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Spatial consistency between real and virtual workspaces for individual and collaborative tasks in virtual environments

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Yiran Zhang. Spatial consistency between real and virtual workspaces for individual and collaborative tasks in virtual environments. Human-Computer Interaction [cs.HC]. Université Paris-Saclay, 2021. English. NNT : 2021UPASG107 . tel-03628367

HAL Id: tel-03628367

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Spatial consistency between real and virtual
workspaces for individual and collaborative tasks
in virtual environments

*Cohérence spatiale entre les espaces de travail réels et
virtuels pour les tâches individuelles et collaboratives dans
les environnements virtuels*

Thèse de doctorat de l'université Paris-Saclay

École doctorale n° 580, Sciences et technologies de l'information et de la
communication (STIC)

Spécialité de doctorat : Informatique

Unité de recherche : Laboratoire Interdisciplinaire des Sciences du Numérique (Université
Paris-Saclay, CNRS)

Graduate School : Informatique et sciences du numérique.

Référent : Faculté des sciences d'Orsay

Thèse préparée au **Laboratoire Interdisciplinaire des Sciences du Numérique** (Université
Paris-Saclay, CNRS), sous la direction de **Patrick BOURDOT**, Directeur de recherche, et le
co-encadrement de **Cédric FLEURY**, Maître de conférences

Thèse présentée et soutenue à Paris-Saclay,
le 16 décembre 2021, par

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Titre: Cohérence spatiale entre les espaces de travail réels et virtuels pour les tâches individuelles et collaboratives dans les environnements virtuels

Mots clés: Réalité virtuelle, Consistance spatiale, Techniques interactives, Navigation, Téléportation

Résumé: De nombreuses applications de réalité virtuelle (RV) se basent sur une parfaite mise en correspondance du positionnement de l'utilisateur entre l'environnement réel et celui virtuel. Cette cohérence spatiale est nécessaire pour maximiser l'espace de travail virtuel qui est accessible par les mouvements physiques dans le monde réel. Elle est également requise pour l'interaction tangible, mais aussi celle co-localisée dans le cadre de tâches collaboratives complexes. Cependant, dans certaines situations, la navigation individuelle de l'utilisateur induit une perte de cette cohérence spatiale. Afin d'éviter ce problème, la navigation dans les environnements virtuels à grande échelle est généralement exclue et les scénarios d'utilisation sont alors construits autour d'une séquence d'expériences virtuelles.

L'objectif de cette thèse est de permettre aux utilisateurs d'explorer un environnement virtuel à grande échelle tout en étant en mesure de rétablir la cohérence spatiale dans des zones appropriées de l'environnement virtuel là où les tâches à accomplir le nécessitent. La contribution principale de ces travaux est de proposer une solution générique pour rétablir cette cohérence spatiale lorsque les déplacements virtuels sont opérés par téléportation. Cette métaphore de navigation est l'une des plus utilisées dans les applications de RV et il a aussi été démontré qu'elle réduit le mal du simulateur du fait du déplacement instantané qu'elle opère. Ma thèse explore différentes techniques permettant de rétablir la cohérence spatiale après

téléportation sur différents dispositifs immersifs (CAVE vs. HMD) et contextes interactifs (interaction individuelle, tangible et collaboration complexe en situation co-localisée). Elle présente aussi des résultats expérimentaux qui valident ces techniques. Tout d'abord, j'ai étudié deux techniques interactives qui aident les utilisateurs à optimiser l'utilisation de leur espace de travail physique dans des zones spécifiques de l'environnement virtuel, zones qui pour ces techniques sont prédéfinies par le concepteur d'applications. Ces techniques sont adaptées aux systèmes de RV dont les espaces de travail ont une forme et une taille bien déterminées, comme par exemple avec des systèmes de type CAVE. Ensuite, j'ai proposé deux solutions plus génériques, qui peuvent s'appliquer à une gamme des systèmes plus large, y compris les HMDs, pour lesquels l'espace de travail physique n'est pas forcément connu a priori. A la différence des techniques précédentes, elles permettent aux utilisateurs de positionner leur espace de travail physique dans l'environnement virtuel. Par ailleurs, j'ai aussi exploré comment rétablir la cohérence spatiale en alignant la position d'un objet du monde réel avec sa contrepartie virtuelle lors de la téléportation, afin de permettre une interaction tangible. Enfin, j'ai conçu et évalué deux stratégies permettant à des paires d'utilisateurs de gérer et de rétablir la consistance spatiale lors d'interactions co-localisées dans le cadre de tâches collaboratives complexes.

Title: Spatial consistency between real and virtual workspaces for individual and collaborative tasks in virtual environments

Keywords: Virtual reality, Spatial consistency, Interactive techniques, Navigation, Teleportation

Abstract: A number of virtual reality (VR) applications rely on a one-to-one mapping of the user's position between real and virtual environments. This spatial consistency is mandatory for maximizing the virtual workspace accessible by physical movements in the real world. It is also required for tangible interaction and co-located interaction in complex collaborative tasks. However, the user's individual navigation may break the spatial consistency. To prevent this issue, navigation in large-scale virtual environments is usually excluded, and use-case scenarios are divided into a set of virtual experiences.

The research focus of this Ph.D. thesis is to allow users to explore a large-scale virtual environment and recover spatial consistency in some appropriate areas of the virtual environment when necessary to complete the task. The main contribution is a general solution to recover spatial consistency for teleportation. This navigation technique is one of the most commonly used in VR applications, and it has been shown that its instant transition displacement principle reduces simulator sickness. My dissertation explores different

techniques to recover spatial consistency in several VR systems (CAVE vs. HMD) and interactive contexts (individual interaction, tangible situation, and co-localized collaboration). It also presents experimental results that validate these techniques. First, I studied two interactive techniques that can help users to maximize the use of their physical workspace within specific areas of the virtual environment predefined by application designers. These techniques are suitable for virtual reality systems with previously known shapes and sizes, such as CAVE-like systems. Then, I proposed two more generic solutions for a wider range of VR systems, including HMDs. Conversely to the prior approach, these solutions allow users to position their physical workspace in the virtual environment. Next, I investigated how to recover the spatial consistency by aligning the position of a real-world object with its virtual counterpart during teleportation, in order to allow a tangible interaction with this object. Finally, I designed two strategies to allow pairs of users to manage and recover the spatial consistency for co-located interaction in complex collaborative tasks.

Acknowledgements

First of all, I would like to express my deepest gratitude to my supervisor Patrick Bourdot and my co-advisor Cédric Fleury, for their continuous and tireless support during my four years of PhD study. They both gave me great help on experiment design, analysis, and particularly paper and thesis writing.

Moreover, I gratefully acknowledge my jury members, Victoria Interrante and Thierry Duval, for taking their time on reading my thesis and providing constructive feedback on the dissertation, as well as Daniel Mestre, Weiya Chen, Ferran Argelaguet, and Nicolas Sabouret for attending physically and remotely my defense and their insightful comments.

My thanks also go on to all the colleagues in VENISE and ExSitu teams. In particular, I would like to express my sincere gratitude to Wendy Mackey and Michel Beaudouin-Lafon for providing me with different knowledge in HCI during PhD seminars. I appreciate Huyen Nguyen, who always worked with me until the last minute of submitting the paper, and Nicolas Ladevèze, who provided different help. I also thank Nawel, Yujiro, Mengchen, Iuliia, Valentin, and Inoussa for their encouragement and kindness. It has been such a pleasure to work with you.

Finally, I would like to express my heartfelt gratitude to my family and friends for the support and love they have brought to me. Without you, I could not have reached where I am now. Also, thanks to my little fur-ball, who always cheers me on (sleeps on my keyboard) when I'm writing my papers.

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Synthèse

De nombreuses applications de réalité virtuelle (RV) se basent sur une parfaite mise en correspondance du positionnement de l'utilisateur entre l'environnement réel et celui virtuel. Cette cohérence spatiale est nécessaire pour maximiser l'espace de travail virtuel qui est accessible par les mouvements physiques dans le monde réel. Elle est également requise pour l'interaction tangible, mais aussi celle co-localisée dans le cadre de tâches collaboratives complexes. Cependant, dans certaines situations, la navigation individuelle de l'utilisateur induit une perte de cette cohérence spatiale. Afin d'éviter ce problème, la navigation dans les environnements virtuels à grande échelle est généralement exclue et les scénarios d'utilisation sont alors construits autour d'une séquence d'expériences virtuelles.

L'objectif de cette thèse est de permettre aux utilisateurs d'explorer un environnement virtuel à grande échelle tout en étant en mesure de rétablir la cohérence spatiale dans des zones appropriées de l'environnement virtuel là où les tâches à accomplir le nécessitent. La contribution principale de ces travaux est de proposer une solution générique pour rétablir cette cohérence spatiale lorsque les déplacements virtuels sont opérés par téléportation. Cette métaphore de navigation est l'une des plus utilisées dans les applications de RV et il a aussi été démontré qu'elle réduit le mal du simulateur du fait du déplacement instantané qu'elle opère. Ma thèse explore différentes techniques permettant de rétablir la cohérence spatiale après téléportation sur différents dispositifs immersifs (CAVE vs. HMD) et contextes interactifs (interaction individuelle, tangible et collaboration complexe en situation co-localisée). Elle présente aussi des résultats expérimentaux qui valident ces techniques.

Tout d'abord, j'ai étudié deux techniques interactives qui aident les utilisateurs à optimiser l'utilisation de leur espace de travail physique dans des zones spécifiques de l'environnement virtuel, zones qui pour ces techniques sont prédéfinies par le concepteur d'applications. Ces techniques utilisent un volume 3D pour représenter les zones prédéfinies dans l'environnement virtuel. L'utilisateur peut sélectionner

l'une de ces zones avec le rayon virtuel et trouver la cohérence spatiale après s'y être téléporté. Pour améliorer la conscience spatiale de l'utilisateur, l'une de ces techniques comprend un retour visuel supplémentaire pour la destination d'arrivée de l'utilisateur après la téléportation. J'ai mené une première expérience auprès des utilisateurs pour évaluer ces techniques par rapport à la téléportation basique. Les résultats montrent que le fait d'aider l'utilisateur à retrouver la cohérence spatiale peut augmenter de manière significative la performance de la tâche. Cependant, je n'ai pas trouvé de différence significative entre les deux techniques. Puisque le concepteur de l'application doit utiliser les valeurs des paramètres de l'espace de travail réel de l'utilisateur pour définir les zones à l'avance, ces techniques sont adaptées aux systèmes de RV dont les espaces de travail ont une forme et une taille bien déterminées, comme par exemple avec des systèmes de type CAVE.

Ensuite, j'ai proposé deux solutions plus génériques, qui peuvent s'appliquer à une gamme des systèmes plus large, y compris les HMDs, pour lesquels l'espace de travail physique n'est pas forcément connu a priori. A la différence des techniques précédentes, elles permettent aux utilisateurs de positionner leur espace de travail physique dans l'environnement virtuel. L'une de ces solutions permet à l'utilisateur de manipuler une représentation virtuelle de son espace de travail réel dans l'environnement virtuel pour définir une zone de cohérence spatiale. Une autre solution utilise un algorithme pour permettre au système de générer automatiquement l'espace de travail virtuel possible pour l'utilisateur sur la base de la configuration de l'environnement virtuel. J'ai réalisé deux études d'utilisateurs pour évaluer et comparer ces technologies à la téléportation basique. Les résultats montrent que le fait de permettre à l'utilisateur de positionner manuellement son espace de travail virtuel est plus approprié pour une scène chargée. Les résultats montrent que le fait de permettre à l'utilisateur de positionner manuellement son espace de travail virtuel semble mieux approprié pour une scène chargée. Et la méthode automatique semble mieux convenir à une scène non chargée.

Par ailleurs, j'ai aussi exploré comment rétablir la cohérence spatiale en alignant la position d'un objet du monde réel avec sa contrepartie virtuelle lors de la téléportation, afin de permettre une interaction tangible. Ces techniques téléportent l'utilisateur, l'objet ou les deux pour reconfigurer la relation spatiale lorsqu'un objet virtuel ciblé est sélectionné. Cependant, en tant qu'étude préliminaire, ces techniques doivent encore être améliorées, notamment dans les situations où de nombreuses configurations de mappage peuvent être générées et les situations liées à des obstacles. En outre, une expérience utilisateur est également nécessaire à l'avenir pour évaluer ces techniques dans différents contextes virtuels.

Enfin, j'ai conçu et évalué deux stratégies permettant à des paires d'utilisateurs de gérer et de rétablir la consistance spatiale lors d'interactions co-localisées dans le cadre de tâches collaboratives complexes. Ces techniques utilisent un volume en

3D pour représenter l'espace de travail réel partagé par les utilisateurs co-localisés. L'une de ces techniques permet à l'un des utilisateurs de charger entièrement le positionnement de l'espace de travail virtuel. L'autre technique intègre les entrées des deux utilisateurs à l'aide d'un système de ressorts et d'amortisseurs et permet la manipulation simultanée des utilisateurs. J'ai mené une étude auprès des utilisateurs afin d'évaluer ces deux techniques dans une tâche collaborative complexe de rivetage. Les résultats ont montré que la co-manipulation de l'espace de travail virtuel était plus efficace.

Introduction

Context and Motivation

Virtual reality (VR) immerse users in a simulated virtual environment (VE) by allowing them to perform virtual activities based on their behavior in the real world. In a VR system, user actions are performed in an area of the real world and transposed into interaction with the VE. This area, referred below as the user "real or physical workspace", is usually limited by the available motion tracking area, the presence of physical obstacles, and the range of devices (e.g., haptics). Its corresponding area in the VE is where the user can have a direct access to virtual objects to perform tasks, referred as the "virtual workspace" in this dissertation.

Many VR application designs rely on a one-to-one mapping between user real and virtual workspaces. The spatial consistency provided by such mapping allows users to take advantage of the entire physical workspace to walk and interact intuitively with the real/virtual contents around them. Real walking could be highly beneficial for improving immersion and promoting user spatial understating of the virtual environment. Moreover, spatial consistency enables users to interact with the physical object existing in the scene. Real-world objects can thus provide tangibility to the virtual objects paired with them. The blended real and virtual environment enriches the user virtual experiences, contributes to a higher sense of presence, and overcomes the lack of tactile feedback of VR.

In co-located collaborative VR systems, this spatial consistency facilitates co-manipulation based on shared tangible props and enables users to have direct physical interaction among each other, such as performing handshakes. In addition, it helps prevent perceptual conflicts due to the dual presence of users and their avatar in the scene. This can happen, for example, on the visual, audio, and haptic channels in a multi-stereoscopic rear-projection system, or on the audio and haptic channels for co-located collaboration with HMDs. Since all users have the same spatial understanding of the workspace, spatial information can be

exchanged as in the real world. In particular, for a projection-based immersive system, co-located users can implicitly communicate information through social cues (e.g., gestures, facial expressions, and gaze direction), enhancing mutual awareness and simplifying negotiation of common goals.

The one-to-one mapping required by such applications often limits the user's virtual navigation capability, as it may break the spatial configuration between the real and virtual world. Consequently, users can only explore a virtual environment of approximately similar size and shape compared to their physical workspace. Furthermore, in a co-located collaborative system, users' individual navigation can lead to spatial desynchronization issues when their positions in the VE are no longer the same as in the real world, which increases the risk of collisions between them. To avoid these problems, continuous task scenarios often have to be split into different virtual experiences that do not follow the actual workflow.

Some previous studies attempted to maintain a spatial consistency during navigation. For example, different technologies and algorithms can be used to create a VE that fits the user physical workspace [34, 104], or the user physical workspace can be reconfigured to match the virtual scene on the fly [31, 8]. However, the former can limit the design of VE, while the latter relies on complex setups such as human actuators or robots, making it difficult to apply to everyday VR experiences. Some virtual navigation techniques embed the user physical workspace into the VE as a whole unit to preserve the spatial relationship between the real and virtual world [36]. However, navigating while always maintaining spatial consistency can be very restrictive for interaction and cognitively overwhelming for the user when this consistency is not needed. It is also not possible for tangible interaction if the tangible objects do not travel with users. In a multi-user context, spatial consistency can be maintained by allowing users to navigate as a group [14, 111]. Nevertheless, group navigation also limits users' individual abilities to explore the virtual environment.

This Ph.D. thesis addresses these issues and aims to provide users with a general solution to recover spatial consistency after individual virtual navigation. Such a recovery technique preserves the user's individual navigation capabilities for exploring large-scale VEs and helps them to recover spatial consistency in some appropriate areas of the VE when necessary to accomplish specific tasks. It can be applied in both single and multi-user contexts. For an individual user, a possible scenario can be an escape game where a user is required to escape from imprisonment by exploiting a series of virtual rooms. The recovery technique can help this user to recover spatial consistency in areas where the clues are possibly hidden. Then, the user can physically walk to explore the virtual surroundings inside each area. As an example of collaborative scenarios, co-located users can first navigate to different warehouses individually to obtain mechanical parts during a virtual

assembly process. If the spatial consistency can be restored in a following collaborative phase, they can then walk freely within this area and have direct physical interaction with each other while avoiding any perceptual conflicts. Besides, shared tangible objects can also be integrated into the assembly task to coordinate users' movements and provide them with additional passive haptic feedback.

The spatial consistency recovery technique should be designed according to the characteristics of the system and the virtual navigation metaphor used. This thesis mainly investigates spatial consistency recovery techniques for teleportation. I choose such a navigation technique since it is one of the most commonly used techniques in VR applications. In addition, teleportation allows users to reach a remote destination defined by themselves instantaneously. Compared to other navigation techniques, such instant transitions can reduce simulator sickness caused by sensory conflicts between the user's visual and vestibular systems [44, 54, 109].

This dissertation contributes to the spatial consistency recovery techniques by considering the following four research questions:

1. How users can transition from individual navigation to a spatially consistent state while maintaining awareness of their surroundings?
2. How to allow users to define an area of VE to recover spatial consistency to meet the needs of the subsequent tasks?
3. How to make tangible interaction possible after user individual navigation?
4. How to help multiple users to plan and achieve efficient spatial consistency recovery for performing collaborative tasks?

To reach these objectives, this thesis proposes different interactive techniques suitable with the teleportation metaphor, which help users recover spatial consistency across different VR systems and use cases. It also provides experimental findings that validate these techniques.

Organization of Thesis

This thesis is organized in five chapters. Chapter 1 presents a general state-of-the-art related to the spatial consistency. Chapters 2 to 5 describe in detail my research work consisting of paradigm design and user experiments.

