liked the horizontal surface for shorter journeys, as interacting with the tray table was seen to be more "socially comfortable" in such a public context. It would not bother passengers to the side or in front (as opposed to a vertical orientation, which would lead to tapping on the back of the seat in front, which may be noticeable to the person sitting in it) (see Section 3.7.1). We also noticed neck fatigue in the Vertical surface conditions, as pointed out in the post-test interviews (Section 3.7.2).

To overcome the issues found related to comfort, a second study was designed to examine how we could maximise performance and comfort to take advantage of the best virtual and physical surface orientations. This study was conducted three months after the first. Perception manipulation techniques were used to remap the workspace and hand movements for a more comfortable experience. For the vertical orientation, we aligned the top of the virtual surface to match the users' eye line (Figure 7-E).

For the horizontal orientation, we also remapped the virtual surface's position according to the user's height. To improve the visibility of the surface, we also rotated it 90° and then positioned it similarly to its vertical counterpart. This would potentially solve the comfort issue, but at the risk of increased task workload since a 90° hand remapping makes movement difficult (here called *Horizontal 90*, Figure 7-D). Therefore, three additional intermediary remapping rotations were included to find the best compromise between rotation and interaction performance: 45°, 60°and 75°.

Our task differed from previously used indirect manipulation techniques [26, 27] as it included a 3D Reaching component - common in VR tasks where users reach to interact with a UI directly - that made participants take their hands away from the physical surface to reach for a 3D sphere aligned with the centre of the it.

To maintain tracking accuracy in the confines of the seating, before each of the conditions participants were instructed to point with their index finger and to keep their hands open, with the palm facing the surface (see Figure 1-D). This gesture enabled the cameras on the Oculus Quest 2 to recognise the hands even when they were positioned on the horizontal surface and the head faced forward.

4.1 Remapped Surfaces

On the remapped conditions, the centre of the virtual surface's height position **c** (z-coordinate) was adapted according to the ratio (X/90) * d, where **d** is the difference between the user's eye position and the height position of the physical surface and **X** being the rotated angles on those conditions. Each of the conditions **d** was adapted to the user's height.

The conditions were: *Hor45*: The virtual surface was rotated 45° and placed halfway between the surface and eye height (Figure 7-A); *Hor60*, where the surface was rotated 60° and placed at a height 2/3 of **d** (2/3 * d) (Figure 7-B); *Hor75:*, where the virtual surface was rotated 75° and placed at a height 0.833 of **d** (0.833 * d or 75/90*d) (Figure 7-C); *Hor90:* where the surface was rotated 90° and placed at the user's height (Figure 7-D); and finally *VertRemapped:* where the vertical virtual surface was placed at user's eye height **h** (Figure 7-E).

4.2 Design & Measures

The task design and methodology were the same as the previous study. However, due to fewer conditions, we doubled the number of selections per condition to 44. For a full comparison, we included two baselines for Vertical and Horizontal orientations, where the virtual planes were located at the same positions as their physical counterparts.

For the quantitative measures, we used the same Precision, PathLength, which was used as a measure of movement precision, and Time measures as the previous study, which was computed for the Reaching and Dragging sub-tasks. We also calculated the Throughput between targets on the 2D plane.

As before, the qualitative questionnaire was comprised of five 7-Point Likert Scale questions, which were the same used in the previous study. One of those related to Presence[64], and three were about the Sense of Embodiment and its sub-components: Agency, Body-Ownership, and Self-Location [37]. We added an extra question for the rating of Neck Fatigue.We also included a post-test interview, where we asked participants to talk about their subjective preferences for the conditions. We also asked them to rank their preferred conditions in relation to Comfort, Social Acceptability and Overall preference.

The Research Questions were similar to the previous study but included an additional one related to Neck Fatigue:

RQ1 - How does movement remapping influence Task Performance?

RQ2 - How does movement remapping influence User Presence, Embodiment, and Task Workload?

RQ3 - How does movement remapping influence Neck Fatigue?

The measures collected and experimental procedure were the same as Study 1. The experiment was approved by the University ethics committee.

4.3 Participants

We recruited 21 participants aged between 20 to 39 years (average of 27), 15 identifying as male and six as female. Six of the 21 took part in the previous experiment. We included both horizontal and vertical baseline conditions to provide all participants with equal training for surfaces in both orientations. The second study was completed three months after the first, and so this time gap, combined with the equal training given before each condition, meant any effects of previous experience were likely to be small. These participants were recruited through university mailing lists and paid £10 for participating. Of these participants, all had some previous knowledge of VR, with ten using it at least once a week. The rest of the participants reported using such devices rarely.

4.4 Results

4.4.1 *Quantitative Results:*

To assess for data normality, we used the Shapiro-Wilk test. Since the quantitative measures used were not normally distributed, we used Friedman non-parametric tests with Wilcoxon Signed Ranks tests with Bonferroni correction applied as *post hoc* tests. Results can be seen in Figure 8.

Reaching Time: Reaching time was significantly different the conditions ($\chi^2(6) = 999.736 p < 0.001$). The Vertical (VerticalB) and Horizontal (HorizontalB) baselines were the best overall performing techniques (see Figure 8-A). The VerticalB was significantly faster than all the remapped conditions (all p<0.001): Vertical Remapped (Z=-17.478), Hor45 (Z=-5.359), Hor60 (Z=-5.997), Hor75 (Z=-12.693), and Hor90 (Z=-13.091).