Chapter 1 presents the general background of this thesis by introducing the current state-of-the-art related to spatial consistency applications and the existing virtual-navigation techniques that are compatible with such spatial consistency. This chapter also proposes a taxonomy of the spatial consistency issues and a design space of the spatial consistency recovery techniques.

Chapter 2 begins by presenting two spatial consistency recovery techniques designed for teleportation navigation. It also describes a controlled experiment which investigates if the recovered spatial consistency led to higher task performance and if participants could correctly anticipate the resulting spatial configuration after the recovery. Since these techniques require prior knowledge of the user physical workspace to define the areas where to restore the spatial consistency, they are better suited for VR systems with predetermined shapes and sizes, such as CAVE-like systems.

Chapter 3 then proposes two more generic solutions to define areas in the VE to restore spatial consistency. These approaches address the problems that in a VR walk-through, the real workspace for users is diverse and usually unknown to the application designer during the application design phase. One approach allows users to manually position the corresponding virtual workspace before recovering the spatial consistency, and the other enables the system to automatically propose possible virtual workspaces based on a real-time detection by an algorithm. Two controlled experiments were carried out to evaluate these two methods facing different layouts of the virtual environment.

Chapter 4 describes three techniques that allow the user to explore large virtual environments while supporting haptic feedback with tangible props. The required one-to-one mapping between the real and virtual object constrains the positioning of virtual workspace where spatial consistency can be recovered. By teleporting the user, the object, or both of them to a new position accordingly, tangible interaction becomes possible after navigation with the teleportation technique. Each one of these three techniques is more or less suitable for different virtual objects and the tasks to be accomplished with them.

Chapter 5 explores the concepts of spatial consistency recovery techniques in a multi-user context. I propose two strategies to allow a pair of users to manage and recover the spatial consistency for collaborative tasks. The first technique allows one of the users (the leader) to define the position of the virtual workspace, and the other user (the follower) could only select this area to join the leader. Based on a spring-damper system, the second technique enables both users to position the virtual workspace simultaneously. I designed and implemented a virtual riveting task to assess the difference between these two techniques in a controlled experiment.

Finally, I summarize the main contributions of this thesis and propose future research directions for spatial consistency recovery techniques.

Spatial Consistency in Virtual Reality

1

This chapter begins with a short introduction to virtual reality technologies. I then focus on the spatial relationships between the real and virtual worlds when using these technologies to enable real-time user interaction in the virtual environment. In particular, I detail the benefits of maintaining consistent spatial relationships by presenting their applications, and address spatial desynchronization issues when providing virtual navigation in these applications. Finally, I summarize previous literature on maintaining spatial consistency during virtual navigation and address the research questions of this Ph. D. thesis regarding spatial consistency recovery techniques.

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1.1 Introduction

Virtual reality (VR) aims to provide users multi-sensorimotor immersion to allow them to interact in a natural way with numerical representations or simulations, also named virtual world or virtual environment (VE). A number of technologies are used to create such virtual experiences. First, tracking systems are mandatory to capture user motion in the real world and apply it in the virtual one. Then, user-centered headsets (also named HMD) or on room-centered rear projection setups (including Workbench and CAVE-like systems), allow displaying stereoscopic images to provide a depth perception on the visual sensory channel of humans. Moreover, other 3D sensorimotor channels are also stimulated to increase the realism of the immersion and the sensation of presence, such as 3D spatialized sound and tactile-kinesthetic interaction (also named haptics).

Users can immerse themselves in a simulated virtual world and interact with the artificial 3D environment in real-time. Since 1968, when Ivan Sutherland created the first head-mounted display system named the "Sword of Damocles" for immersive simulation applications, this technology developed rapidly and has been gradually moved from laboratory to marketplace. It has now been widely applied in various contexts, including entertainment (e.g., video games), education (e.g., medical and industry training), product design (e.g., CAD), therapy, etc. With the increase of computation capacity and computer network speed, it becomes possible for co-located or remote group of users to immerse in a same virtual environment to accomplish collaborative tasks.

Unlike traditional human-computer interfaces that serve as communication tools between humans and computer systems (e.g., using a keyboard as an input device), VR aims to connect real-world users to simulated virtual environments with a full sensory-motor experience. In other words, VR technology allows users to perform actions in the virtual world by using movements and gestures. Accordingly, users can perceive computer-generated feedback in response to their actions through multiple sensory channels. As a result, the interface between the user and the computer system tends to become transparent, even imperceptible when in use.

Based on these observations, Fuchs et al. [45] introduce the term "behavioral interfaces" to define VR technically as "a scientific and technical domain that uses computer science and behavioral interfaces to simulate in a virtual world the behaviors of 3D entities, which interact in the real with each other and with one or more users in pseudo-natural immersion via sensorimotor channels". The behavioral interface is composed of motor and sensory interfaces, connecting the user located in the real world to a virtual world. The motor interfaces capture the user's actions (e.g., movement and gesture) and transfer these activities to

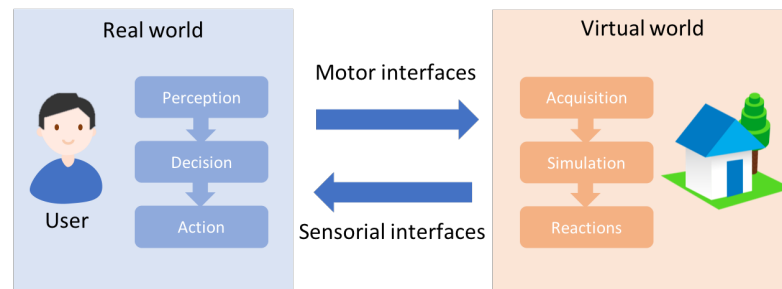


Figure 1.1 – The "perception, decision, and action" loop in the virtual environment [45]

the system. After acquiring the information, the system modifies the environment and the sensorial reactions (e.g., images and sound) via sensory interfaces. To sum up, VR systems are divided into three main components: the user, the behavioral interface, and the virtual world, which forms a "perception, decision, and action" loop (see Figure 1.1). Such a loop transposes the "perception, cognition, action" loop of human behavior in the real world into a virtual context.

1.1.1 Immersive Technologies

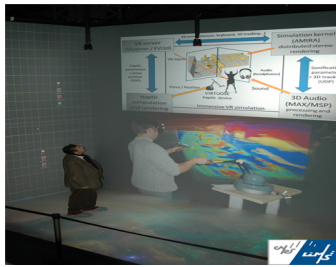
The virtual environment is not only a computer-generated space similar to the real world. Moreover, it should also be able to respond to the user's actions [41]. To achieve this, various technologies are designed and marketed today to meet the requirements of different needs. These technologies track users' actions and allow them to see, hear, and touch the virtual environment in real-time.

Real-time user interaction is first based on tracking technologies to capture the user's movements, such as the user's head and hand movements, or even full-body movements. The captured information is then transmitted to the system as input, enabling the system to modify the contents of the virtual environment accordingly. For example, the system can update the visual rendering based on the user's viewpoint in real-time. In VR systems, user position tracking can be achieved by physical principles such as mechanics, optics, magnetism, and acoustics [78]. In addition, computer vision-based solutions, such as Kinect¹ and Leap motion², are also widely used to track user movement for their low cost and ease of set up.

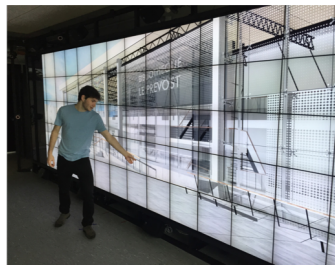
In addition to the tracking, the visual technology is another key component in implementing real-time interaction. There are many display systems on the market to provide the user with stereoscopic vision. These systems come in different

¹<https://developer.microsoft.com/en-us/windows/kinect/>

²<https://www.ultraleap.com>



(a) EVE system: a large immersive projection-based system.



(b) WILDER: Large wall-sized display composed of 75 touch screens.



(c) Head-Mounted Display (HMD): HTC Vive Pro.
©HTC

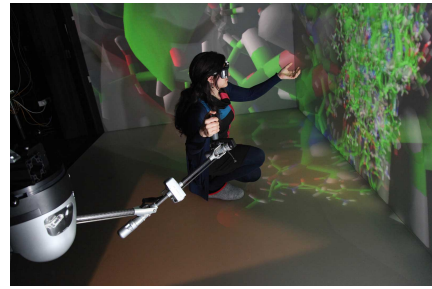
Figure 1.2 – Different types of VR display systems.

sizes, varying from large CAVE like systems (see Figure 1.2a), wall-size displays (see Figure 1.2b) to head-mounted devices (HMDs) (see Figure 1.2c). They have different application areas and target users. For example, HMDs can be easily set up to provide users with an immersive experience in their home environment. However, the wall-size displays can be more suitable for labs and companies to foster collaboration and achieve specific tasks, such as data visualization and data exploration.

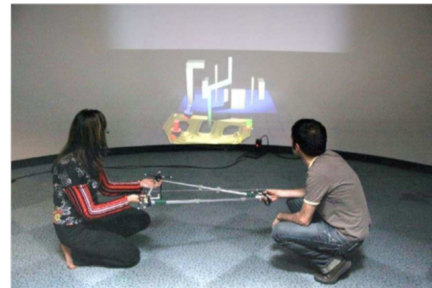
Moreover, audio technologies are also often provided in VR systems to enable a more compelling and realistic user experience. For example, users can infer the position of an object outside their field of view by referring to the auditory stimuli associated with it. In addition, sounds made by the user can be captured, recognized, and fed back to the system as input. For example, use voice commands to operate HoloLens³.

Other essential immersive technologies are the haptic ones, which can be integrated into VR applications to provide users with a sense of touch and kinesthetic with different modalities, including force feedback, pressure, skin stretch, vibration, and temperature. For example, electromechanical haptic arms can provide force feedback and vibration for the user, with accessibility ranging from desktop-based (see Figure 1.3a) to room-sized (see Figure 1.3b). Some devices, such as wearable mechanical exoskeletons, use finger-level motors to support fine force feedback for object grasping and manipulation (see Figure 1.3c). As opposed to dedicated VR setups found in academic labs or big companies, these devices are not always available at home or in SME offices, and they are quite expensive for the general public. Therefore, tactile and kinesthetic feedback is usually absent in home-based VR applications. However, some works propose integrating real-world

³<https://www.microsoft.com/en-us/hololens>

(a) PHANTOM[®] haptic arm. © Sensable

(b) Room-sized haptic device in the EVE system [26]

(c) Dexmo[®], a wearable mechanical exoskeleton. © Dexta Robotics

(d) Passive haptic feedback provided by a shared prop [7].

Figure 1.3 – Different types of haptic devices.

objects, such as a tangible prop (see Figure 1.3d), into a virtual environment by pairing them with their virtual counterparts to address this limitation. The real-world objects can provide tangibility to their virtual counterparts and provide the user with a compelling experience and a better sense of presence [56]. Such passive haptic feedback does not require technical devices, such as robots or sensorimotor effectors.

1.1.2 Integrate Immersive Technologies into the VE

VR technologies connect the real and virtual worlds, enabling users to interact with simulated environments in real-time. This can often be achieved by integrating the workspace associated with the technology into a virtual environment. For example, the user's motion tracking area can be integrated into the virtual environment, allowing the user to use an intuitive way (walking) to explore a virtual environment that is larger than their tracking volume size. Previous study,

such as 3DM (see Figure 1.4a), allows the user to walk on a magic carpet that represented their tracking area. The user can apply a long-distance translation to the carpet by pointing in one direction. In a similar technique, Magic Barrier Tape (see Figure 1.4c) uses a virtual barrier tape to describe the boundaries of the tracking area. The user can "push" the tape to go beyond this area and achieve virtual navigation.

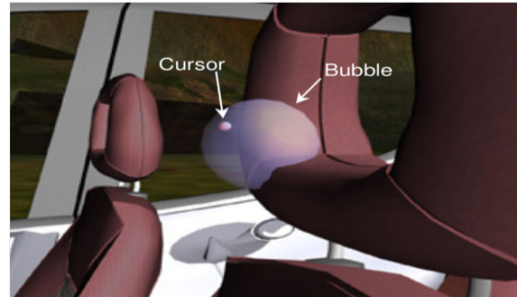
Other settings, such as haptic devices, can also be integrated into the VE in a similar way. For example, the "bubble" technique (see Figure 1.4b) uses a semi-transparent sphere to represent the available range of a haptic device for tangible interactions. The user can move the cursor within the sphere using one-to-one position mapping. By moving the cursor outside the sphere, the user can use velocity control to move the bubble in the virtual environment outside the range of the device.

In some other studies, the user physical workspace associated with a specific device is entirely integrated into the virtual environment with a one-to-one mapping. In these VR systems, the user real/physical workspace is an area of the real world in which the user can interact with the virtual environment. This area defines the capabilities of the VR setups and merges their limitations. For example, the user real workspace is often limited by the size and shape of the user's available motion tracking area, the existing physical obstacles, and the range of the device (e.g., haptics). The user real workspace can be incorporated into the virtual environment by being imagined as a virtual vehicle [19]. The virtual vehicle represents the real workspace of the user within the virtual world. Using some virtual navigation techniques, the user can move this virtual vehicle to explore the entire virtual environment. The original navigation technique was based on a relative 6DoF tracking of the user, also named the Human Joystick metaphor, and it has been demonstrated that it provided less cybersickness than Joystick-based navigation control [27].

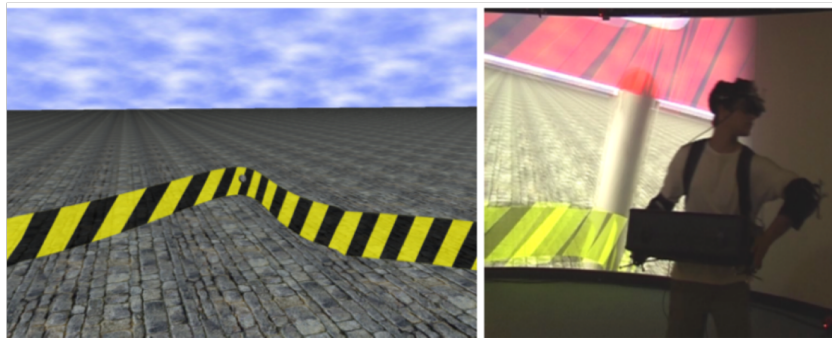
Based on this idea, the Immersive Interactive Virtual Cabin (IIVC) [40] (see Figure 1.5) then proposed a generic model that integrates the user's physical workspace into a virtual environment. This model proposes two different components: the stage and the conveyor. The stage is a virtual representation of the user's physical workspace defined by the VR technology characteristics (visual, sound, interaction, or motion tracking area), similar to the previous virtual vehicle concept. The conveyor is the integration frame of the stage in the virtual world, which has its own position, rotation, and scale in the coordinate system of the virtual environment. These concepts can also be extended to a multi-user environment by providing each user with a corresponding stage or virtual vehicle.



(a) A magic carpet representing the tracking boundaries [24].



(b) The “bubble” displays the limits of the haptic workspace [38].



(c) Magic Barrier Tape surround the user real workspace [36].

Figure 1.4 – Integrating the workspace associated with the technology into a virtual environment.

1.2 Spatial Consistency

Refer to the "virtual vehicle" and "stage" models, the user real workspace is mapped into the virtual world through an integration frame. Its corresponding area in the virtual world, named as the user virtual workspace in the following, is an area used by the user to perform virtual tasks. This thesis focuses on the position mapping between the real and virtual workspaces, and the spatial relationships between them.

1.2.1 Definition

The real workspace can be mapped within the virtual environment by a given translation, rotation, and scale. In this thesis, I use the general term "position" to describe these three elements. In some cases, the application designer adds a mapping offset between these two spaces for specific needs. For example, introducing a different mapping scale allows users use similar real workspaces to obtain completely different sized virtual workspaces [70].

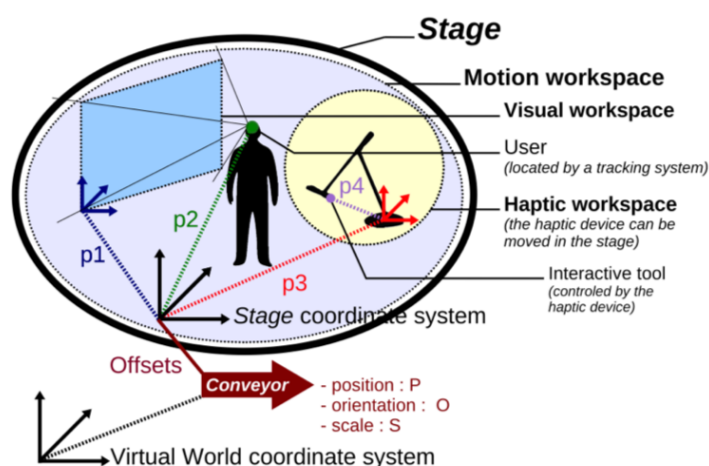


Figure 1.5 – Immersive Interactive Virtual Cabin model: the conveyor carries the stage with its workspaces in the virtual world

In most VR applications, the real and virtual workspaces are perfectly mapped together in a static way. As a result, the user's real and virtual interactions will have the same form, coordinate system, and scale, bringing a spatial consistency to the user. Such spatially consistent situation can also be found in some co-located collaborations. When the virtual workspaces of all users are strictly superposed, the user spatial configurations in the virtual workspace will be consistent with those in the real world.

1.2.2 Spatial Consistency for Individual User Applications

For individual users, the spatial consistency between the real and virtual workspace first allows them to make full use of their real workspace to interact with the virtual environment. Users can thus walk within the tracking area to access the virtual surroundings and interact intuitively with them. Real walking is the most direct and natural technique for traveling in a virtual environment. It promotes spatial understanding and provides users with vestibular cues which help them understand the size of the environment [20]. Compared to other alternative locomotion techniques, such as steering, walking also offers the user with a more immersive experience [105].