Reaching was significantly faster for HorizontalB compared to all Remapped conditions (all p<0.001): Hor45 (Z=-9.835), Hor60 (Z=-9.886), Hor75 (Z=-14.669), Hor90 (Z=-20.053), and Vertical Remapped (Z=-16.775). The HorizontalB was significantly faster than the VerticalB (Z=-5.240 p<0.001).

For the remapped conditions, Hor45 was significantly faster than Vertical Remapped (Z=-13.091 p<0.001), Hor75 (Z=-8.201 p<0.001), and Hor90 (Z=-14.722 p<0.001). The Hor60 was also significantly faster than Hor75(Z=-14.468 p<0.001), Hor90 (Z=-14.722 p<0.001) and Vertical Remapped(Z=-5.284 p<0.001). Vertical 75 was significantly faster than the Hor90 (Z=-10.550 p<0.001) and Vertical Remapped (Z=-5.284 p<0.001). Hor90 was the slowest of all conditions.

Dragging Time: Dragging time was significantly different between the conditions ($\chi^2(6) = 273.898 p < 0.001$). The baselines were only faster than the more extreme re-mappings: Vertical Remapped (Z=-9.646 p<0.001, Hor75 (Z=-4.657 p<0.001), and Hor90 (Z=-9.243 p<0.001). Participants were significantly faster with the HorizontalB than Hor75 (Z=-6.969 p<0.001), Hor90 (Z=-12.106 p<0.001) and Vertical Remapped conditions (Z=-9.243 p<0.001). Regarding baselines, in contrast to the Reaching task, the Dragging

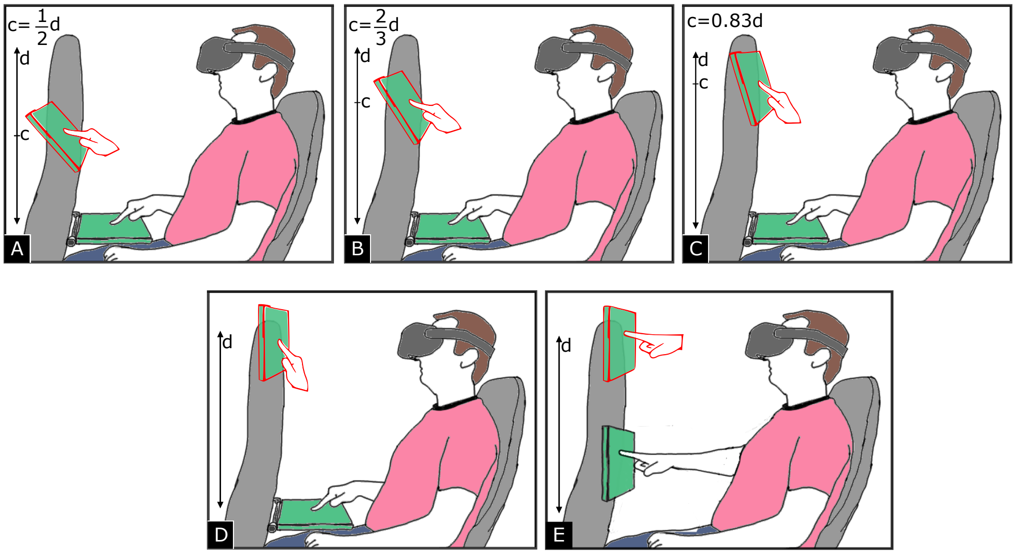

Figure 7: Depiction of the Remapping conditions. In the figure, the surfaces and hands outlined in red represent where those were remapped to. C indicates the position of the centre of the virtual surface in z-coordinates, which is calculated in relation to d, which is the difference between users' height and the position of the physical surface. Remapped Conditions : (A) Horizontal 45°, (B) Horizontal 60°, (C) Horizontal 75°, (D) Horizontal 90°, (E) Vertical Remapped.

task was significantly faster when using the VerticalB condition (Z=-3.153 p<0.001). There were no other significant differences.

For the remapped conditions, Hor45 and Hor60 were the fastest. significantly faster than Hor75 (Hor45:Z=-6.388 p<0.001;Hor60:Z=-3.818 p<0.001), Hor90 (45:Z=-8.565 p<0.001; 60:Z=-8.765) and Vertical Remapped conditions (45:Z=-8.565 p<0.001; 60: Z=-8.756 p<0.001). The Hor75 was significantly faster than the Hor90 (Z=-6.324 p<0.001) and Vertical Remapped (Z=-3.772 p<0.001). Vertical Remapped and Hor90 were significantly slower than all the other remapped conditions. Figure 8-B shows a distribution of times split by condition.

Reaching Precision: Reaching precision was significantly different between the conditions ($\chi^2(6) = 145.811p < 0.001$). The VerticalB condition was significantly less precise than the HorizontalB.Participants were also less precise with the VerticalB when compared to Vertical Remapped (Z=-4.053 p<0.001), Hor45 (Z=-7.860 p<0.001), Hor60 (Z=-4.943 p<0.001), and Hor75 (Z=-3.006 p<0.001). HorizontalB was significantly more precise than Hor60 (Z=-2.979 p<0.001), Hor75 (Z=-4.978 p<0.001), Hor90 (Z=-2.979 p<0.001), and Vertical Remapped conditions (Z=-3.770 p<0.001).

For the remapped conditions, Hor45 was significantly more precise than all others (60: Z=-3.220 p<0.001; 75: Z=-3.024 p=0.002; 90: Z=-6.799 p<0.001; VerticalRemapped:Z=-4.303 p<0.001), and also when compared to the VerticalB condition. Hor60 was more precise than Hor90 (Z=-4.125 p<0.001) and Vertical Remapped conditions (Z=-6.106 p<0.001). The Hor75 was significantly less precise than all other remapped conditions, except for the Vertical Remapped (Z=-0.943 p=0.346). Please refer to Figure 8-C for the distribution of the precision results for the Reaching Task.