Moreover, spatial consistency allows users to access a real-world object and its virtual counterpart simultaneously, enabling the tangible interaction. For example, CavePainting allows the artist to take advantage of real workspace to create a new type of art using props and gestures (see Figure 1.6a). Another example can be

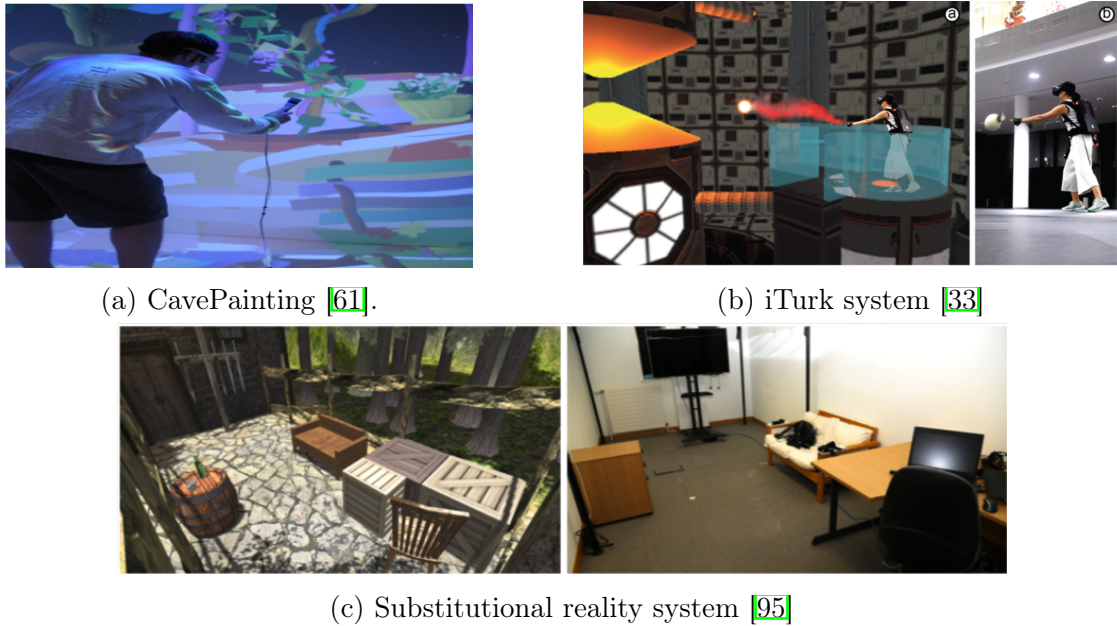


Figure 1.6 – Spatial consistency applications for a single user.

the iTurk system, which complements the VR experience with a physical prop that can be reconfigured as a suitcase or a fuse box in the virtual world (see Figure 1.6b). This iTurk system focuses on mapping one physical object to several virtual objects of a similar form and shape. Meanwhile, the Substitutional reality system [95] pairs every physical object and architectural feature surrounding the user to its virtual counterpart, allowing some degree of discrepancy between them. For example, a real living room can be replaced by a virtual courtyard, or a real umbrella can substitute a sword or a lightsaber (see Figure 1.6c).

Adding physical qualities to virtual objects can enhance the sense of presence of the users. Indeed, in the study of Hoffman et al., participants who were allowed to "touch and see" an object had more accurate prediction of the object properties than those who were only allowed to "see" it [56]. Insko et al. showed that augmenting a visual-cliff environment with a real wooden plank as a ledge significantly impacted participants' behavioral presence, heart rate, and skin conductivity compared to a virtual-ledge-only condition [57]. Moreover, in their experiment, they demonstrated that using passive haptics could lead to significant increase in presence and spatial knowledge training transfer. Besides, passive haptics can also be applied in medical fields. For example, allowing patients to touch a spider replica's hairy texture can enhance the treatment of spider phobia [25]. In the work of Kotranza and Lok, augmenting a virtual patient with a tangible interface makes the interaction during a breast exam more similar to human-human interaction [65].

	Same time	Different time
Same place	Face to face interactions (e.g., wall-sized displays)	Continuous task (e.g., teamwork groupware)
Different places	Remote interactions (e.g., video conference)	Communication + coordination (e.g., workflow management)

Table 1.1 – The time-location matrix for group interaction [39].

1.2.3 Spatial Consistency in Multi-user Contexts

Collaborative VR systems allow users to meet and interact with each other in a shared virtual environment. User’s collaborative interactions can be categorized in different ways. Depending on the degree of collaboration, Margery et al. [74] classified the collaborative interaction into three levels: simple communication (level 1), individual change of the shared world (level 2), and concurrent change of different and same attributes of the shared world (level 3). Moreover, the group interaction can also be categorized by a time/location matrix (see table 1.1). In this matrix, the distinction is made between the same times (synchronous) and different times (asynchronous), and the same places (face-to-face) and different places (distributed). Besides, a collaborative system can also be symmetric and asymmetric according to whether the collaborators are using the same device or not.

The design of many collaborative VR applications relies on a one-to-one position mapping between the real and virtual environments. In particular, for those described as closely coupled collaborations [82], where object manipulation and human interaction are tightly coupled and the actions of the collaborators are directly dependent on each other. The spatial consistency condition is well suited for such tasks as it simplifies the exchange of spatial information and allows co-located users to receive passive haptic feedback during collaborative manipulation.

Under the spatial consistency condition, the virtual workspaces of all users are consistent with the shared physical workspace. Thus, for co-located users, their positions in the real world are the same as their position in the virtual environment. This is important to prevent users from bumping into each other during walking, especially if they are equipped with head-mounted devices. In addition, another user’s can be seen and heard from the virtual position of their avatar, avoiding possible perception conflicts during the collaboration. As all users share the same spatial understanding of the virtual environment, spatial information can be communicated as if it was in the real world. For example, in a multi-stereoscopic projection-based immersive system, co-located users can communicate the coordination information and negotiate common goals implicitly using social cues such

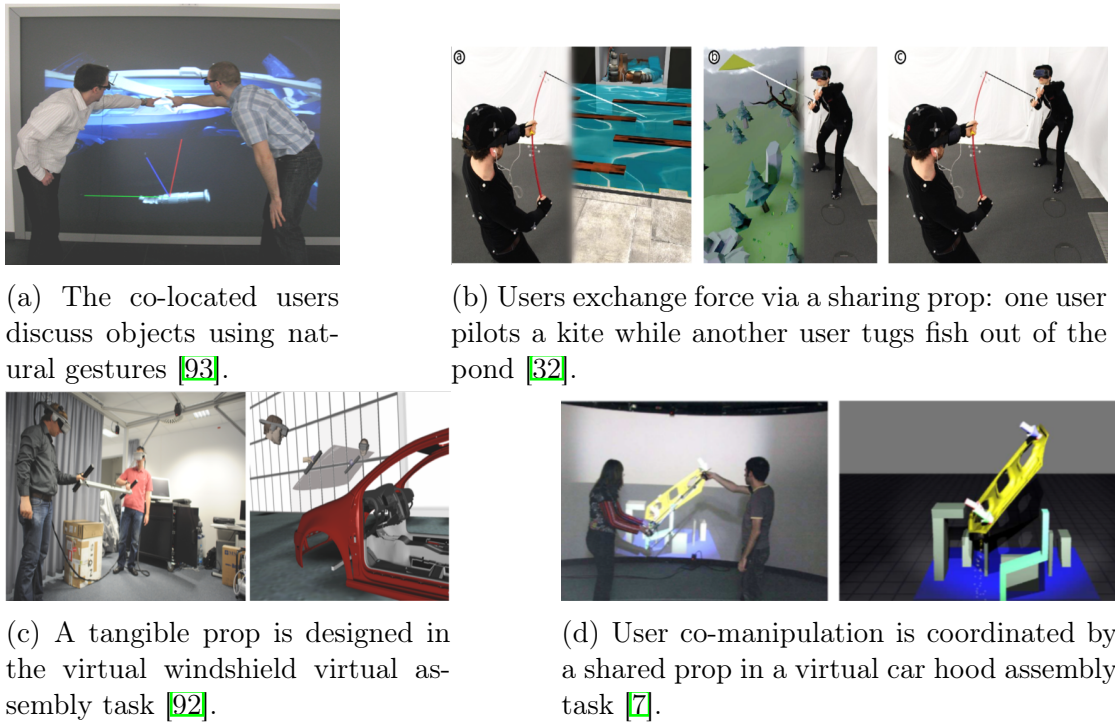


Figure 1.7 – Spatial consistency applications in multi-user contexts.

as posture, gestures, facial expressions, and gazes. Furthermore, as users' physical bodies are integrated into the virtual environment, the information can be communicated without the mediation of an embedded avatar. Accordingly, the user can communicate the desired object with the collaborator by pointing to it [97] or by drawing its outline directly in the air (see Figure 1.7a).

The spatial consistency also enables the possibility of introducing a tangible interface among co-located users. For example, a shared prop can be designed in a virtual windshield (see Figure 1.7c) or a virtual car hood (see Figure 1.7d) assembly task to coordinate users' co-manipulation. In addition, the spatial consistency between real and virtual workspaces allows co-located users to interact directly with each other without going through an intermediary, such as a handshake between two users [79]. The blended real and virtual environment enriches the user's virtual experiences and overcomes the lack of tactile feedback of VR, contributing to a higher sense of presence [56].

1.2.4 Classification of Spatial Consistency

Depending on how real and virtual workspaces are coupled, the resulted spatial relation between them can be varied from completely consistent to partially consistent (see Figure 1.8).

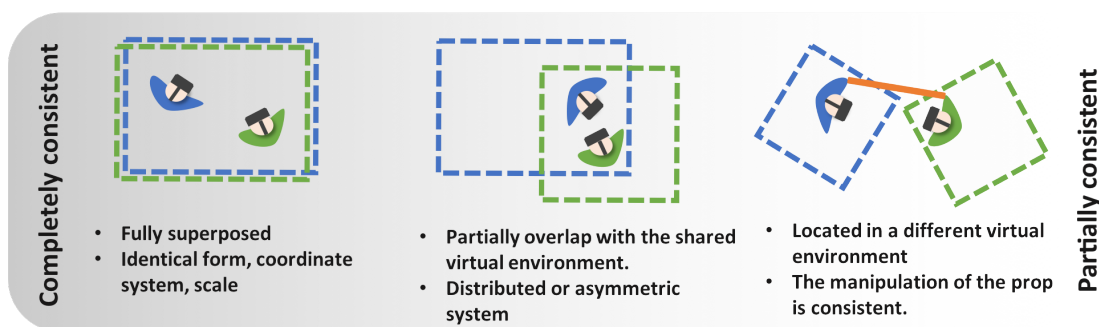


Figure 1.8 – Broad classification of spatial consistency from completely consistent to partially consistent in multi-user contexts.

As already highlighted in the previous sections, most VR applications [7, 92] keep a complete spatial consistency. However, the spatial relation can also be consistent when users' real workspace partially intersects with the virtual one. For example, in a distributed collaborative system, users usually own different real workspace configurations and are immersed in a shared virtual environment. By overlapping a part of each user's real workspace with a shared virtual workspace, users can perform a collaborative task inside the shared area. Simultaneously, each user can retain a certain part of the interaction area to perform some individual tasks [40].

In some extreme cases, users are no longer located in the same virtual environment, but the spatial relation among users maintains consistent and is used for application designs. For example, users are immersed in different virtual environments in the Mutual Turk system, with one user flying a kite and another tugging fish out of a pond. However, the system still allows users to exchange forces via a shared prop since their timelines are synchronized, and the way they manipulate the shared props is consistent across virtual worlds [32].

1.3 Mismatch Between Real and Virtual Environments

In most VR applications that rely on such one-to-one mapping, the user virtual workspace size is limited to the size of their tracking area. For example, users could "walk about 2 meters" in a virtual windshield assembly task [92], and the virtual workspace for a virtual car hood assembly task was restricted as $4\text{m} \times 4\text{m}$ [7]. Virtual navigation techniques can be deployed to allow users to explore a virtual environment larger than their real workspace. However, VR applications with

one-to-one mapping usually do not support virtual navigation features. The main reason for this is that when the user is able to have virtual navigation capabilities, what they perceive in the virtual environment will no longer correspond to the spatial configuration in the real world.

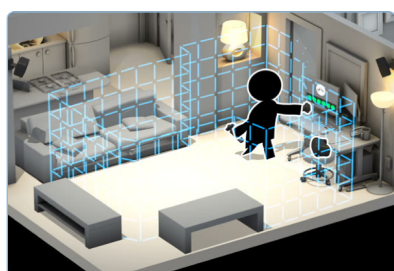
1.3.1 Spatial Desynchronization Issues

The "spatial desynchronization" [68] between the user's real and virtual workspaces hinders the full utilization of the real workspace and endangers user safety. The position offset introduced by the spatial desynchronization makes many interactions that rely on one-to-one mapping impossible. For example, the position mismatch between the tangible interface and its virtual counterpart hinders the use of the tangible interface. Moreover, direct interaction between co-located users is also limited since users' position in the virtual environment is no longer relevant to their spatial configuration in the real world. In addition, co-located users can hear/see each other in a different direction than their avatars' position in the virtual world. For example, in a multi-stereoscopic projection system, providing the user with an individual navigation capability induces a dual presence of the user and their avatar in the scene. The combination of hardware and software creates perceptual conflicts in the audio/visual channels of the real and virtual worlds and can affect the user's task performance [28]. In addition to these perceptual conflicts, such co-located immersion may lead to the blocking of one user's stereoscopic image by other users, as well as collisions between users. To address these problems, some solutions are proposed based on a virtual vehicle applied to each user and coupled with extensions of the Human Joystick navigation metaphor [29, 30].

More importantly, the mismatch between the real and virtual environments may lead to safety issues as users may run into physical obstacles that are not visible in the virtual world. This could be even more problematic for co-located users equipped with head-mounted displays, as they could collide with each other due to a lack of knowledge of another user's position in the real world. This can distract the user from the task and increase their focus on collision avoidance [84]. Such unconscious processes can influence the user's experience and the effectiveness of cooperation [17]. In addition, due to the mistrust of the virtual environment, users may fear colliding with real-world obstacles [35] and alter movement behaviors [35, 96].

1.3.2 Obstacles Awareness Enhancement

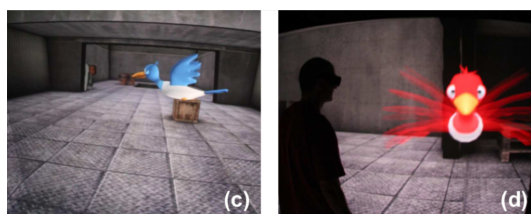
In response to the safety concerns of users in spatially asynchronous conditions, some studies have focused on enhancing obstacle awareness through the use of



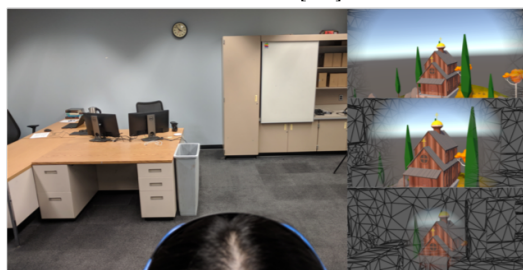
(a) Chaperone system used in SteamVR.



(b) Different representations of the collaborator's position in the shared physical workspace: a virtual cylinder (left), a ghost (middle) and a safe-navigation space on the floor [68].



(c) Virtual Companion: the bird in "rest mode" (left) and "protection mode" (right) to avoid user's collision [37].



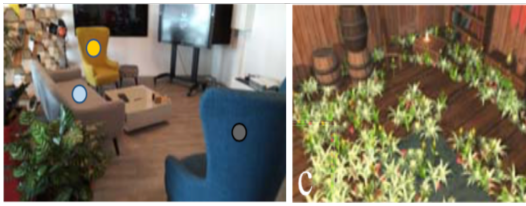
(d) Reduce the display of the virtual environment while revealing the scanned physical environment [117].

Figure 1.9 – Different feedback for obstacle awareness enhancements.

different visual feedback. The common solution is to provide the user with an additional visual indication when approaching an obstacle or reaching the boundary of the physical workspace. For example, the Chaperone system used by SteamVR can warn the user when they approach the real workspace limits (see Figure 1.9a). Other visual feedback, such as a virtual bird, can also accompany the user and protect them from reaching real workspace limits [37] (see Figure 1.9c).

To ensure a safe cohabitation of HMD users, Lacoche et al. [68] propose three methods to inform users about the position of collaborators in the real world. The first and second methods deploy a virtual cylinder and a ghost representation of the user at the collaborator's real position accordingly. The last method displays a safe walking space on the floor (see Figure 1.9b). However, adding such a completely out-of-context information layer in a virtual environment may affect the user's immersion and presence [98]. To address this issue, Wu et al. [117] proposed to gradually reduce the display of the virtual environment while revealing the wire-frame 3D grid of the scanned physical environment to prevent collisions (see Figure 1.9d).

Obstacles in the real world can also be detected in real-time and incorporated into the virtual environment in a way more imperceptible. For example, Keller et



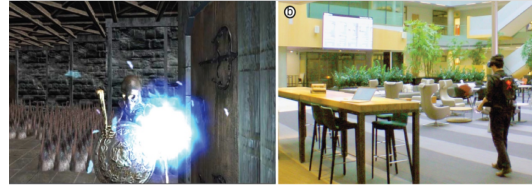
(a) The areas containing obstacles are replaced by vegetation [62].



(b) The alignment of real and virtual 3D structures [58].



(c) Insertion of visual barriers, such as fences or water based on the 3D model of a room [99].



(d) VRoamer builds the virtual environment in real-time based on the detected walkable areas and physical obstacles [34].

Figure 1.10 – Adaptation of the virtual environment according to the user real workspace.

al. used an RGB-D sensor to obtain an occupancy map of the real room. Areas with obstacles were then integrated into the virtual environment by generating different floor textures, such as lava lakes or vegetation (see Figure 1.10a). Instead of displaying obstacles through 2D floor textures, Sra et al. [99] proposed to insert virtual obstacles, such as fences or water, to prevent users from going beyond the detected walkable area [99]. Similarly, Valentini et al. [106] scanned the real scene and then created virtual obstacles to align them with the real obstacles. The alignment of the real and virtual 3D structures ensured the user’s awareness of the real environment. In addition, the detected objects were paired with virtual counterparts to enable a haptic experience (see Figure 1.10b).

However, such applications usually require pre-scanning of the physical environment. To solve this problem, VRoamer [34] further enables the generation of virtual scenes on the fly. It extracts walkable areas, detects physical obstacles in unseen physical spaces in real time, and procedurally generates a virtual scene. For example, it instantiates the detected walkable areas as virtual rooms and generates virtual corridors and doors to connect these rooms (see Figure 1.10d).

Real-world objects can also be integrated into the virtual environment to inform the user of the real-world context. By selectively blending real-world objects that the user engages with into the virtual environment, users can become aware of their real-world context while retaining a sense of presence in VR (see Figure 1.11a).



(a) Blending real-world objects with virtual environment [75].