Target Confirmation Precision: Target confirmation precision was significantly different between the conditions ($\chi^2(6) = 121.825p < 0.001$). Analysis showed that the VerticalB condition was significantly less precise than Vertical Remapped (Z=-4.303 p<0.001) and also than the HorizontalB condition (Z=-7.340 p<0.001). The HorizontalB was less precise than the Hor75 condition (Z=-4.369 p<0.001) and Vertical Remapped (Z=-4.303 p<0.001). We did not find any significant differences between the other remapped conditions. Similar to the Reaching task, participants were less precise using the Hor45 compared to Hor75 (Z=-5.424 p<0.001) but more precise with Hor45 when compared to the Vertical Remapped (Z=-3.620 p<0.001). Participants performed similarly using the Hor60 and Hor75, with less error than only the Vertical Remapped Condition (Hor60: Z=-6.106 p<0.001; Hor75: Z=-4.369 p<0.001). Hor90 and Vertical Remapped were the worst performing conditions among the remapped condition (see Figure 8-D).

Throughput: We calculated throughput, which combines movement time, speed and Index of Difficulty (see Figure 8-E for raw data). Throughput was significantly different between the conditions ($\chi^2(6)$=14.122 p=0.028).

HorizontalB (μ: 1.9633 bits/s σ: 0.5923) had a significantly higher throughput than VerticalB (μ: 1.6104 σ: 0.42) (Z=2.242 p=0.025). For the remapped conditions, the Hor45 had the highest throughput (avg: 1.94 std:0.4875), significantly higher than VerticalB (Z=-2.311 p=0.021), VerticalPos (Z=-2.207 p=0.027), and Hor90 (Z=-2.242 p=0.025). This was followed by Hor60 (μ: 1.9 σ:0.44), having a higher throughput than VerticalB (Z=-2.694 p=0.007), VerticalPos (Z=-2.381 p=0.017), and Hor90 (Z=-2.285 p=0.013). The Hor75 had a throughput of (μ: 1.64 σ:0.53). The lowest throughputs were in the VerticalB condition (μ:1.61 σ:0.44) followed by Hor90 (μ:1.61 σ:0.42).

Path Length: Path length was significantly different between the conditions ($\chi^2(6) = 202.511p < 0.001$). When analysing baselines,