(b) Superimposing the 3D point cloud of the real world objects on the VR environment [59].



(c) Vibro-tactile actuators integrated in HMD cushions [107].

Figure 1.11 – Augmenting virtual environments with real world objects and haptic feedback used in risk situations.

In addition, real-world objects can be superimposed on the VR environment as 3D point clouds (Figure 1.11b). Users can see through the point cloud to recognize real-world information and explore the virtual world simultaneously. Apart from visual feedback, haptic feedback can also be used to alert the user in risk situations by embedding vibrotactile actuators into the HMD’s face cushion (see Figure 1.11c).

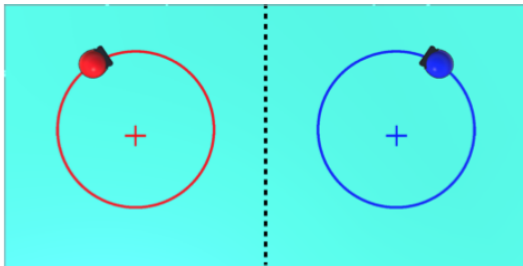
1.3.3 Adapted Navigation Techniques

Apart from introducing different feedback to improve user awareness of obstacles, different adaptive navigation techniques are proposed to avoid user collisions with physical obstacles and to ensure safe cohabitation of co-located users.

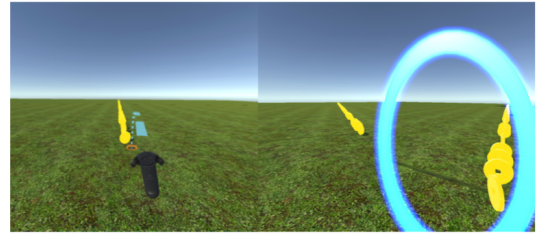
Redirected walking can imperceptibly steer immersed users away from physical obstacles by comprising a different translation and rotation gain between the user’s movement in virtual and physical space [85]. However, the main limitation of this technique is that it requires a large real workspace and cannot further execute when the user reaches the physical limits of this workspace. Targeting this issue, resetting techniques reorient the user into an open space, avoiding imminent collisions [115]. These approaches freeze the user’s position in the virtual environ-



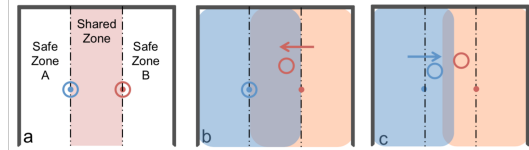
(a) The user is redirected to the CAVE Center by walking through the portal. [42].



(c) Subdivision strategy splits equally the tracking area for each user [10].



(b) Users step into the portal (blue circle) to activate teleportation, which unobtrusively reorients and repositions them away from the tracking space boundary. [71].



(d) Adaptive borders of workspace: a) Initial state. b) User B moves into the shared zone while user A is in the safe zone. User B can use the entire shared zone. c) User A also moves into the shared zone and pushes the workspace border of user B to the right. [29].

Figure 1.12 – Adaptive navigation techniques that ensure safe co-habitation of co-located users and avoid collisions with physical obstacles.

ment, and the user physically steps back or turns around 180° to gain more space for virtual exploration. Besides, an artificial potential field can also be introduced to the redirected walking to "push" the user away from obstacles [11]. Meanwhile, Portals redirect the user to a safe location via a portal in the center of the CAVE (see Figure 1.12a). In addition to redirected walking, other navigation metaphors, such as Redirected teleport, can also be used to keep the user away from tracking space boundaries by asking the user to step into the portal to activate teleportation (see Figure 1.12b).

When multiple users are present in the same system, the position of the co-located users must be taken into account to avoid the mutual collision. The most straightforward strategy is to split the tracking area into dedicated walkable subspaces for each user [10, 68]. However, this constrains users to a smaller physical space and impedes some closely coupled interaction (see Figure 1.12c). One possible solution is to adapt the virtual workspace boundaries to the user's activities by assigning each user a zone for individual use and a shared zone for interaction with

other users [29]. Besides, a gain function can be applied to the velocity control of user navigation to prevent them from reaching the limits of the motion tracking area and avoid the mutual collision in the shared zones (see Figure 1.12d).

1.4 Spatial Consistency Management

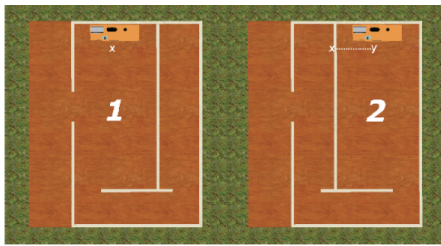
Maintaining a one-to-one position mapping between the user real and virtual workspaces avoids collision issues due to the spatial desynchronization, and enables the full use of the user real workspace. To make the spatial consistency compatible with a large-scale environment, some previous studies try to maintain real-world spatial configuration during navigation, and others attempt to restore the one-to-one mapping between the real and virtual world in case of spatial desynchronization.

1.4.1 Consistency Maintenance during Individual Navigation

Based on specific design mechanisms of the virtual environment or algorithms, the user can go beyond the restrictions imposed by the physical area and explore a large-scale virtual environment while maintaining consistent spatial relationships between the real and virtual worlds.

A possible solution is to create a virtual environment that fits the physical workspace. For example, Impossible Space uses a self-overlapping architectural layout that compresses a relatively sizable virtual environment into a smaller physical area. The virtual environment consists of adjacent rooms that spatially overlap, and the user can only see one room at a time. When the user reaches an overlapping area, such as a corridor, the system will shift the rendering state of the room. Therefore, the user can explore a larger virtual environment within a limited physical workspace by real walking (see Figure 1.13a). However, it is not easy to apply this technique to real VR walk-through since the application designers usually do not know the size and shape of the user tracking volume during the virtual environment design phase.

Targeting this issue, Sun et al. [104] proposed a more general solution using algorithms to compute a mapping between virtual and physical floor plans. Such mapping can properly fold large virtual scenes into smaller real scenes and can be applied to a given pair of virtual and real scenes. Some other techniques, such as VRoamer [34], detect the real environment through depth cameras and automatically generate a virtual environment using the real world as a template in real-time.



(a) An example of an impossible virtual environment consisting of a building with two adjacent rooms that spatially overlap, and only a single room visible at any one time [103].



(b) Employing "Human actuators" to create large virtual worlds [31].

Figure 1.13 – Real walking in a relatively large virtual environment with limited physical workspaces.

In addition to using algorithms, it is also possible to match virtual and real environments through human workers. For example, TurkDeck employs a group of human workers to operate a set of props when and where the user reaches them, allowing to produce of virtual worlds of arbitrary size (Figure 1.13b). These human workers act as sensors to modify the configuration of the real world, allowing users to see, hear, and touch the virtual environment. However, employing a team of human actuators is difficult in everyday VR experience.

These techniques mentioned above allow users to explore a large-scale virtual environment by walking while maintaining a one-to-one mapping between real and virtual environments. Although real walking can be one of the most direct and natural ways to allow users to navigate a large virtual environment, it can also be tiresome when users need to travel long distances. As an alternative allowing users to explore larger virtual environments, virtual navigation is a critical feature that requires spatial consistency management. Some virtual navigation techniques try to maintain spatial consistency by embedding the user real workspace into the virtual environment as a whole unit, such as the Magic Barrier Tape [36] technique presented in Section 1.1.2. The user can keep a one-to-one mapping when waking within the motion tracking area. In addition, the user can go beyond tracking limitations by translating a virtual representation of their physical workspace in the virtual environment. However, it is often difficult for them to adequately position their virtual workspace according to the requirements of the subsequent tasks. As a result, the user needs to simultaneously maintain object accessibility and perform related tasks, increasing the cognitive load and the time required to complete the task.

1.4.2 Group Navigation

In the multi-user case, the spatial configuration between users can be maintained during the virtual navigation by allowing only one user to control the navigation. For example, C1x6 allows multiple groups of users to meet in a shared virtual 3D world using projection-based setups. The spatial relationships between co-located users are consistent in the real and virtual workspaces, as users always navigate as a group. Each group is equipped with a fixed input device, the Spheron, to process the group navigation (Figure [1.14a](#)).

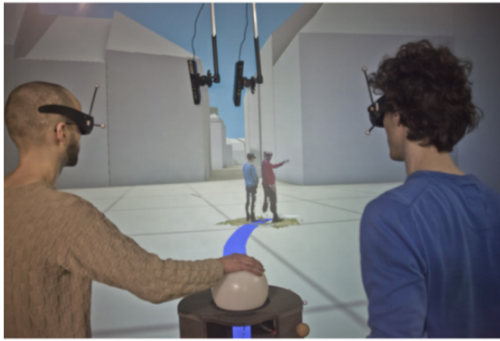
Similarly, multi-ray jumps allow co-located users to teleport together while preserving spatial relationships between them. In this method, one of the users (the navigator) uses a parabola to specify a target destination of teleportation. The corresponding future position of another user (the passenger) is then computed depending on their spatial relationship in the real world. Passengers can see a second parabola emerges from their controller and ends with the calculated teleportation destination. This pre-travel information is provided to the user to communicate their position after the teleportation and enhance comprehension of the group jump (see Figure [1.14b](#)).

Navigating as a group has its limits and is sometimes unnecessary. In some crowded virtual environments, such as corridors, some users can collide with virtual objects when the spatial relationships among the group is maintained. A previous study [\[14\]](#) proposes automatically moving the users close to each other when they path through a narrow place, and recover the spatial consistent configuration after reaching a collision-free state. However, this approach can cause short-term spatial desynchronization and can be uncomfortable for users depending on users' shifted offset to the open passage. Moreover, group navigation limits users' individual activities in some loosely coupled collaboration stage (e.g., individual object searching before the collaborative assembly task described in [\[30\]](#)).

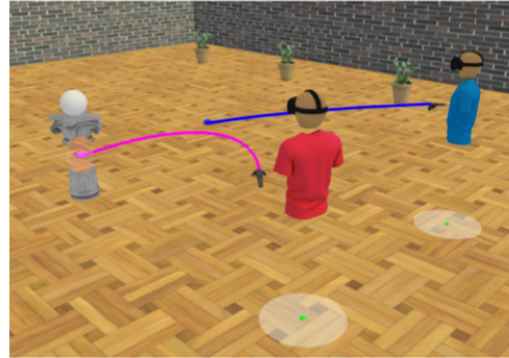
1.4.3 Mapping Reconfiguration for Tangible Interactions

Tangible interaction allows the user to touch a virtual object while touching its corresponding real object, which requires one-to-one positional mapping between real and virtual objects. Such mapping limits the use of tangible interactions in many VR applications. For example, for applications that use large-scale virtual environments, allowing users to navigate may introduce spatial discrepancies between the real and virtual worlds.

These problems can be overcome by reconfiguring the physical prop during its use with the help of robots or human actuators. For example, Robotic Graphics used a robotic arm to correctly position a real object in front of the user's hand



(a) One user uses the Spheron to process group navigation [67].



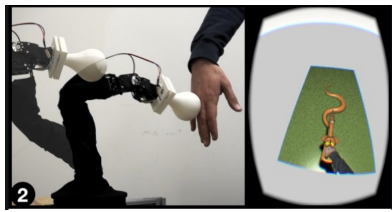
(b) Group teleportation [111]

Figure 1.14 – Group navigation preserving spatial consistency.

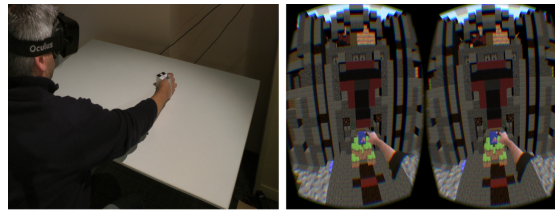
when the user tries to reach its virtual counterpart [77]. To reuse a physical prop in a complex VR experience so that it matches more than one specific type of virtual object, Snake-charmer revisited the concept of Robotic Graphics with current commodity hardware. It aligns a robotic arm with the object’s virtual representation and allows the user to feel one or more of the object’s shape, texture, and temperature (see Figure 1.15a). In addition to using robots, some applications employ human actuators to modify the physical workspace on the fly, such as TurkDeck [31] presented in Section 1.4.1. However, using robot technologies or employing a team of human workers are difficult in everyday VR experiences.

Some redirection techniques can also solve the passive haptic constraint. For example, Redirected Touching [63, 64] and Haptic Retargeting [9] introduce a discrepancy between the user’s real and virtual hand motion (see Figure 1.15b). As the user’s hand movement in the virtual environment is no longer the same as their real-world motion, the real and virtual hands can reach the real and virtual objects at the same time. By generating different mappings between the real and virtual spaces, a single physical object can provide haptic feedback for various virtual objects with different shapes. However, people also reported strange sensations as the virtual space is warped to map a variety of virtual objects onto a single real object, and a phase of adaptation is necessary to achieve the same task performance as in the non-warped condition [64].

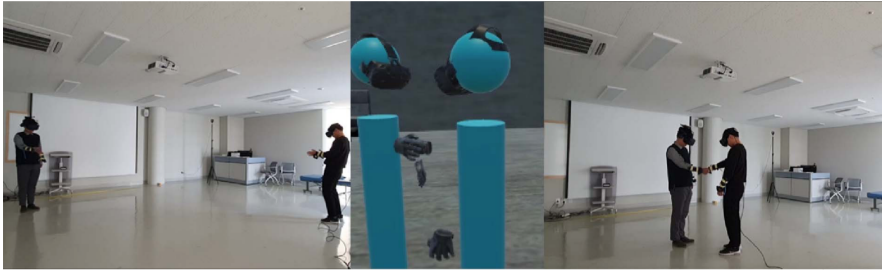
Similarly, Min et al. [79] proposed a recovery algorithm based on redirected walking to adjust the relative positions and orientations between co-located users in both virtual and physical spaces. Once a recovery state is reached, users can directly meet and directly interact in the virtual and physical workspaces simultaneously (see Figure 1.15c). However, like other redirected walking techniques, it typically requires a larger physical space than $6\text{m} \times 6\text{m}$ which is unsuitable for certain scenarios, such as home use.



(a) Snake-charmer brings physicality to a virtual scene by the means of a robotic arm [8].



(b) User stacks multiple virtual cubes, which are mapped to a single physical cube. [9].



(c) The recovery algorithm allows two users to meet in physical space as well as virtual space. Co-located users can therefore shake hands in virtual space using a redirected walking technique [79].

Figure 1.15 – Recover the one-to-one mapping for tangible interaction.

1.5 Spatial Consistency Recovery Technique

Different methods can be used to maintain or restore spatial consistency during navigation. However, these methods still have limitations. For example, deploying specific design mechanisms or algorithms to match the real and virtual worlds may limit the layout of the virtual environment to some extent. In addition, it can be cognitively overwhelming for the user to maintain spatial consistency during navigation by translating a virtual workspace in the virtual environment. Moreover, navigating as a group hinders users' individual activities. Besides, using robots, human workers, or redirection algorithms is difficult in some VR systems due to the high costs or requirements of the tracking areas.

This Ph.D. thesis addresses these problems and aims to provide users with a general solution to help them recover spatial consistency after individual navigation. As a result, users are provided with individual navigation capabilities to navigate in a large-scale virtual environment and perform individual tasks. When the subsequent tasks require spatial consistency, they can trigger the recovery process to recover the one-to-one position mapping between the real and virtual worlds. After completing the corresponding task, the user can continue their indi-

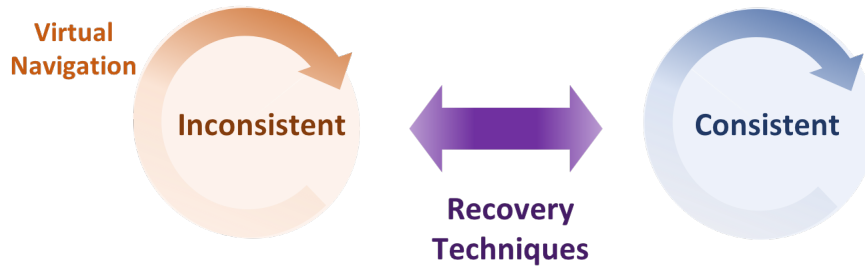


Figure 1.16 – Spatial consistency management illustration.

vidual navigation. Such recovery technique achieves a seamless transition between the spatial inconsistent state and spatial consistent state, providing the user with a continuous VR experience (see Figure 1.16).

The spatial consistency recovery techniques can be used in many scenarios, including individual and multi-user contexts. For an individual user, a possible use case can be in an escape room game [2, 3], if the user can position their virtual workspace close to the areas where the clues are possibly hidden, they could fully explore this area by walking and thus avoiding a lot of unnecessary teleportations. Another example can be in some first-person shooter games that use teleportation, such as *Half-Life Alyx* [5], if the user can choose their future virtual workspace position, they could directly reach some appropriate places where they could physically move to hide and attack enemies without being worried about colliding with their real workspace limits.

Introducing such recovery techniques can also enrich the possible scenarios in multi-user contexts, particularly those mixing individual and collaborative tasks. A possible scenario can be a VR training [4] such as for complex assembly tasks which usually include several assembly tasks at different locations within the VE. After positioning the virtual workspace around an assembly area of a sub-task, the user can access the required tools located on different workbenches and walk back to the assembly area to complete a sub-task without any teleportation. As the user does not need to manage virtual objects' accessibility while completing this sub-task, they can focus on knowledge acquisition and assembly procedure learning. Then, they can use again the teleportation to move to the next sub-task, and thus experience a complete complex task scenario in a continuous virtual experience. In addition, for users co-located in a shared physical workspace, they can interact directly with each other to accomplish subsequent collaborative tasks after arriving in the assembly area with recovered spatial consistency. Besides, a shared prop can be integrated into the scene to coordinate their movements and allow them to perceive passive haptic feedback.

1.5.1 The Design Space of Consistency Recovery Technique

Four key design dimensions are identified based on the analysis of the spatial consistency related studies. These dimensions, including *navigation metaphor*, *VR system*, *tangibility* and the *number of the users*, shape a design space of spatial consistency recovery techniques and show the possibilities of this concept (see Figure 1.17). The design of the spatial consistency recovery technique is usually composed of one or more of these dimensions. For each dimension, some intriguing considerations are discussed in the following to inspire interaction designers to design appropriate recovery techniques facing different requirements of applications.