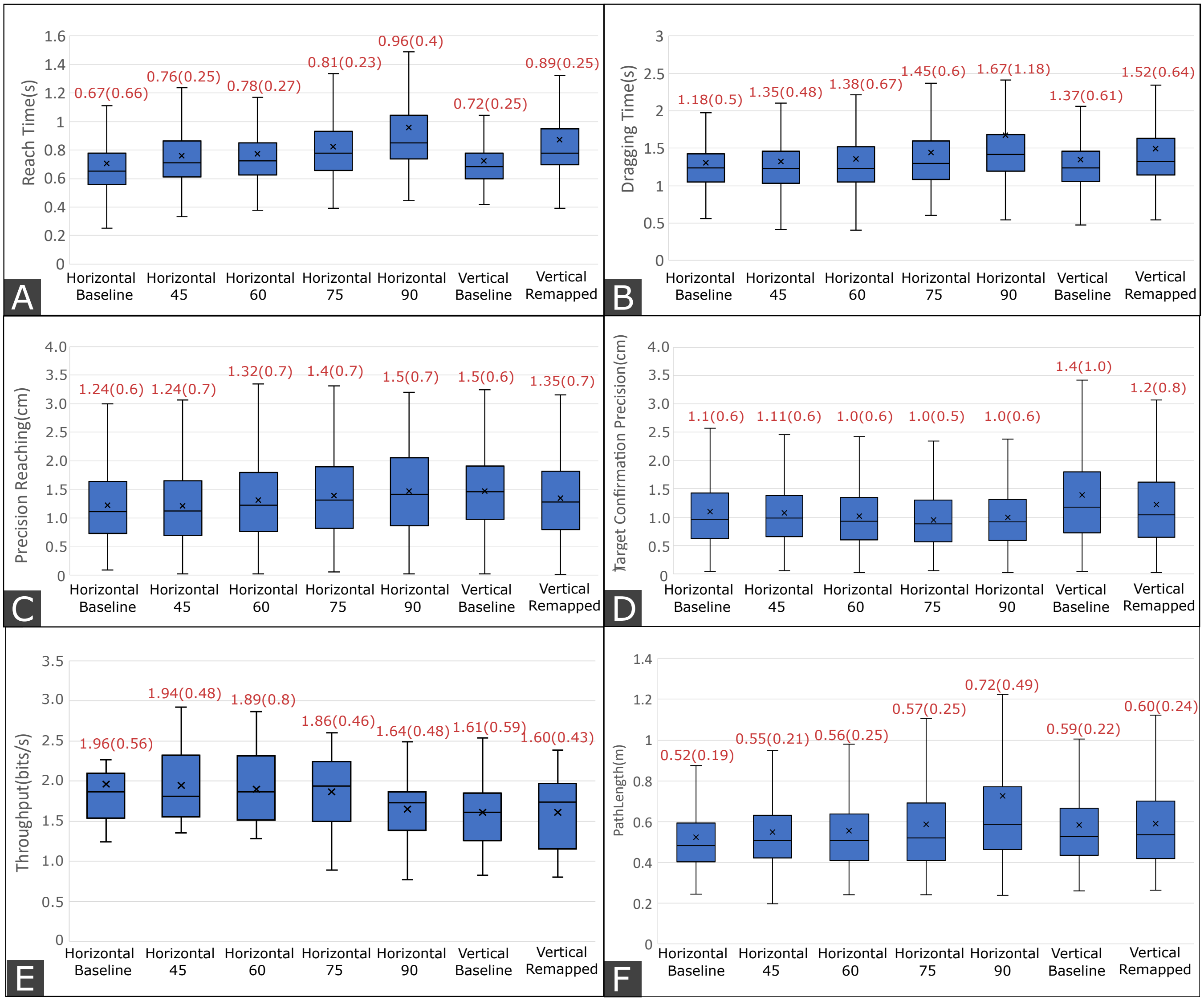

Figure 8: Quantitative results: (A) Reaching Task, (B) Dragging Task; *Precision* for: (C) Reaching Task, (D), Dragging Task; (E) *Throughput (bits/s)*; (F) *Path Length* (m). Numbers in Red are in the format: Mean (Standard Deviation).

we found different behaviours in the vertical and horizontal conditions. HorizontalB had a short path length, shorter than all the Remapped conditions (Hor45:-3.939 p<0.001, Hor60:-4.245 p<0.001, Hor75:-6.671 p<0.001 Hor90: Z=-11.843 p<0.001 and VertRemap: Z=-6.752). It also had a significantly shorter path length than the VerticalB condition (Z=-6.546 p<0.001). Conversely, the vertical baseline had longer path lengths than the remapped conditions, longer than Hor45 (Z=-4.035 p<0.001), Hor60(Z=-4.245 p<0.001), and rot90, but no significant difference compared to VertRemap and Hor75. Regarding Remapped conditions, we found the Hor45 (avg:0.55 stddev:0.21) and Hor60 (avg:0.56 stddev:0.25) had the lowest path lengths. The Hor45 had a significantly shorter path length than Hor90 (Z=7.196 p<0.001) and VertRemap (Z=-2.943 p<0.001). A similar behaviour was shown for Hor60, which had shorter lengths than Hor90 (Z=-7.196 p<0.001) and VertRemap (Z=-3.173 p=0.002). More extreme remappings such as Hor75, Hor90 had longer path lengths, followed by the VertRemap condition.

4.4.2 ***Subjective Results***.

Since the subjective questionnaires comprised non-continuous data, we used Friedman Non-parametric tests with Wilcoxon Signed Rank *post hoc* tests with Bonferroni Correction. Results can be found in Table 2 and Table 3.

Presence: There were no significant differences in Presence between the conditions ($\chi^2(6)=3.541$ p=0.739).

Embodiment: There were significant differences for all three embodiment subcomponents: Agency ($\chi^2(6)=33.104$ p<0.001), Body-Ownership ($\chi^2(6)=27.792$ p<0.001) and Self-Location ($\chi^2(6)=44.952$ p<0.001).

	REACH							DRAG						
	VertBase	VertRemap	HorBase	Hor45	Hor60	Hor75	Hor90	VerticalB	VertRemap	HorBase	Hor45	Hor60	Hor75	Hor90
Mental	2.00 (2)	4.00 (4)	2.00 (2)	3.00 (2.75)	3.50 (3)	4.00 (3)	5.00 (4)	2.00 (2)	3.00 (2.75)	2.00 (2)	3.00 (2)	2.50 (2.75)	3.00 (2)	4.00 (3.75)
Physical	3.00 (3)	4.00 (2.75)	2.00 (1)	3.00 (1.75)	3.00 (2)	2.50 (3.5)	3.50 (3.75)	3.50 (2)	4.00 (2.75)	2.00 (1.75)	2.00 (2.75)	2.50 (2.75)	2.50 (3.75)	3.00 (2.75)
Performance	8.00 (2)	7.00 (2.75)	8.00 (2)	7.00 (2)	7.00 (2.75)	6.50 (3)	6.00 (2.75)	7.50 (1)	7.00 (2)	8.00 (1.75)	7.50 (1.75)	7.00 (2)	6.50 (2.75)	6.00 (2.75)
Effort	3.00 (2)	5.00 (2)	2.00 (1.75)	3.00 (2.5)	4.50 (3.75)	4.00 (3)	5.00 (2.75)	3.00 (2.75)	4.00 (2)	2.00 (1.75)	3.00 (3.75)	3.00 (3.75)	3.50 (2)	4.50 (3.75)
Frustration	2.00 (1.75)	3.00 (2)	2.00 (2)	2.00 (1)	2.50 (3)	2.50 (2.75)	3.50 (2.75)	2.00 (1.75)	2.00 (1)	2.00 (2)	2.00 (2)	2.00 (1.75)	2.00 (2)	3.00 (1.75)

Table 2: Results for NASA TLX Workload, split by the reaching and dragging sub-tasks. These questionnaires were comprised of 9-Point Likert scale statements. Results indicate Median (Interquartile range). Cells shaded from white (low) to purple (high).

	VerticalB	VertRemap	HorizontalB	Hor45	Hor60	Hor75	Hor90
Presence	5.00 (3)	5.00 (2)	5.00 (1.75)	5.00 (2.75)	5.00 (2.75)	5.00 (3)	5.00 (1.75)
Agency	6.00 (1)	5.00 (3)	6.00 (2)	6.00 (1)	5.00 (2.75)	5.00 (3)	4.00 (3)
Body-Ownership	6.00 (1.75)	5.00 (1.75)	6.00 (1)	5.00 (2)	5.00 (3)	5.00 (3)	5.00 (2.75)
Self-location	6.00 (1)	3.00 (3.5)	6.00 (1)	5.00 (1.75)	4.00 (2.75)	4.00 (3.5)	3.50 (3)
Neck Fatigue	3.00 (2)	1.00 (1.75)	3.00 (3)	2.00 (2)	2.00 (2.75)	2.00 (2)	2.00 (1.75)

Table 3: Results for the user preference questionnaires. The questions used 7-Point Likert scales. Results indicate Median (Interquartile range). Cells shaded from white (low) to purple (high).

Regarding *Agency*, we found the VerticalB condition elicited a higher sense of agency compared to both Vertical Remapped (Z=-3.353 p=0.001) and Hor90 (Z=-3.067 p=0.002). We also found the HorizontalB to be higher in Agency compared to Vertical Remapped (Z=-3.214 p=0.001) and Hor90 (Z=-3.025 p=0.002). Results were similar for *Body-Ownership* with VerticalB eliciting a significanly higher sense of body-ownership than both Vertical Remapped (Z=-3.579 p<0.001) and Hor90 (Z=-3.210 p=0.001). Finally, *Self-Location* results showed that the Remapped Conditions elicited a lower sense of self-location when compared to both Vertical and HorizontalB conditions. VerticalB had significantly higher self-location than Vertical Remapped (Z=-3.499 p<0.001), Hor45 (Z=-3.519 p<0.001), Hor60 (Z=-3.440 p=0.001), Hor75 (Z=-3.533 p<0.001) and Hori90 (Z=-3.576 p<0.001). The HorizontalB, on the other hand, elicited a higher sense of self-location when compared to Vertical Remapped (Z=-3.215 p=0.001), Hor45 (Z=-2.880 p=0.004), Hor75 (Z=-3.102 p=0.002) and Hor90 (Z=-2.998 p=0.003) (Table 3).

NASA TLX Overall Workload - Reaching Task: There was significant effect for workload in the reaching task (χ^2(6)=31.399 p<0.001) (Figure 9). When comparing remapped conditions with the Baseline conditions, we found significant differences between Hor90 and HorizontalB (Z=-2.846 p=0.005), VerticalB and Vertical Remapped (Z=-3.184 p=0.001), and lastly, between Vertical Remapped and HorizontalB (Z=-2.777 p=0.005). In all the comparisons, the baseline conditions had lower workload scores than the remapped ones. Additionally, the Hor45 had a significantly lower overall workload than Vertical Remapped (Z=-3.386 p=0.002). Results can be seen in Table 2.

NASA TLX Overall Workload - Dragging Task: There was significant effect for workload in the dragging task (χ^2(6)=27.011 p<0.001) (Figure 9). When comparing baselines against the remapped condition, comparisons showed that participants had overall lower scores for the Horizontal Baseline when compared to the Hor90 (Z=-2.806 p=0.005) and VerticalRemap (Z=-2.945 p=0.003). The VerticalB had higher scores than the Hor45 (Z=-2.868 p=0.004) and HorizontalB (Z=-3.390 p=0.001). For the remapped conditions, there were lower average scores between Hor45 when compared to Hor90 (Z=-2.906 p=0.004) and VerticalRemap (Z=-2.986 p=0.003).

Since we found significant main effects on the overall workload, we performed additional statistical tests for the workload sub-components. By performing Friedman Non-parametric tests, we found a significant effect on all Workload sub-components: Mental Demand (χ^2(6)=29.979 p<0.001), Physical Demand (χ^2(6)=15.440 p=0.009), Performance (χ^2(6)=19.805 p=0.003), Effort (χ^2(6)=24.578 p<0.001), Overall Performance (χ^2(6)=17.822 p=0.007) and Frustration (χ^2(6)=12.790 p=0.046).

Regarding Mental Demand, we found that VerticalB had significantly lower Mental Demand than both Vertical Remapped (Z=-2.899 p=0.004) and Hor90 (Z=-3.134 p=0.002). HorizontalB had significantly lower Mental Demand compared to the Hor90 condition (Z=-3.243 p=0.001). Hor90 also had significantly higher demand than the Hor45 (Z=-2.914 p=0.004). For Physical Demand, HorizontalB had lower workload than the Vertical Remapped condition (Z=-2.889 p=0.004). The Hor45 condition also scored significantly lower physical demand than Vertical Remapped (Z=-3.128 p=0.002).

Neck Fatigue: There was a significant effect of Neck Fatigue between conditions (χ^2(6)=27.584 p<0.001) (Table 3). HorizontalB led to significantly higher fatigue than the Hor45 (Z=-3.220 p=0.001), Hor60 (Z=-2.958 p=0.003), Hor75 (Z=-2.877 p=0.004) and Hor90 (Z=-2.853 p=0.004). Additionally, the Vertical Remapped condition led to significantly lower neck fatigue than VerticalB (Z=2.307 p=0.001).