First of all, the design of the recovery technique should take into account the characteristics of the virtual navigation technique used by the user. It is important to ensure how and when these techniques can be applied to provide the users with a seamless transition between the individual navigation and spatially consistent state. For example, the teleportation technique instantly moves the user to a predetermined destination. Therefore, the user can determine their future virtual workspace destination in the VE every time when the spatial consistency is necessary after teleportation, and then they can be instantly moved inside that workspace to reconfigure the spatial relationships. However, such immediate recovery can be unsuitable for steering techniques, as the user is used to getting continuous spatial information during the path integration. Moreover, some additional controls to define the virtual workspace destination and trigger the spatial consistency recovery process are also necessary when using the steering techniques.

Apart from the navigation techniques, the recovery techniques design should also account for the features of systems. It is essential to consider whether these recovery techniques can be applied to immersive systems facing different target users, tracking spaces, and input types. For example, large companies or laboratories often use projection-based immersive systems where the size and shape of the user's physical workspace are often predefined. These values can be therefore used in the interaction design process to customize a virtual workspace for consistency recovery. However, HMD users who use VR at home usually have different motion tracking areas, and the shape and size of these areas are often unknown to the designer during the application design phase. In addition, the interaction design, such as how to start/end the recovery process, should also be adapted to the input devices used in the system.

In addition, tangibility, which serves as the third dimension in the design space, is crucial to define the areas in VE where spatial consistency can be restored. Introducing tangible interaction in VR applications can limit the possible configurations when mapping real-world objects to their virtual counterparts. The number of possible mappings can be related to different factors, such as the symmetry axis of the tangible device, the number of devices, and the mobility of the device.

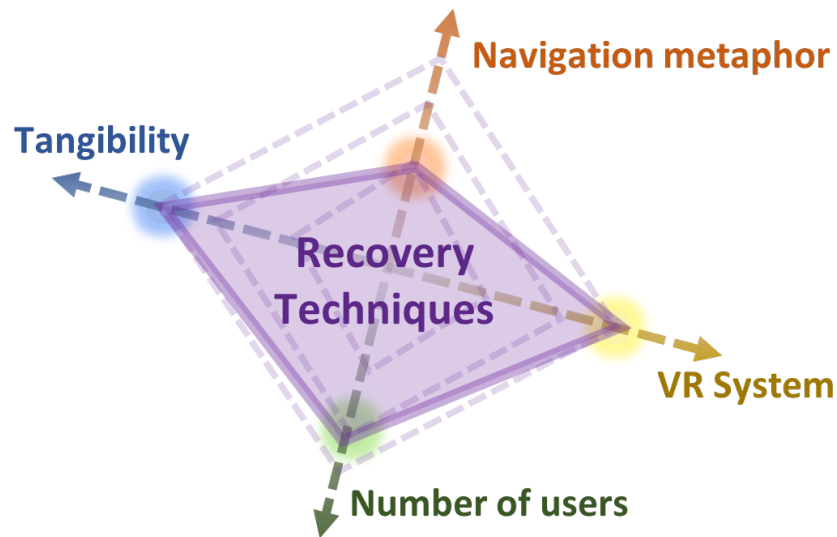


Figure 1.17 – Exploring the design space of spatial consistency recovery techniques.

For example, if we pair a real ball suspended from a long pendulum with a virtual flying drone that physically attacks the user, the number of ways to position the user around the drone tends to be infinite [33]. However, if we want to pair architectural features with virtual objects in a substitutional reality system, the mapping is strictly limited to one-to-one [95]. Moreover, if the user carries the target tangible device with him, there is no restriction on the definition of the spatial consistency areas in VE, which changed back to the situation where there is no tangible device.

In collaborative systems, the design of recovery techniques can also be challenging, especially to enable multiple users to define an area in the virtual environment to recover spatial consistency. Since collaborative interactions can be symmetric or asymmetric, users can have different or equal control over the recovery process. In synchronous collaboration, when all users can define the shared workspace simultaneously, interaction design should be aware of the possible conflicts of manipulation, especially when the number of users is high. The choice of techniques and the assignment of roles should also be appropriate to the application scenario. For example, during a museum tour, the guide should be allowed to lead the recovery process and place the virtual workspace shared by all visitors near the target exhibits. Such a design could also be extended to asynchronous collaborative interactions, e.g., one user could position a virtual workspace and leave a tangible prop in it. A second user could join the predefined workspace later and reuse the same prop.

Finally, maintaining awareness of users' surroundings during and after travel, i.e., spatial awareness [21], is critical for spatial consistency technique assessment. Therefore, it is important to provide appropriate feedback to users during the consistency recovery process. For example, providing users with prior knowledge of where they will arrive in the virtual environment after recovering the spatial consistency can help them find the targeted virtual object and thus improve subsequent task performance. In a multi-user context, presenting another user's future destination through a ghost avatar may help the user to have a better "up-to-moment understanding of another person's interaction with the shared workspace" [53] and thus enhance mutual awareness.

1.5.2 Spatial Consistency Recovery for Teleportation

This thesis focuses on the design and evaluation of the spatial consistency recovery techniques for teleportation navigation. There are many reasons for choosing this navigation metaphor. First, among various virtual navigation techniques, teleportation is a navigation metaphor widely used in many VR applications. Besides, with teleportation technique, user viewpoint will be instantly transferred to a targeted position [21]. This instant transition avoids the sensory conflict between the visual feedback and the user's vestibular systems. As a result, the teleportation lowers simulator sickness and leads to the least discomfort compared to other controller-based locomotion techniques [44, 54, 109].

The teleportation process can be generally divided into two phases: selecting the targeted destination and activating the transition. In most applications, the targeted teleportation position is specified by ray casting using a tracked input device. The user uses linear or parabolic shaped virtual representation to select the position of their future teleportation destination. However, most teleportation metaphors are limited to two dimensions (2D position) and do not allow the user to define the orientation while teleporting. As a result, users usually need to physically rotate their bodies to adjust the rotation after teleportation. This may not be suitable for some CAVE-like systems due to the lack of a screen. In addition, the rotation increases the risk of HMD users getting tangled in cables when using wired devices.

To overcome these issues, Bozgeyikli et al. [22] proposed the point & teleport technique, which adds a direction component to allow the user to specify their desired orientation during teleportation. A 3D arrow is placed above the future teleportation position to indicate the future direction of the user when being teleported. The user can rotate the rolling axis of the pointing hand to turn the arrow on the Y-axis (see Figure 1.18a). Later, Funk et al. [46] revisited the idea and included more control over teleportation. In their techniques, the user can use a parabola to specify the teleportation destination. In addition, the user can

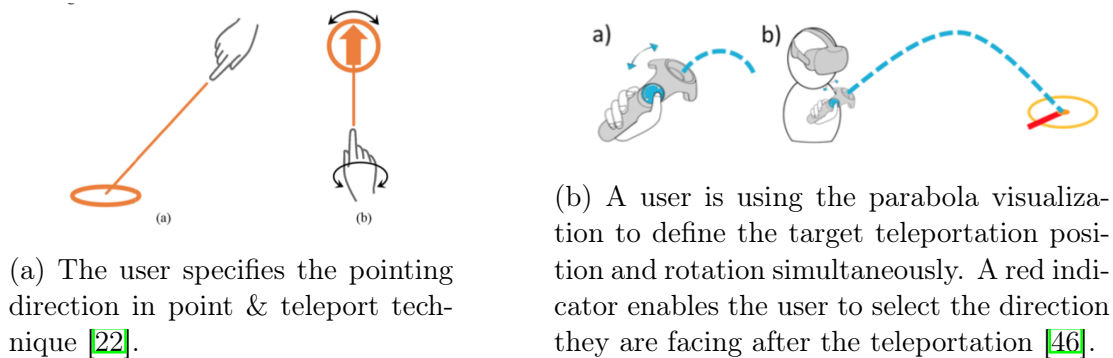


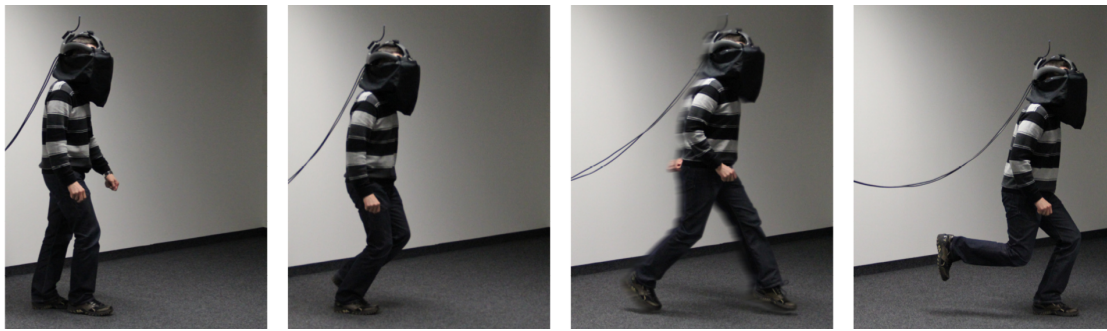
Figure 1.18 – Including orientation indication to the teleportation.

select the direction of the teleportation by moving their finger in a circle on the touch-pad, with a red indicator showing the direction they have selected (see Figure 1.18b). They evaluated this technology in a user study, which showed that including directional control increases average teleportation time, but reduces the need to correct direction after teleportation.

The teleportation process can also be implemented without the need for additional 3D input devices. For example, the jumper metaphor [16] allows users to use eye gaze to specify a targeted point and thus enables hands-free teleportation. The jumper metaphor implicitly predicts the teleportation position of the user by calculating the first intersection point of a ray extending from the user's virtual head position along their viewing direction with the virtual scene. After specifying the teleportation destination, the user can activate the teleportation by physically jumping towards the target (see Figure 1.19a).

It has been argued that teleportation is an unnatural way of moving [21]. The lack of path integration makes it difficult for users to gain spatial knowledge of the virtual environment during teleportation, e.g., to estimate travel distances [69, 12, 15]. To address these issues, a jump animation with a blurring effect can be interpolated from the user's current position to the transmission destination point (see Figure 1.19b). Similarly, an optical flow for path integration can also be generated to continuously move the user to the destination [15]. Besides, the user's viewpoint can be faded to gray for a short period of time during the teleportation process to avoid user discomfort and help them adapt to the immediate changes in the virtual world [42]. However, these methods may lead to sensory conflicts between the user's vestibular system and visual perception, which may again induce motion sickness.

Teleportation can also be enhanced by combining it with real walking. For example, the jumper metaphor allows the user to perform short-distance real walk-



(a) The user activates the teleportation in the jumper metaphor by physically jumping.



(b) Blur effect during jumping interpolation.

Figure 1.19 – The user activates the teleportation in the jumper metaphor by physically jumping [16].

ing while using teleportation for long-distance navigation [16]. Real walking is the most intuitive way to move [23]. It provides users with multi-sensory cues that combine sensory and visual information to understand better their movements, such as the speed and the direction of travel [89].

Given the characteristics of teleportation in the related studies outlined above, this thesis focuses on proposing a generic solution adapted to this navigation technique to help users recover spatial consistency after individual navigation. I argue that helping users recover spatial consistency will improve subsequent task performance compared to basic teleportation. Spatial consistency allows users to access the virtual surroundings by walking. Moreover, the restored one-to-one position mapping between the real and virtual worlds enables tangible interaction, and facilitates the manipulation and communication between co-located users in collaborative contexts. In this thesis, I will explore spatial consistency recovery techniques suitable for different VR systems (CAVE vs. HMD). I will also investigate the application of these techniques in different interactive contexts, including individual interactions, tangible situations, and co-located collaboration.

1.6 Conclusion

This chapter begins with a brief introduction to VR technologies and then describes how these technologies can be integrated into virtual environments to enable real-time user interaction. Next, I contextualize the notion of spatial consistency by presenting an overview of relevant applications. To follow, I summarize the existing solutions to avoid spatial desynchronization issues due to the user's individual virtual navigation. Finally, I discuss the possibilities to introduce a recovery process to help the user recover spatial consistency after individual navigation in a large-scale virtual environment and propose a design space for such techniques.

The design of the spatial consistency recovery techniques should be adapted to the characteristics of the navigation metaphor and VR system used. It should also meet the requirements of different interactive contexts. This thesis aims to propose a general solution to help the user recover the spatial consistency with teleportation navigation. Such a navigation metaphor was chosen as it is widely used in many VR applications and has been shown to reduce simulator sickness. Next chapter describes two spatial consistency recovery techniques that I have designed for teleportation navigation. In particular, it highlights my considerations for maintaining the user's awareness of their surroundings during the recovery process. These techniques are suitable for VR systems with predetermined shapes and sizes, such as CAVE-like systems.

Consistency Recovery for Teleportation

2

This chapter presents two spatial consistency recovery techniques designed for teleportation navigation. These techniques are designed to help users recover the one-to-one position mapping between the real and virtual worlds in some areas previously defined by the application designer. Therefore, these techniques are suitable for VR systems with predetermined shapes and sizes, such as CAVE-like systems. First, I detail the technical aspects of these two approaches. Then, I describe a formative user experiment that investigates user performance and subjective perceptions when using these techniques.

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2.1 Introduction

Many VR applications rely on a one-to-one position mapping between the user's real and virtual workspaces. The resulting spatial consistency allows the user to use the entire real workspace to perform the corresponding tasks. The user can thus access all virtual objects enclosed in the virtual workspace through physical walking and interact with them using real gestures.

The main limitation in such applications is that the user can only explore a virtual environment that has a similar size and shape compared to their physical workspace. In addition, tasks requiring spatial consistency often need to be taken out of the continuous scenario when virtual navigation is required in the workflow. This is driven by the fact that providing the user with individual navigation capability may break the spatial consistency. When the user employs virtual navigation metaphors to explore a large-scale virtual environment, the virtual environment is no longer mapped with the spatial configuration of the real world.

In order to provide the user with a continuous virtual experience, a seamless transition is thus necessary to help the user recover the spatial consistency after individual navigation. The spatial consistency recovery techniques should be adapted to the navigation metaphor used in the application. In this chapter, I focus on spatial consistency recovery techniques for teleportation navigation, as it is widely used in many VR applications and has been shown to reduce simulated sickness in previous studies.

This chapter is based on work published at EuroVR 2019 (see Publications [\(a\)](#)). It first presents two spatial consistency recovery techniques designed for teleportation navigation: *Simple-switch* and *Improved-switch*. The *Simple-switch* allows the user to quickly recover the spatial consistency in specific areas defined by the application designer. The *Improved-switch* provides an additional visual feedback of the user future destination, aiming to reduce user disorientation after teleportation. I then describe the user study I conducted to evaluate these techniques and compare them to a baseline condition. In this baseline, the user employs a basic teleportation without any spatial consistency recovery. I argue that recovering the spatial consistency contributes to a better performance on subsequent tasks compared to the baseline condition. In addition, including additional visual feedback during the recovery process will help users better understand their future destinations.

2.2 Switch Techniques

To help the user to recover spatial consistency after individual teleportation navigation, I propose two interaction techniques. These techniques are designed for VR

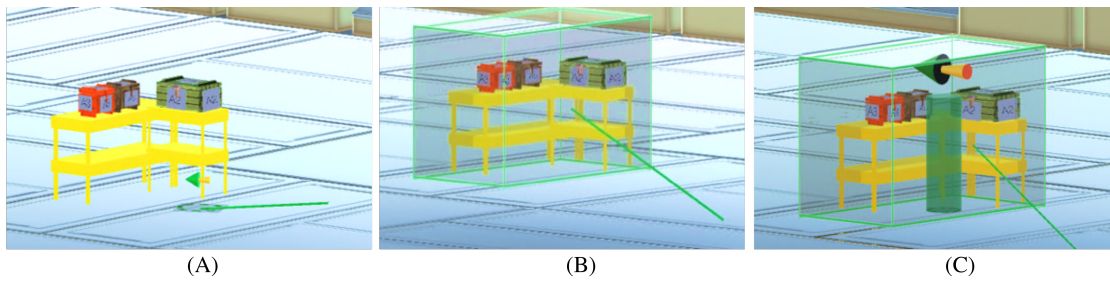


Figure 2.1 – (A) Standard teleportation without any spatial consistency recovery technique. (B) *Simple-switch*: the interactive area is highlighted when it is selected. (C) *Improved-switch*: an additional 3D arrow and a semi-transparent cylinder are displayed when the interactive area is selected, showing the user’s future position and rotation.

systems where the shape and size of the user physical workspace can be previously determined, such as in cave-like systems.

According to the layout of the user physical workspace, the application designer can define some specific areas of the virtual environment where the spatial consistency is required, such as in escape games where clues are possibly hidden or in assembly training where the user needs to act with tangible tools. These areas, denoted below as user interactive areas, can be defined in the scene according to the storyline so that the user can visit them one by one. Alternatively, the user can be guided to these areas via a predefined path [47] or using a guided avatar [113].

By superposing the user physical workspace with one of the interactive areas, the spatial consistency between the real and virtual worlds can be recovered within that area, achieving a transition from user individual navigation to spatial consistency state. I proposed two interactive methods to allow the user to select their desirable interactive area and perform such transition: *Simple-switch* and *Improved-switch* (see Figure 2.1).

2.2.1 Simple-switch

In the *Simple-switch* approach, each interactive area is represented as a 3D volume with the same shape and size as the user physical workspace. These volumes are invisible to the user at first sight. Collision detection is performed between the 3D volume and the virtual ray used for teleportation. The user can select an area by pointing the virtual ray at it. Once an area is selected, it is displayed with a green border. The user can activate the switch by pressing the same button used for teleportation. After that, the user will be transferred into the selected area and recover the spatial consistency. Moreover, the user arrival position in the interactive area is computed by mapping the user’s real-time position and rotation

in the real workspace to this area.

After the user is arrived in the selected interactive area, it is not possible to use teleportation inside this area. The virtual ray will turn red when the user tries to select a teleportation destination within this area. Under such circumstances the user will stay in place even if the teleportation is triggered. Once the user finishes the task in an interactive area, they can continue the navigation by selecting a teleportation destination outside this area. Thus, the user can seamlessly switch back to the individual teleportation navigation, i.e., to a spatial inconsistent situation.

This technique allows a quick and straightforward spatial consistency recovery in two steps: selection and activation. However, the user is transferred directly to the interactive area without receiving any indication of their arrival position. After being transferred without knowing exactly the final destination, the user may need some time to perceive spatial information and reconstruct a mental representation of the virtual surroundings. Lack of awareness about the destination point may prolong the user adaptation process to the new environment and increase the risk of disorientation (also known as one of the cybersickness factors) after the teleportation.