4.5 Discussion

4.5.1 *RQ1 - How does movement remapping influence Task Performance?*

Overall, the horizontal conditions performed better than the verticals. The non-remapped horizontal baseline condition performed very well in terms of throughput, path length, and short reaching and dragging times. This again shows the benefit of the

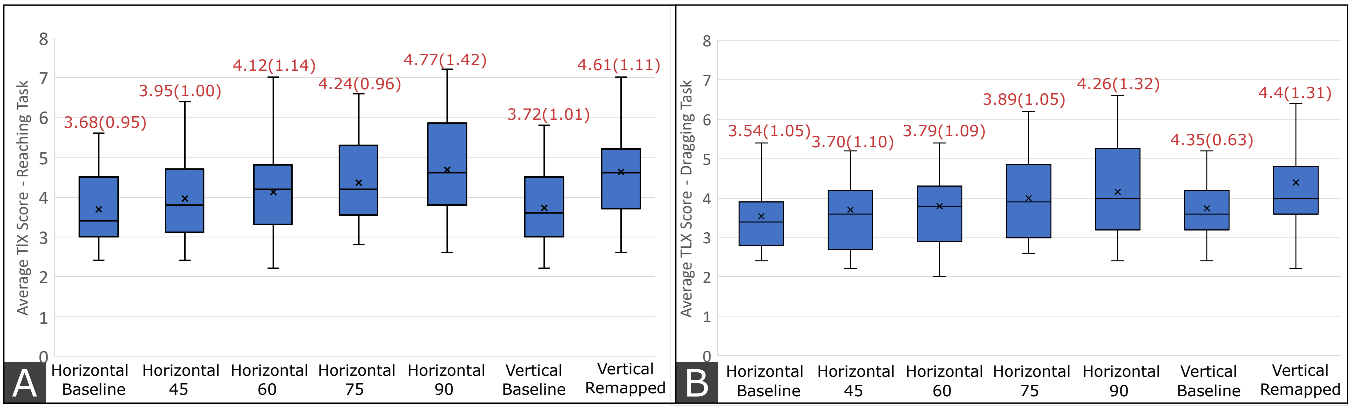

Figure 9: Results for mean *NASA TLX Overall Workload* separated by task: (A) Reaching Task (B) Dragging Task.

horizontal orientation and the lack of remapping means that interaction is good (however, this comes at a cost of higher neck fatigue, see below). Low-level remapping of the horizontal conditions (Hor45, Hor60) kept performance high across the measures, with benefits for neck fatigue. This shows that small manipulations can be effective. The throughput and path length of the Hor45 condition, for example, were very close to the horizontal baseline.

There was a higher throughput in the lower remappings of Hor45 and Hor60 compared to more extreme rotations such as Hor75 and Hor90. Hor45 and Hor60 also had higher throughput compared to both the Vertical Baseline and Vertical Remapped conditions. The extreme conditions (Vertical Remapped, Hor75 and Hor90) were considerably slower in both Reaching and Dragging. Hor45 and 60 had no significant impact on time to complete both Reaching and Dragging when compared to baseline conditions.

4.5.2 RQ2 - How does movement remapping influence Presence, Embodiment, and Task Workload? Our results showed that the remapped conditions generally reduced performance across the subjective measures, with the baseline vertical and horizontal conditions performing the best. However, smaller horizontal rotations again performed at a level close to the baselines. The larger remapped conditions produced significantly lower ratings of agency, and body ownership. The remapped conditions elicited a lower sense of self-location when compared to both Vertical and Horizontal baselines, as would be expected as they change the relationship between the real and virtual environment. Even low levels of rotation caused reductions in ratings of self-location, so the changes are clearly noticed by users. However, as shown in RQ1, this does not necessarily impact task performance. The baselines were again had the lowest NASA Task Workload scores. However, less extreme manipulations, such as Hor45 and Hor60, performed well in the different workload categories. Only the higher levels of manipulation increased workload significantly. There were no effects on Presence, which suggests that such manipulations do not affect a user's presence in a VR environment.

The Vertical Remapped condition, which only manipulated translational movements of users' hands, did not perform well. When asked about this issue in the post-test interviews, participants pointed out that the manipulation placed their arms too close to where their real hands were, making them believe the surface was located higher than it was, and so they tried to match their real hands to where they saw their virtual hands. This issue also affected the Agency and Body-Ownership sub-components of Embodiment, which had significantly lower scores in the Vertical Remapped condition.

When comparing conditions in the Dragging Task, we found less pronounced differences regarding Preferences, Embodiment and Comfort. Users justified this as, once they reached the physical surface, the passive haptics gave them a better reference to the real world, which helped them finish the task.

4.5.3 RQ3 - How does movement remapping influence Neck Fatigue?

There was a significant reduction in neck fatigue for the remapped conditions compared to the baselines, overcoming the issues found in the previous study. The Horizontal baseline led to the highest level of neck fatigue, as predicted from Study 1. Neck fatigue was significantly reduced by all the rotations of Hor45 and above. The Vertical remapping reduced neck fatigue to the lowest median level of all conditions. Participants stated that the compromise between remapping movement and neck comfort was positive, especially for less extreme surface and hand rotations.

However, Neck comfort impacted user preferences, as stated by users in the post-test interview. For example, 7 out of 21 participants had a preference for more extreme conditions (7 for the Hor75 and 2 for the Hor90), as they felt this would be "more comfortable for long-term use" (P8) and "less fatiguing" (P18). These participants said the increase in Mental Demand was less important than comfort issues. The rest of the participants found the Hor45 and Hor60 represented a comfortable position without putting excessive strain on the neck or hands.

4.5.4 Overall Preferences. We asked participants to rank their preferred surfaces for interaction for short- and long-term use. The post-test interview also asked about the impact of social acceptability and comfort of the ranked conditions. 20 out of 21 participants preferred the horizontal surfaces over the HorizontalB and VerticalB conditions, with Hor45 being the most preferred (with 14 participants choosing this as their preferred condition). The Hor60 condition was chosen as the favourite condition by one participant, but it was the second choice of 14 .Participants pointed out that their choice was based on a positive trade-off between task workload and both arm and neck comfort.

The least preferred condition was Vertical Remapped, where 18 out of the participants pointed this condition to be their least preferred due to feelings of mismatch between the users' virtual and real hands, as previously shown. P20, for instance, pointed out that this remapping felt very “dissonant" from their real movements and felt like they were controlling a virtual cursor resembling their hands, instead of their real hands. This is similar to the effect reported previously in the literature [13]. Another reason for preferring the Horizontal conditions, pointed out by 10 out of 14 participants, , was that this put the virtual surface in a “socially acceptable" position: “they would not bother the person in front", while “keeping a comfortable position for the hand".

Based on these findings, we suggest that horizontal surfaces remapped to 45° or 60° present the optimal trade-off of performance, neck fatigue, embodiment, and comfort, evidenced by user preferences - exemplifying the benefits of passive haptics and remapping in creating a more usable virtual environment in confined plane seating settings.

4.6 Limitations and Generalisability

Given the use of real plane seats and a seat pitch commensurate with economy airline travel, our findings have strong validity for interaction in the constrained space of a plane seat. Our study was lab-based and so did not include real-world factors such as motion; it represents a controlled baseline to identify the best performing conditions which could then be tested in a real plane environment.

The findings could also transfer to other modes of transport as this type of seating configuration is common. We see the particular benefit in considering in-car interactions in particular, as rear car seats often feature not-dissimilar seat pitches, with seatbacks (and possibly tray tables) within reach of the passenger. Trains also feature similar designs in terms of having reachable seatbacks and tray tables. Consequently, future research should consider the impact of varying seat pitch and seatback reachability on interaction usability and user preferences. In doing so, we could move towards XR headsets that can automatically appropriate the available surfaces of the constrained passenger space based on suitability.

There are several limitations to consider. Firstly, we did not simulate the motion of the plane, which could impact the results, for example provoking a larger discrepancy between mid-air and grounded surface-based interactions. However, apart from takeoff and landing (and turbulence), plane flights are mostly smooth with few direction or acceleration changes, meaning our lab results are valid. Secondly, the study did not involve other non-participant passengers. The social co-presence and proximity of others may have an impact on preferences, for example. However, we note that all interactions remained within the constrained boundaries of the individual passenger's seat and so it is unlikely that our performance metrics would be meaningfully impacted by social presence. Thirdly, we tested with only one seat type and one fixed seat pitch, representative of the worst case of economy airline travel. Different seat types/pitches (e.g. business, first class) could be expected to significantly impact interaction, for example, putting seatback surfaces out-of-reach but providing larger arm rests and tray tables. Future work should consider these caveats in moving towards full in-flight testing.

5 GUIDELINES FOR XR INTERACTIONS WITH PLANAR SURFACES IN CONSTRAINED SPACES

Travelling in constrained spaces poses notable physical challenges for interactive XR. However, our findings demonstrate that the ability of XR devices to appropriate and manipulate the perception of physical surfaces also unlocks new comfortable, low exertion, and high accuracy interaction capabilities. We distil our findings into guidelines for interactions with planar 2D content in constrained spaces:

5.1 Guideline 1: Appropriate nearby physical surfaces for passive haptics

Across both studies, the benefits of passive haptics were repeatedly seen in terms of reaching/dragging time, workload, and arm exertion. Appropriating the horizontal tray table in particular and the vertical seatback to a lesser degree offered users rich interaction surfaces upon which planar virtual content could be overlaid. Its use also supports real haptic confirmatory feedback, which was strongly preferred by users. These surfaces are parts of the physical boundaries of the seating environment, making it potentially more likely that users will remain within the bounds of the space, which is conducive to maintaining social acceptability. Consequently, XR devices should strive to appropriate available surfaces in constrained spaces, providing a viable alternative to mid-air hand interactions for a breadth of XR use cases where some direct UI manipulation is required.

This guideline does, however, have some caveats to consider. Firstly, we have not examined the impact that utilising passive haptics for interaction has on the comfort (and consequently perceived social acceptability) of the passenger directly in front of the XR user. For the vertical seatback in particular, it may be that repeated fingertip contact with the seatback could negatively impact other passengers; an issue that does not occur with interaction on the tray table.

Secondly, some consideration should be given to the relative trade-offs and merits of direct and indirect perceptually manipulated passive haptic approaches versus more traditional indirect inputs such as mice/trackpads. For example, frequent, high-accuracy interactions around high-performance productivity tasks may benefit from more traditional inputs. However, for more casual interactions with planar UIs (e.g. for web-browsing, video playback) with similar interactions to our study, passive haptics offers a viable, beneficial alternative to passengers compared to direct mid-air interactions for planar virtual displays.

5.2 Guideline 2: Use moderate perceptual remapping to maintain performance and improve comfort

Passive haptic surfaces may have ergonomic drawbacks due to their position around the passenger. The tray table is positioned such that it requires uncomfortable head/neck movements to view, whilst the seat-back requires a degree of arm extension, reducing the benefits of utilizing a physical surface. Our findings can, however, directly address these problems.

We demonstrated that, by rotating the horizontal display 45° or 60° and translating upwards, we could retain many benefits of tray table passive haptic interactions whilst overcoming the ergonomic drawbacks by moving the virtual representation of the interactive surface into a more comfortable viewing position. This moderate remapping maintained similar Dragging Time, Reaching/Targeting Precision, and Dragging Workload as baseline passive haptic conditions, though at the expense of increased Reaching Time and Workload, as well as lower Embodiment. Our findings contribute to mounting evidence around the ergonomic benefits of XR for planar displays [47, 49].