2.2.2 Improved-switch

Unlike the *Simple-switch*, the *Improved-switch* provides the user with an additional visual feedback of their future destination (see Figure 2.1). This visual feedback is displayed when an interactive area is selected and shows directly where the user will arrive inside this area. Its position and rotation are computed by maintaining a one-to-one mapping in real-time between the user's position and rotation in the physical workspace and those in the virtual workspace. The visual feedback consists of a semi-transparent cylinder with 0.5m diameter and a 3D textured arrow placed above the cylinder pointing to the forward direction of the user future orientation. The flat dashed circle used to demonstrate the teleportation position is replaced by a cylinder, as the latter can be easily hidden by other virtual objects near the interactive area.

The user can use this visual feedback to anticipate their future destination and locate themselves in the cognitive map of the selected interactive area. This can facilitate the tasks performed in this interactive area. Therefore, before teleporting to the selected interactive area, the user can check the target virtual object's position relative to their future destination. For example, by seeing that the target object is located to the right of their arrival destination, users can realize that they can find it on their right side after jumping into the area. In addition, the user can physically move within the real workspace, making slight adjustments to their arrival destination. By observing the change of the visual feedback, the user can better comprehend the spatial relationship between the target object and their

future destination. This may enhance their understanding of the resulting spatial configuration and improve their estimation of their arrival destination.

2.3 User Study on Recovery Techniques

I used a box-opening task to evaluate these two spatial consistency recovery techniques, and compare them to a baseline condition which uses a basic teleportation navigation. I aimed to evaluate the benefits of helping the user to recover spatial consistency regarding the accessibility of virtual objects. In addition, I wanted to evaluate the benefits of including an additional visual feedback of the user arrival destination in terms of spatial awareness and task performance. The experiment thus compared the following three conditions:

- *Simple-switch*, which recovers the spatial consistency within an interactive area selected by the user. Each interactive area has the same size and form as the user physical workspace and encloses all required virtual boxes to complete the subsequent task. After the user is teleported into the selected interactive area, the restored spatial consistency allows them to access the required virtual boxes by physically walking.
- *Improved-switch*, which provides an additional visual feedback of the user arrival destination in the spatial consistency recovery process. When the user selects an interactive area, a 3D cylinder with a directional arrow will be displayed, indicating the user future position and orientation. The user can use this visual feedback as a cue to anticipate their future position relative to the targeted virtual boxes.
- *Without-switch*, which is a baseline condition using basic teleportation without spatial consistency recovery capability. The user needs to use teleportation to access all targeted virtual boxes and complete the task.

The experiment followed a within-subject design with the spatial consistency recovery technique as an independent value. The order of the techniques was counterbalanced across participants using a balanced Latin square.

2.3.1 Hypotheses

I expected that the restored spatial consistency would help the user focus on the virtual box-opening task without worrying about the accessibility of the boxes. I also assumed that additional visual feedback would help the user predict where they will land after the switch and reduce the risk of getting disoriented. The hypotheses built for this experiment were as follows:

H1: Compared to the *Without-switch*, conditions with a switch (the *Simple-switch* and the *Improved-switch*) will result in higher task performance.

H2: Compared to the *Simple-switch*, *Improved-switch* will provoke less disorientation.

H3: Compared to the *Improved-switch*, where the user will spend more time predicting their next position by observing the additional feedback, *Simple-switch* can be less time-consuming.

2.3.2 Participants

18 participants (7 female, 11 male) aged between 19 and 36 ($\mu = 26.65$, $\sigma = 3.88$) participated in this experiment. All participants were the right-handed. None were color-blind. Participants had none to intermediate knowledge of virtual reality, and half of them had virtual reality experience before.

2.3.3 Experimental Setup

The experiment was carried out within a CAVE-like system (the EVE system of the VENISE team [1]) using the Unity game engine. Stereoscopic images were projected on all three screens surrounding a floor screen with BARCO technologies [2]. User motion was tracked by ART tracking system [2] composed of infrared cameras. User head position and gaze direction were computed from the markers attached on shutter glasses. Thus, the adaptive stereoscopic images following the user viewpoint can be correctly rendered on the screen. User hand information was computed from the marker installed on a Nintendo Wii remote controller held by the user dominant hand. This information was used for controlling the virtual ray and performing the virtual manipulation task.

2.3.4 Box-opening Task

In the virtual environment, four box sets were located within four similar rooms (A, B, C, and D). These rooms were connected to a center room by corridors. A virtual desktop monitor was placed in the middle of the center room.

Each box set composed of four boxes, formed a U-shape and was placed with four different orientations (0° , 90° , 180° , 270°) regarding to the corresponding corridor's direction. The U-shape box setting would map the three wall screens of the CAVE system after the switch completed, which allowed users to take maximum advantage of physical workspace to complete the task. Each participant needed to

¹<https://www.barco.com/en/products/caves>

²<https://ar-tracking.com/en>

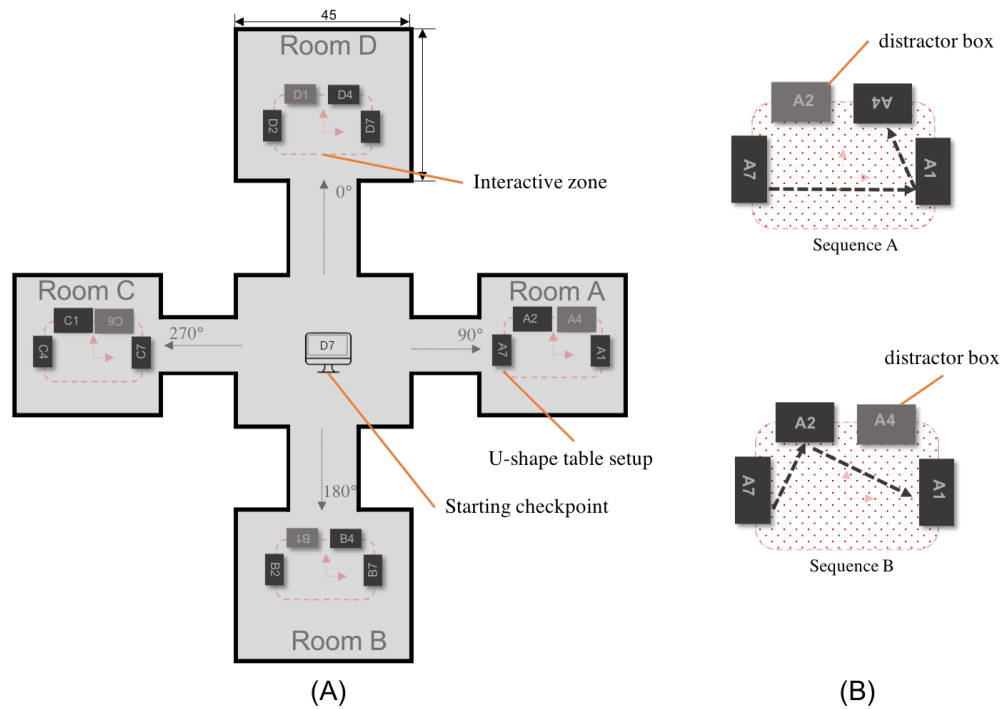


Figure 2.2 – (A) Top view of the virtual environment. (B) Illustration of the U-shape box setup and the two sequences defined for opening the box.

navigate to the corresponding room to open successively three of four boxes following a previously defined order. For avoiding the learning effect, two sequences for opening the three boxes were defined. The fourth box was deployed as a distractor and was positioned randomly in the box set (see Figure 2.2).

All boxes had a similar shape, but different colors and were named by the room name connecting with a random number (e.g. box B2 located in room B). The label of the box could be seen at each side of the box and was placed with a random orientation. Users thus made the same cognitive effort to read and understand the box label from either side of the box. By holding the “A” button on the Wii remote controller, a virtual key would be displayed at the user’s virtual hand position. Then, the ray used for teleportation would disappear. The box could be opened from any side whenever a collision was detected between the virtual key and the box.

Participants started the task by standing in front of the virtual monitor where the label of the first box to open was displayed. Participants needed to teleport to the corresponding room via the connecting corridor and opened the target box. The label of the next box to open could be found in the previously opened box.

Participants would be guided to the next room when all three boxes were opened in the current room. The task repeated eight times and ended when all 4 rooms been visited twice. The order of visiting the rooms was randomly generated. In contrast to *Without-switch* condition where users needed to teleport between the boxes, the switch techniques allowed participants to open all three boxes inside one room by waking.

When traveling in the virtual environment, the teleportation destination was determined in virtual environment by ray casting. For reducing the discomfort from wearing a redundant tracking device, the ray started from the user's virtual hand position, and its direction was determined by the vector from virtual head position to virtual hand position. In order to ensure the teleportation accuracy, different ray lengths were tested in-house before 12m is set. Collision detection was performed between the ray and the ground of the virtual environment. Once the collision was detected, the position of the collision point was stored and used as a target position in the next frame.

Due to the lack of a fourth wall screen in the EVE system, which is common in many CAVE-like systems, the teleportation must include orientation indication. Inspired by the work of Bozgeyikli et al. [22], the rolling axis of hand was used as an additional control to specify the direction of teleportation. For an ergonomic reason, a linear gain function was then applied for mapping limited hand rotation $(\theta_{left}, \theta_{right})$ to teleportation direction control with 360-degree capability $(\theta'_{left}, \theta'_{right})$. The computation was symmetric for left and right-handed users.

$$\theta'_{left} = \theta_{left} \times 3, \theta_{left} \in [0^\circ, 60^\circ] \quad (2.1)$$

$$\theta'_{right} = \theta_{right} \times 2, \theta_{right} \in [0^\circ, 90^\circ] \quad (2.2)$$

Teleportation was activated by pulling the trigger on the Wii controller. Same as Bozgeyikli et al. [22], the visual cues used for teleportation consists of a virtual ray, a dotted ring lay on the destination position and a 3D arrow above the ring for showing direction. The default color for the whole setup was green (see Figure 2.3).

When no collision between the ray and virtual ground was detected (e.g. users choose a position far exceed the length of the ray), the virtual ray was presented as red. Under this circumstance, the user stayed at the same place in the virtual environment if the teleportation was activated.

A cube shape collider surrounded every virtual obstacle in the virtual environment (e.g. walls and tables). Users can only be teleported next to the obstacle instead of entering into it. During the whole navigation, user can move physically inside the real workspace, which remedy the inevitable accuracy limits from the gesture-based destination selection. To ensure user security, a warning sign faded into user viewpoint once the user got too close to the real workspace boundaries.

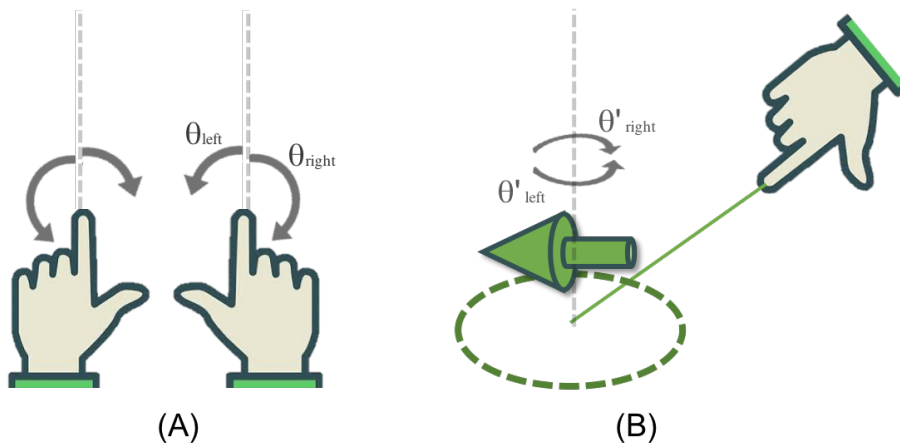


Figure 2.3 – (A) Illustrate the rolling axis of hand for teleportation orientation control. (B) Visual presentation for teleportation with direction control

The warning sign consists of a red exclamation mark and a barrier tape following the edges of the physical workspace. With the slanted black and tallow stripes texture of the barrier tape, a message “do not cross” is displayed to inform the user explicitly.

2.3.5 Procedure

After participants entered our laboratory, they read and signed the formed consent and filled the background information questionnaire. After a short explanation of the system and the objective of this experiment, I helped participants wearing the shutter glasses. Participants first went through 5 minutes of training in a similar virtual scene to become familiar with the navigation technique, the switch techniques, and the task procedure. Then, the experiment started, and the participants were asked to open 24 boxes in one condition.

After each condition, participants were given a Witmer and Singer’s presence questionnaires [116] to measure the presence with five levels (0: not at all, 5: completely). Finally, after they completed all three conditions, participants were asked if they found the interaction techniques mentally and physically demanding in an overall survey. They also had to rank the three techniques depending on how successful, disoriented and frustrated they perceived.

2.3.6 Data Collection

For each trail, I logged the time, the number of times the user teleported (i.e., the user pulled the trigger on the Wii remote controller), the number of times the user attempted to open the box (when the user pressed the “A” button on the Wii remote controller), the number of times that warning signs were triggered, as well as the user real and virtual head position and orientation. From this data, following measures were extracted:

- *Task completion time (TCT)*: the duration the users took to complete the task. The measurement started when participants entered a room and ended when the third box was opened.
- *Manipulation numbers*: the sum of the teleportation times and the number of attempts to open the box. This number was computed inside each room. It could be considered as a quantitative measurement of cognitive effort paid for completing the task.
- *Warning numbers*: the number of times that the warning was triggered when the user was staying too close to the physical workspace boundary. This number was computed inside each room. It was measured since an excessive display of the warning may frustrate users and disturb them in their task, as well as affect the sensation of continuity of the virtual experience.
- *Switch time*: the time used to achieve the transition from individual teleportation to the spatial consistency situation. The measurement started when users selected an interactive area and ended when they activated the switch.
- *Reaction time*: the time that the user spent to find and open the target virtual box after teleporting inside the interactive area. It started when users entered the interactive area and ended when the first target box was opened. The “ability of the user to retain an awareness of their surroundings during and after travel”, namely spatial awareness [21] was deployed as an important factor to evaluate these switch approaches. To quantify the spatial awareness, I measured the time that users needed to reorient themselves to a previously seen object in the scene, as it was suggested in some similar studies [21, 111].
- *Head rotation*: the cumulative sum of user real head rotation movement. The measurement started when users entered the interactive area. It stopped when the first box was opened. In addition to measure the *reaction time*, I investigated how users reorient themselves to a target object by observing their head movement.

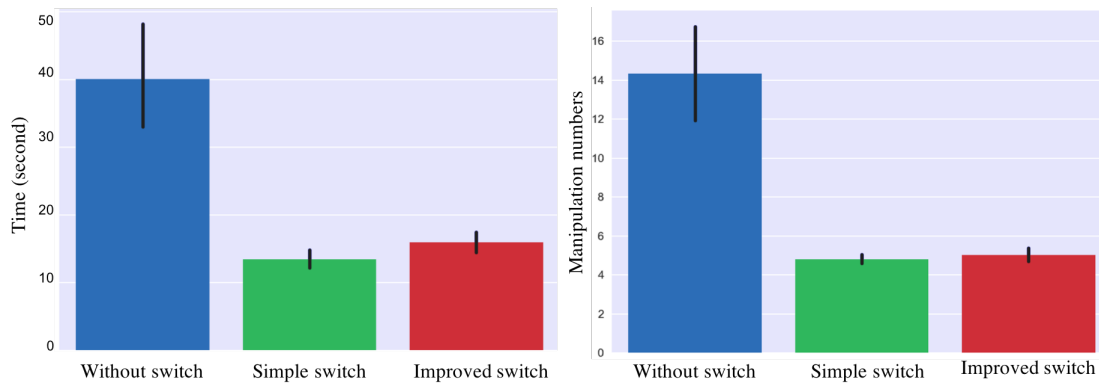


Figure 2.4 – Bar plots for *TCT* (left) and *manipulation numbers* (right)

2.3.7 Statistical Results

I registered 432 trials: 3 conditions \times 4 rooms \times 2 repetitions \times 18 participants. To minimize the noise in my data, I averaged the data for each participant in each condition. I run the analysis based on 54 aggregated data sets.

The results presented in this section were considered statistically significant when $p < 0.05$. In all bar plots, error bars show the 95% confidence intervals (CI). I found the data was not normally distributed in a Shapiro test, and the data variance was not homogeneous in a Levene test. In the following part of this section, I firstly performed non-parametric Friedman test to compare the three switch techniques at a global level. Then more detailed analyses were conducted for paired techniques using the Wilcoxon Signed Rank test with Bonferroni correction. All the analyses were performed using Python with `scipy.stats` library.

For *TCT*, a main effect was found [$F(3, 54) = 29.78, p < 0.0001$] with *Without-switch* (Mean = 40.02, $SD = 15.95$), *Simple-switch* (Mean = 13.43, $SD = 2.92$) and *Improved-switch* (Mean = 15.95, $SD = 3.20$). Then, a further Wilcoxon Signed Rank test with Bonferroni correction revealed that the task was significantly longer to achieve for *Without-switch* than for *Simple-switch* ($p = 0.0006$) and for *Improved-switch* ($p = 0.0006$). A Wilcoxon Signed Rank test with Bonferroni correction also revealed a significant difference between *Simple-switch* and *Improved-switch* ($p = 0.0469$) (see Figure 2.4).

For *Manipulation numbers*, a main effect was revealed [$F(3, 54) = 28.8, p < 0.0001$] between *Without-switch* (Mean=14.33, $SD=5.35$), *Simple-switch* (Mean = 4.79, $SD = 0.49$) and *Improved-switch* (Mean = 5.01, $SD = 0.77$). A Wilcoxon Signed Rank with Bonferroni correction detected that *Without-switch* induced significant higher *Manipulation numbers* compared to *Simple-switch* ($p = 0.0006$) and to *Improved-switch* ($p = 0.0006$). No significant difference was found between *Simple-switch* and *Improved-switch* ($p = 0.3985$) (see Figure 2.4).

For *Warning numbers*, a significant effect was found [$F(3, 54) = 28.59, p <$

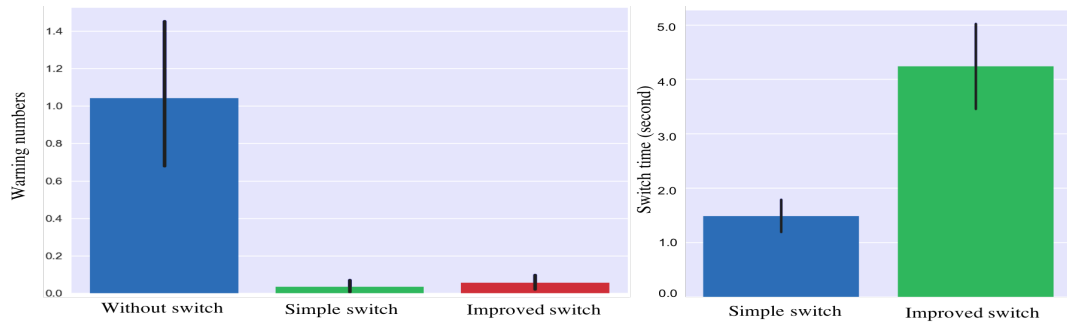


Figure 2.5 – Bar plots for *warning numbers* (left) and *switch time* (right)

0.0001] with *Without-switch* ($Mean = 1.04, SD = 0.88$), *Simple-switch* ($Mean = 0.03, SD = 0.07$) and *Improved-switch* ($Mean = 0.05, SD = 0.09$). Wilcoxon Signed Rank test with Bonferroni correction indicated that more warning signs were triggered for *Without-switch* than for *Simple-switch* ($p = 0.0013$) and *Improved-switch* ($p = 0.0013$). No significant difference was found between *Simple-switch* and *Improved-switch* ($p = 0.9519$) (see Figure 2.5).

For *switch time*, a Wilcoxon Signed Rank test with Bonferroni correction revealed that, compared to *Simple-switch* ($Mean = 1.48, SD = 0.65$), *Improved-switch* ($Mean = 4.24, SD = 1.73$) increased significantly the time used for achieving the switch ($p = 0.0006$) (see Figure 2.5).

For *reaction time*, *Simple-switch* ($Mean = 3.63, SD = 0.82$) required the user more time to find the previously seen box compared to *Improved-switch* ($Mean = 3.30, SD = 0.93$). Nevertheless, the difference was not significant according to a Wilcoxon Signed Rank test with Bonferroni correction ($p = 0.3990$). (see Figure 2.6).

For *head rotation*, *Simple-switch* ($Mean = 264.84, SD = 108.78$) led more head movement compared to *Improved-switch* ($Mean = 207.94, SD = 119.40$). However, the difference was not significant ($p = 0.5103$) in a Wilcoxon Signed Rank test with Bonferroni correction (see Figure 2.6).

For the presence questionnaire, Friedman test revealed no significant effect of the three techniques [$F(3, 54) = 5.22, p = 0.073$] (see Figure 2.7).

For the overall survey, Figure 2.8 illustrates the result of participants' subjective perception in terms of usability, disorientation, and preference. At a global level, *Without-switch* was more mentally demanding and more physically demanding compared to with switch conditions. It was less preferred by the users. And users perceived more disoriented, more frustrated, and less successful under this condition. See Table 2.1. A Wilcoxon Signed Rank test with Bonferroni correction revealed that *Improved-switch* was more mentally demanding ($p = 0.0138$) but less

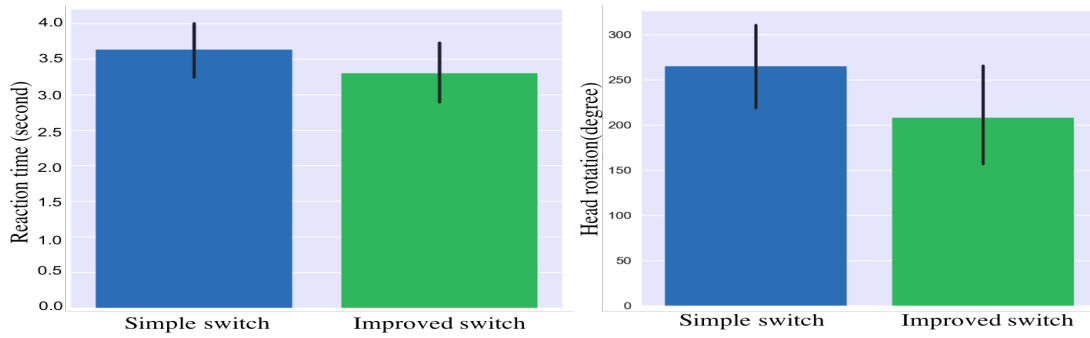


Figure 2.6 – Bar plots for *reaction time*(left) and *head rotation*(right)

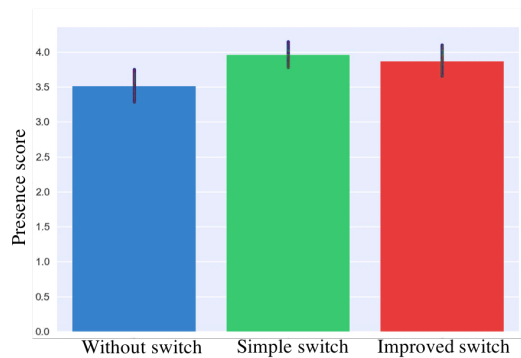


Figure 2.7 – Bar plots for *presence score*.

physical demanding ($p = 0.0078$) compared to the *Simple-switch*. Users felt less frustrated with *Simple-switch* ($p = 0.0243$) and it was more favorite by participants ($p = 0.0138$) compared to the *Improved-switch*. No significant differences were revealed regarding the degree of user disorientation and task success for these two techniques.

2.4 Discussion

The results provide evidence that the recovery of spatial consistency leads to higher task performance in terms of virtual objects accessibility. In addition, the additional visual feedback during the recovery process appears to provide the user with a better understanding of their future spatial configuration.

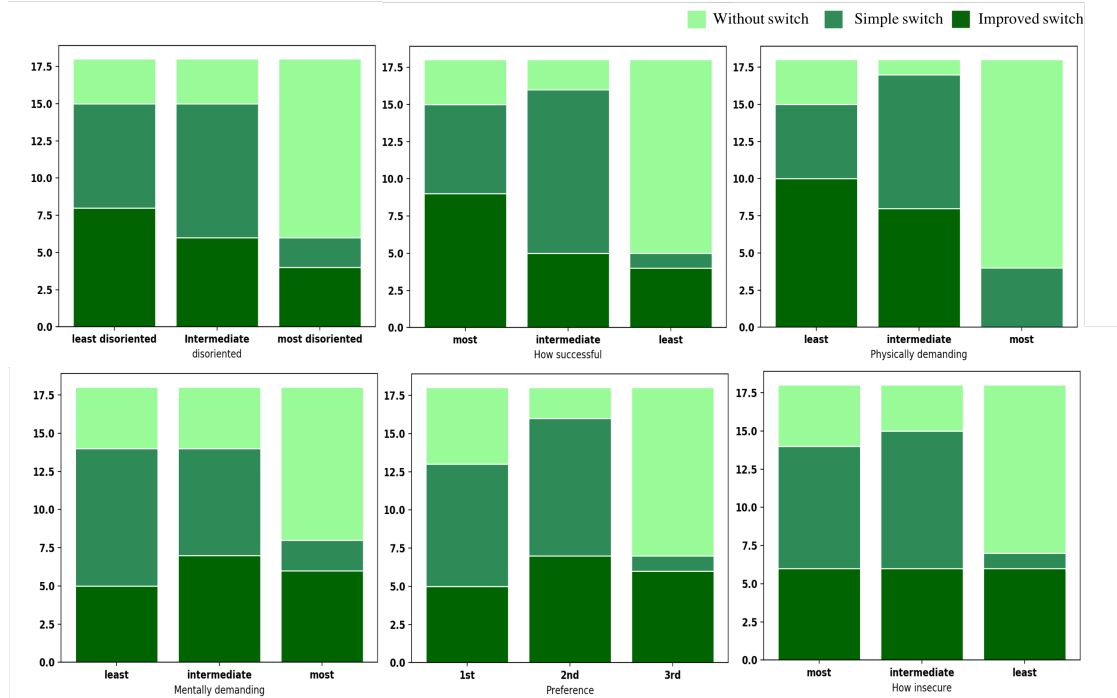


Figure 2.8 – Stacked percentage bar plot for subjective questionnaire result

	Without-switch vs. Simple-switch	Without-switch vs. Improved-switch
Mentally demanding	Avg.1.66 vs. Avg.2.39 P=0.0007	Avg.1.66 vs. Avg. 1.94 P=0.025
Physically demanding	Avg.1.38 vs. Avg.2.05 P=0.0013	Avg.1.38 vs. Avg.2.55 P=0.0004
Disoriented	Avg.1.66 vs. Avg.2.39 P=0.0004	Avg.1.66 vs. Avg.1.94 P=0.0017
How frustrated	Avg.1.61 vs. Avg.2.39 P=0.00046	Avg.1.61 vs. Avg.2 P=0.0081
How successful	Avg.1.44 vs. Avg.2.28 P=0.0002	Avg.1.44 vs. Avg.2.28 P=0.0024
User preference	Avg.1.5 vs. Avg.2.28 P=0.0007	Avg. 1.5 vs. Avg.2.22 P=0.0253

Table 2.1 – Wilcoxon Signed Rank test results for the overall survey.

With-switch compared to Without-switch

In general, participants had better performances when using the two switch techniques to complete the box-opening task. The recovered spatial consistency ensures the user access to the virtual objects they need to complete the task. As a result, both switch conditions reduced the task completion time, the manipulation number, and the number of the warnings triggered. This confirmed **H1**. Besides, compared to the two with-switch conditions, *Without-switch* was expressed as more mentally and physically demanding in subjective assessments.

With basic teleportation, i.e., the *Without-switch* condition, the user can easily trigger warning signs in some situations. Particularly, with no virtual obstacle in front of the user, they may still try to move forward in the virtual environment even

though the edge of the physical workspace was approaching, which may trigger a warning. Therefore, more teleportation and time are needed to get the user to a safe position and corrected the distance gap between them and the target virtual object. The two with-switch approaches help the user to maintain a one-to-one position mapping in an appropriate area, covering the virtual objects needed to complete the task. Users can walk within this area without worrying about reaching the limits of a real workspace. As a result, users can focus on their tasks and avoid being distracted by sudden warning signs.

Simple-switch compared to Improved-switch

The *Improved-switch* seems to provide the user with a better estimation of arrival destination and enhance their spatial awareness. With the additional visual feedback of the arrival destination, the user can anticipate the resulting spatial configuration of switch. Observing the spatial relationship between the user's future destination and the virtual surroundings allows them to have more accurate planning for the following task, thus quickly finding the target object after jumping into the interactive area. As a result, users reported the *Improved-switch* as less physically demanding. Users also used less *reaction time* and less *head rotation* to find the target object with *Improved-switch*, although the differences were not significant compared to *Simple-switch*.

The sensation of disorientation perceived by the user had no significant difference between the two techniques, which contradicts what I expected in **H2**. This may be explained by the fact that using the U-shape box setup provides the user with an additional indication of the arrival destination, reducing the difference in disorientation between the two techniques. The U-shape box setup is designed for using the maximum EVE system. However, it also offers the user with an additional indication of the arrival destination in the *Simple-switch* condition.

Significant less *switch time* was used for *Simple-switch* than for *Improved-switch*, which validates **H3**. *Simple-switch* can help the user recover the spatial consistency quickly and straightforwardly. The user can achieve the transition by pointing the virtual ray at a desired interactive area and activating the switch. This confirmed the fact that users considered the *Simple-switch* as the least mentally demanding, and most of them preferred *Simple-switch* than *Improved-switch*. Although the missing arrival destination increased the time used for users to re-orient themselves to the target object, *Simple-switch* still resulted in the least task completion time among the three techniques. Since, with *Improved-switch*, users spent more time observing and thinking about the spatial relationship between the arrival destination and the nearby virtual contents.

2.5 Conclusion

In this chapter, I focus on the design of recovery techniques to help the user recover a one-to-one mapping between the real and virtual worlds after individual teleportation. The user is allowed to navigate in a large-scale virtual environment and recover the spatial consistency in some areas previously defined by the application designers. The restored spatial consistency allows the user to access the virtual objects required to complete tasks by physically walking.

Two different methods are proposed to achieve such transition: *Simple-switch* and *Improved-switch*. The former allows the user to quickly restore spatial consistency through two steps: selection and activation. The latter has additional visual feedback of user arrival destination, dedicated to enhancing user spatial awareness and planning accuracy. Both techniques are suitable for VR systems with predetermined shapes and sizes, such as CAVE-like systems.

A user study was conducted to evaluate these two techniques and compared them to a baseline condition in which the user uses basic teleportation. The results suggested that, compared to the basic teleportation condition, recovering spatial consistency led to higher task performance. When comparing the two recovery techniques, *Simple-switch* was faster than *Improved-switch* and *Improved-switch* seems to provide the user with a better understanding of the resulting spatial configuration.

However, the use of the U-shape box set up in this experiment also gives the user an additional indication of the arrival destination. After several attempts, the user may realize that they will be teleported somewhere inside the U-shape setup, and the lack of precise indication of the teleportation destination does not seem to affect the user's spatial awareness. Therefore, it would be interesting to use some more generic virtual environment configurations to further evaluate whether it is necessary to indicate arrival designation to the user during the spatial consistency recovery process.

Furthermore, these techniques are designed for the teleportation metaphor, as the user will be moved directly to the corresponding destination to recover spatial consistency. However, such an immediate transition may not suit for other navigation metaphors, such as steering technique, considering its principles and characteristics. Therefore, additional adjustments might be needed when applying spatial consistency recovery to other navigation metaphors.

Apart from these issues, the main limitation of these two recovery techniques is that the areas where the user can recover spatial consistency are defined in advance by the application designer. This requires prior knowledge of the shape and size of the user physical workspace during the application design process. However, in a real VR walkthrough, these values are usually unknown to the application de-

signer. For example, for most head-mounted devices (HMDs), the shape and size of the user physical workspace can only be determined at the time of the system setup. Therefore, it is crucial to propose a more generic consistency recovery solution where these areas can be correctly defined in a virtual environment without knowing these values. To address these issues, the next chapter will describe the design and considerations of two techniques that can define spatial consistency areas in a virtual environment to meet task requirements. These techniques do not rely on prior knowledge of the shape and size of the user physical workspace and can be applied to a wider range of VR systems.

Positioning Spatial Consistency Areas in VE

3

This chapter presents two generic solutions for positioning the virtual workspace in the virtual environment to recover the one-to-one position mapping between real and virtual worlds. These techniques have been designed for teleportation metaphor, but do not rely on a specific virtual environment design or prior knowledge of the shape and size of the user’s physical workspace, and can therefore be applied to many VR applications and systems. I first detail the design and implementation of these techniques. Then, I describe two experiments that I carried out with an HMD setup to evaluate these two methods with different layouts of the virtual environment.

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3.1 Introduction

Depending on the shape and size of the user’s physical workspace and the requirements of the task, the application designer can define some specific areas in the virtual environment (VE) and allow the user to select one of those areas to recover spatial consistency, as proposed in Chapter 2. However, in many deployments of VR, the shape and size of the user real workspace are diverse, and it is difficult for the application designer to know these values in advance during the application design phase. For example, the user’s physical workspace is usually configured during the system setup process for most head-mounted devices (HMDs). As a result, these methods are difficult to apply to most VR systems and meet the application requirements for daily use.

This chapter is based on work published at VRST 2020 (see Publications (b)). In this chapter, I focus on some generic consistency recovery methods to address these issues. I use a 3D volume to represent the user’s physical workspace in the virtual environment, where the spatial consistency can be recovered. I propose two interactive solutions to position this virtual workspace in the virtual environment, namely manual positioning and automatic positioning techniques. The former allows the user to adjust the position and orientation of the future virtual workspace manually. The latter automatically generates a series of possible virtual workspaces considering the layout of the virtual objects in the VE by using a clustering technique. The user can therefore select their future virtual workspace among the relevant options proposed by the system.

This chapter consists of two parts. I first summarize conceptual details about the two positioning techniques. I then describe two experiments I conducted to evaluate these positioning techniques. In the first experiment, I assessed three manual positioning techniques and selected the most appropriate one. In the second experiment, I compared the selected manual positioning and the automatic positioning technique to basic teleportation. I evaluated user performance considering the different techniques and various virtual objects layout in the VE. From the results, I derived some usability guidelines for such virtual workspace positioning techniques.

3.2 Virtual Workspace Positioning Techniques

Interacting with a pre-defined volume is quite common in VR. A 3D volume can be used for multiple-object selection (MOS) by enclosing several targeted objects simultaneously [73, 101]. The user can manipulate this volume to select distant objects using manipulation techniques such as the go-go technique [73]. Inspired by volume-based selection techniques, my approaches deploy a 3D volume with

the same shape and size as the user's physical/real workspace (in this case, the tracking area of the system) to represent the user's future virtual workspace in the VE.

By positioning the virtual workspace in the VE, the user is provided with an intuitive tool to define an area in the VE to recover spatial consistency. In addition, such virtual representation can be considered as volume-based selection tools, allowing the user to select the multiple virtual objects they want to access later by natural gestures and walking. Here, I propose and evaluate two categories of techniques for positioning the virtual workspace in the VE: three manual techniques and an automatic one.

3.2.1 Manual Techniques

Manual Techniques allow the user to position their future virtual workspace in the VE. I extended the ray casting technique [80] to allow the user to control the position and orientation of the virtual workspace to customize spatial consistency areas.

In my first manual technique, the 3D volume of the future virtual workspace appears when the user presses the touch pad of the HTC Vive controller (see Section 1.1.1). The intersection point between the virtual ray and the virtual ground determines the future position of this virtual workspace. The user can rotate the volume around its vertical axis (see Figure 3.1(a)) by sliding the finger in a circle on the touch pad with a one-to-one mapping. The objects fully or partially enclosed by the volume are highlighted with a more intense color to help the user better positioning the future virtual workspace regarding the requirements of the subsequent tasks. The user can release the touch pad to end the manipulation, and then they will be teleported into the newly specified virtual workspace that correctly match their real workspace.

To enhance the spatial awareness [21], I propose two other techniques, which add additional visual information to the virtual workspace representation. Different from my previous study where I used a 3D arrow and a semi-transparent cylinder to present the future position of the user (see Chapter 2), I use a preview avatar showing directly how the user will land after the teleportation. This avatar is a ghost representation of the user at their future position and orientation, which helps them to get self-related information and deepen their understanding of the spatial configuration after the teleportation. The user can consider three factors for this anticipation: a virtual self, its positioning in the future virtual workspace, and the virtual surroundings. In previous studies, similar types of avatars have been used to display the user's future position for teleportation [118, 111, 110].