Therefore, we recommend that such remapping is provided by XR platforms as standard, but that it is also user configurable: either to support individual preferences or to suit seating environments of different sizes and with varying surface positions, where more or less extreme remappings may be preferred (e.g., to overcome the confusion between the closely positioned real and virtual hand in the Vertical Remapped condition). As part of their "Infinite Office" initiative [52], Oculus' Quest line of headsets can incorporate office furniture, including desks and couches [31] into the virtual experience, and so the groundwork is already laid for expanding this "reality-aware" functionality to constrained spaces and remapped surfaces.

Regarding the more extreme perceptual manipulations we tested, the effect on user preferences and performance was less pronounced in the dragging task, representing a fully two-dimensional selection and manipulation. Because of that, where 3D spatial interactions are not required, future work should consider re-examining these extreme manipulations to enable indirect object selection and manipulation while addressing neck and hand strain issues.

We highlight the importance of having the Reaching sub-task as part of our study. This sub-task made users reach for a 3D sphere that was located at the same distance from all the targets. Without this sub-task, users would have kept their fingers on the calibrated surface and this may have influenced the results. As mentioned by one of the participants, regarding the remapped positions: "... the reaching part was difficult, but when my finger was on the surface it was ok (P12)". Future work may look at the effects of 3D and 2D surfaces separately, with varying levels of size and distance between the targets.

5.3 Guideline 3: When remapping vertical surfaces, consider the proximity of real and virtual hands

In our Vertical Remapped condition, several participants were confused because of how close their real hand was to the virtual, and so did not treat it as a remapping; instead, they tried to match their real hand to the virtual position. The Reaching component of the task also resulted in hand movements very close to the face. Issues like these led to generally poorer performance in the Vertical Remapped condition, and future work should fully examine how best to remap vertical passive haptic surfaces. Based on our results, we recommend the virtual surfaces be located at different proportions of **d**, as used for lower rotation remappings and potentially at a greater depth. This could help alleviate the tension between the perceived position mismatch issues about Task Workload.A more speculative alternative, depending on the ergonomic height of the surface, could be to place the surfaces closer together and utilise more imperceptible perceptual manipulation techniques around redirected haptics that guide the hand rather than remap it [17, 19, 23–25, 55].

Another possibility is to use translational gain to map users into a bigger environment, enabling people to interact with further away objects [69], while maintaining haptic feedback capabilities. Also, hand movements and/or gaze can be amplified along the planar surface of the traytable to enable representing bigger surfaces in VR, similarly to Biener et al. [7].

5.4 Example - XR Planar Web Browser in a Constrained Plane Seat

As part of our post-test interview, we asked participants to suggest potential applications where they would use our proposed manipulations. Most of those (17 participants) suggested web browsing and simple games, such as card games (14 participants). That said, we propose an exemplar application where an XR user interacts with a planar web browser while seated in a plane seat. This is a potentially very common interaction scenario, given the anticipated XR adoption. This would quickly become uncomfortable without applying our guidelines and have poor interaction performance. Our guidelines would suggest that the application designer: a) align the planar display with the seatback or tray table, based on the extent and duration of interaction - seatback for shorter interactions due to the physical demands of the passive haptic interaction, tray table for prolonged interactions as the hand is rested against the horizontal surface (Guideline 1); b) employ moderate perceptual remapping (45°) to either rotate and translate the tray table display, or translate the seatback display, to improve usability and ergonomics (Guideline 2); and c) ensure there is sufficient distance between real and virtual hand interactions (a high proportion of **d**), or sufficient difference in hand representation [26, 27] to avoid interactional interference [13] (Guideline 3).

Our guidelines are preliminary, however. Future work is necessary to fully explore how these guidelines could be influenced/directed by different transit contexts, seat types, and seat pitches, as well as the expected duration/extent and necessary accuracy of the interaction. For example, a larger seat pitch, or a user with a more limited reach or limited physical capability for holding their arm up, may suggest more reliance on appropriating rested, nearby surfaces such as the tray table or armrest for interaction. Similarly, if the tray table is in use, or the tray table is not appropriate for passive haptics interactions (uncomfortable height; too rough; already in use; or dirty and consequently taken out of use), then a reliance on seatback interactions may be preferable. This suggests the need for a model to help determine the appropriate choice of interaction based on the context of the constrained space, the available surfaces, and the anthropometrics and capabilities of the user. Our paper contributes notable insights into this challenge, demonstrating that passive haptics and remapped interactions can improve the ergonomics and usability of interaction in constrained spaces, provoking the need for further research to establish such a model.

6 CONCLUSION

In this paper, we explored the use of passive haptics and interaction surface remapping for XR use in an economy aeroplane seating environment. We performed two user studies. First, participants performed a reach-and-drag targeting task on horizontal and vertical surfaces, both with and without passive haptics, and the results showed that passive haptics significantly improved performance and user experience, particularly on a horizontal tray table surface. However, the tight seating environment meant that the location of the tray table caused participants to look down at and awkward angle, leading to discomfort and neck fatigue, which could be exacerbated by long-term flight usage. In the second study, we used rotation and translation to remap the horizontal surface nearer eye level. The results showed that moderate remappings of 45-60° can maintain many task and experience related benefits of passive haptic interaction while moving the visible interaction to a more comfortable position. From the findings, we give three guidelines for using and designing passive haptics and surface remapping in transport seating. Our results open up the use of XR to constrained seating environments commonly found in travel settings, allowing travellers to gain the benefits of XR to improve their journeys.

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