These techniques differ in their rotation axis position. One technique uses an exocentric manipulation by rotating the 3D volume and the avatar around

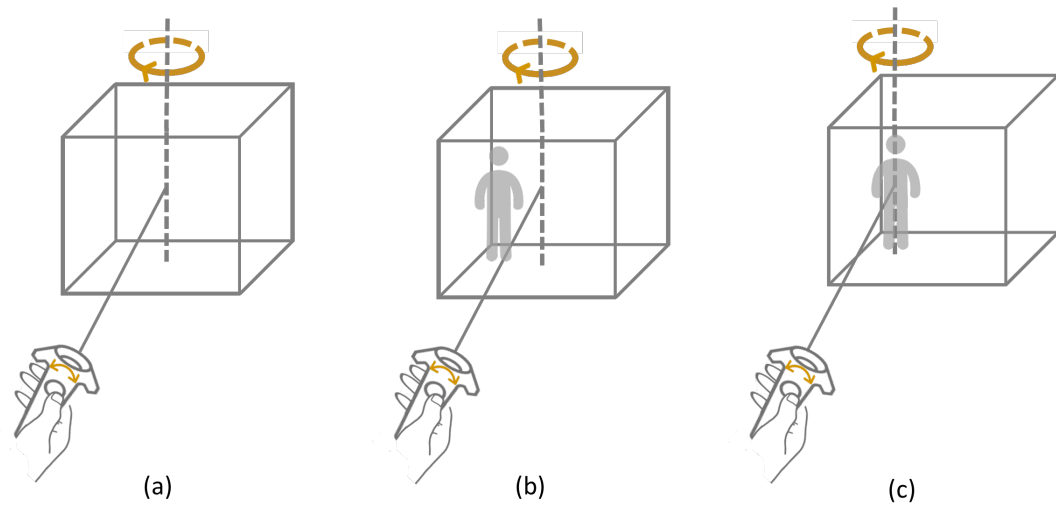


Figure 3.1 – Three manual positioning techniques: the user (a) rotates the volume around its central vertical axis; (b) rotates the 3D volume showing an avatar around the central axis; (c) rotates the 3D volume around the avatar’s vertical axis.

the volume’s central vertical axis (see Figure 3.1(b)). The exocentric information can help people to see global trends [13] and enhances the size judgment [76]. The other technique uses an egocentric manipulation by rotating the 3D volume around the avatar’s vertical axis (see Figure 3.1(c)). The egocentric cues can help people to gather the self-related information and result in more accurate distance estimation [72].

To compare these three manual techniques, I conducted a controlled experiment (see Section 3.3.1).

3.2.2 Automatic Technique

In many VR applications, the virtual objects that the user can directly interact with are usually pre-defined in the scenarios. Based on the layout of these objects and considering the user’s actual real workspace, the system can compute possible virtual workspaces and propose them to the user. The user can then select their future virtual workspace among relevant options depending on the task requirements. My approach to compute a set of suitable virtual workspaces is to: (i) organize objects into clusters by grouping or splitting them; (ii) compute bounding volumes for each cluster; and (iii) repeats the above steps until the size of the bounding volume and the size of the user real workspace become equivalent.

In the first step of the approach, bottom-up or top-down algorithms can be used

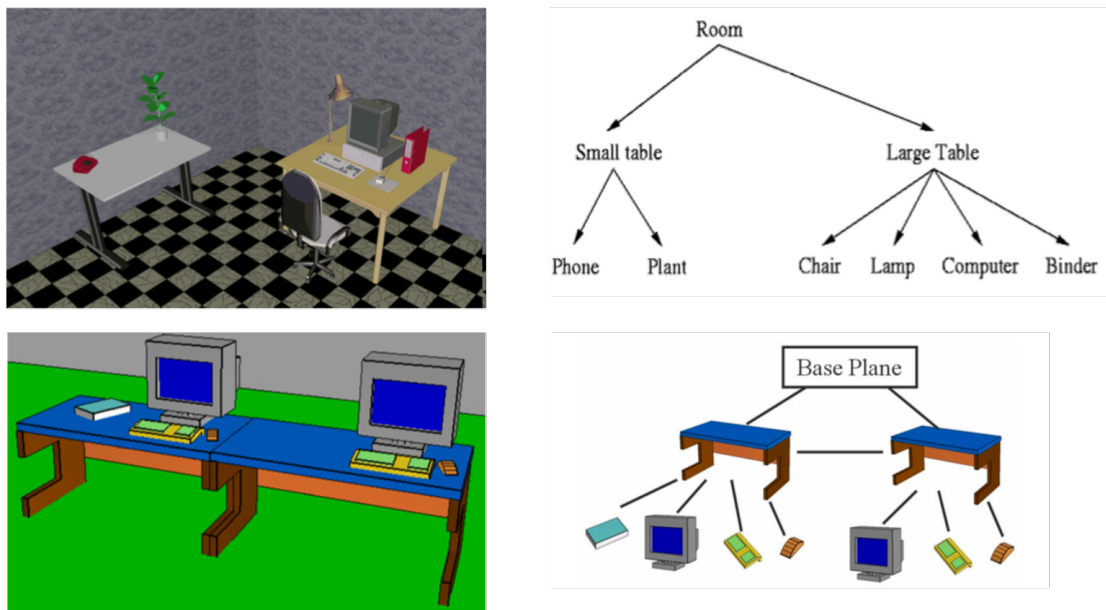


Figure 3.2 – **Top**: a Scene with its associated Scene Graph. **Below**: a scene with its associated Contact Graph.

to cluster virtual objects. The bottom-up algorithms treat each virtual object as a singleton cluster at the beginning, and then successively merge pairs of clusters until the user's real workspace can no longer enclose the bounding volume of a cluster. The top-down algorithms start with a cluster that includes all virtual objects and split the cluster recursively until each sub-cluster is smaller than the user's real workspace.

Different criteria can be applied to organize objects into a cluster. For example, K-means is a fast and straightforward heuristic to group pairs of clusters based on their nearest mean [66]. Beyond those geometrical approaches, one can also use semantic knowledge about the scene to align objects of the same kind [91, 102]. The relationships between objects can be pre-defined and stored in a library called scene graphs. All the descendants of an object in the scene graph can be considered as a group (see Figure 3.2 top). Some other grouping techniques do not require semantic or specified information to work. Instead, objects are clustered via a gravitational hierarchy [81]. This can be achieved by using a collision detector to build a contact graph of a scene (see Figure 3.2 below).

As a first prototype, I implemented a simple top-down algorithm (see Algorithm 1) to compute the possible virtual workspace positions in sublinear time. It uses K-means (with $k=2$) to split the inputting objects (ObjList) into disjoint subsets based on their 2D positions (x, z), and generates a bounding volume around

each subset using axis-aligned bounding box (AABB) approach [51]. The recursive splitting creates a binary tree, and processes until a subset either contains only one virtual object, or its bounding volumes can be encapsulated in a 3D volume having the size of the user's real workspace (UsrRWS). By traversing the binary tree, the algorithm creates and returns a list of bounding volume positions from the leaf nodes. Based on this list, the system can subsequently instantiate 3D volumes at each bounding volume position to represent the possible virtual workspaces.

Algorithm 1 Positioning of Possible Virtual Workspaces

Input: *ObjList*, *UsrRWS*
Output: *PosList*

```

1: procedure TOPDOWN(ObjList, UsrRWS)
2:    $N \leftarrow \text{ObjList.length}$ 
3:   if  $N = 1$  then
4:     PosList.Add(AABB(ObjList).position)
5:     return PosList
6:   else
7:      $bbox \leftarrow \text{AABB}(\text{ObjList})$ 
8:     if  $\neg \text{EncapTest}(bbox, \text{UserRealWS})$  then
9:        $lN, rN \leftarrow \text{Kmeans}(\text{ObjList}, 2)$ 
10:      PosList.append(TOPDOWN(lN, UsrRWS))
11:      PosList.append(TOPDOWN(rN, UsrRWS))
12:     else
13:       return PosList

```

In the example of Figure 3.3, my algorithm provides five virtual workspaces for a given configuration of the VE and a $3\text{m} \times 3\text{m}$ user's real workspace. This algorithm is a first implementation to test the related interaction technique and user acceptability of an automatic technique. It can be improved later by considering arbitrary-oriented bounding boxes (OBB) or other clustering methods.

The proposed virtual workspaces are normally invisible to the user. As soon as the user's virtual ray collides with a possible virtual workspace, it is displayed along with an avatar indicating the user's future destination (see Figure 3.4(a)). When the user walks into an overlapping area between multiple possible virtual workspaces, the system allows the user to switch directly from their current virtual workspace to one of the connected workspaces by showing their related avatars (see Figure 3.4(b)). The user can then select a new workspace by pointing the virtual ray to its associated avatar (see Figure 3.4(c)). The virtual objects enclosed inside the selected workspace are highlighted with a more intense color. Thus, the user can refer to the color change to select the appropriate workspace regarding the virtual objects needed for subsequent tasks.

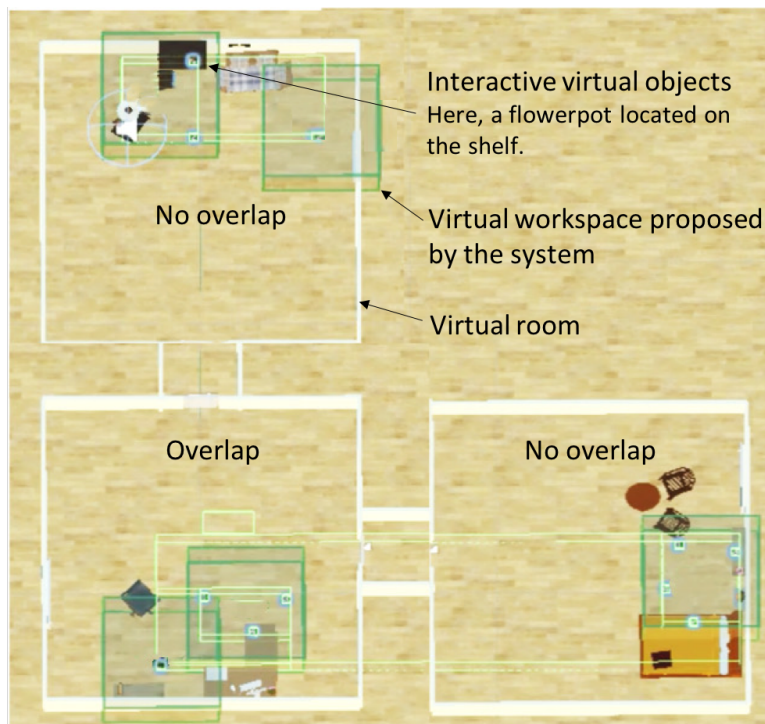


Figure 3.3 – Results of the positioning algorithm: five virtual workspaces (green) are proposed to the user for 12 interactive objects (light blue) located in three virtual rooms (white). Three workspaces are disjointed (no overlap rooms), and two overlap each other (overlap room).

3.3 Experiments

Two formal user studies were conducted to assess these techniques. The first study evaluated the three manual techniques and selected the most appropriate one. The second study compared the selected manual technique and the automatic technique to basic teleportation. As these user evaluations have been carried out with HMD setup, it has been possible to avoid the use of specific VE designs that would provide the user with additional indication of the teleportation destination, such as the U-box setup deployed in my previous study (see Chapter 2).

3.3.1 Experiment 1: Manual Technique Comparison

As a first step, I conducted a controlled experiment to evaluate the three manual techniques proposed in Section 3.2. I aimed to assess the benefits of including a preview avatar at the user's future destination in the virtual workspace. I also wanted to compare egocentric and exocentric manipulation techniques in terms of

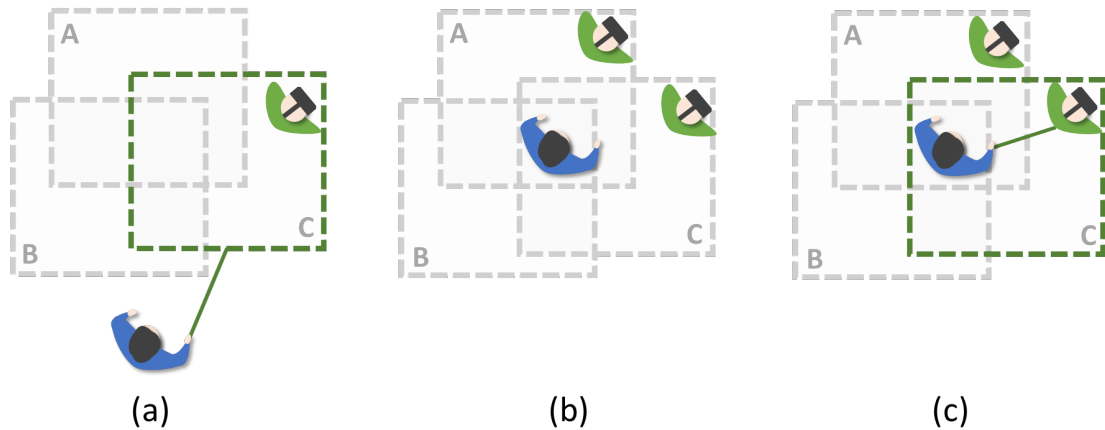


Figure 3.4 – Top view of the user (a) selects a virtual workspace among relevant options; (b) enters an overlapping area and the system displays avatars to represent the connected virtual workspaces; and (c) selects a subsequent workspace by pointing the virtual ray to its corresponding avatar.

user spatial awareness and task performance. The experiment thus compared the following TECHNIQUES (see Figure 3.5):

- *Exo-without-avatar* is an exocentric technique allowing the user to move the virtual workspace representation and to rotate it around its central axis. No preview of the user’s future position is offered.
- *Exo-with-avatar* is an exocentric technique for which the rotation axis is still at the center of the virtual workspace representation. A preview avatar is included to show the user’s future position. This avatar is a simplified human body wearing a head-mounted display.
- *Ego-with-avatar* is an egocentric technique that uses the future position of the user (i.e. the avatar position) as the rotation axis of the virtual workspace representation. The same simplified avatar is used in this condition.

I did not include an egocentric technique without the preview avatar because the rotation axis is invisible, making it difficult for the user to understand the manipulation. The experiment was a within-subject design with TECHNIQUE as a factor. The order of the TECHNIQUES was counterbalanced across participants using a balanced Latin square.

Hypothesis

I expected the conditions with the preview avatar would help the user to anticipate their next position in the virtual scene. I also assumed that *Exo-with-avatar* would

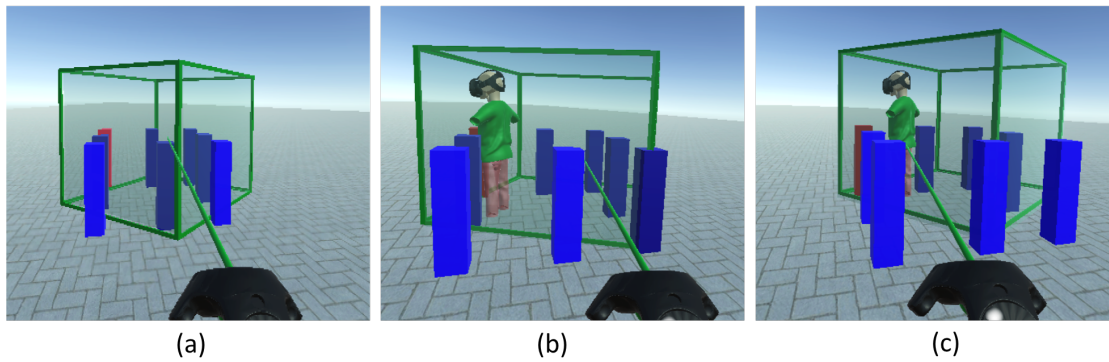


Figure 3.5 – Conditions of the first experiment: (a) *Exo-without-avatar*, (b) *Exo-with-avatar* and (c) *Ego-with-avatar*.

highlight the entire virtual workspace and would make it easier to define the spatial consistency area and enclose the targeted virtual objects. In contrast, *Ego-with-avatar* focuses on the user's future destination and would cause less disorientation. Therefore I formulated the following hypotheses:

- H1** *Exo-with-avatar* and *Ego-with-avatar* will reduce disorientation and less time will be required to find a target after the teleportation, compared to *Exo-without-avatar*.
- H2** Less time will be required for positioning the virtual workspace representation with *Exo-with-avatar* than with *Ego-with-avatar*.
- H3** Less time will be required to find a target after the teleportation with *Ego-with-avatar* than with *Exo-with-avatar*.

Participants

I recruited 12 participants, aged between 25 and 31 (6 men and 6 women). Only one person was left-handed. Three participants had VR experience. 11 out of 12 rated their everyday usage of head-mounted displays as very low.

Experiment Setup

The VR setup consisted of an HTC Vive Pro Eye with both position and orientation tracking, as well as integrated eye-tracking technology. The virtual environment was rendered using Unity with a resolution of 1440×1600 pixels per eye at 90 Hz. The experiment room supported a $3\text{m} \times 3\text{m}$ tracking area. User input was detected using a Vive handheld controller.

Experimental Task

To assess spatial awareness, existing studies [21, 111] measure the time needed for participants to reorient themselves and find objects previously seen in the virtual scene. I used a similar task to evaluate the three TECHNIQUES in terms of spatial awareness and manipulation efficiency.

Before each trial, the participant was asked to walk to a starting point presented by a green dotted circle on the floor. Then, a set of pillars were displayed, and the trial started. The pillar set consists of one red and seven blue pillars located on four sides of a $3\text{m} \times 3\text{m}$ square square (see Figure 3.5). The participant had to adjust the virtual workspace position to enclose all the pillars as if they wanted to be able to access all of them without having to perform additional teleportations.

Once all the pillars were enclosed, the participant could release the Vive controller touch pad to travel to the selected destination. Subsequently, the participant needed to touch the red pillar with the Vive controller to end the trial. Touching this previously seen red pillar was a way of assessing spatial awareness after the teleportation.

Procedure

Each participant was welcomed, received instructions on the task, and signed an informed consent form. After setting up the head-mounted display, I calibrated the eye tracker. For each TECHNIQUE, the participant first experienced training trials. Next, the participant completed 24 trials in randomized order resulting from a particular subset of the full combination of 6 starting points in the real space, 8 relative directions between the starting point and the pillar set (-135° , -90° , -45° , 0° , 45° , 90° , 135° , 180°), 3 distances between the starting point and the pillar set (4m, 6m, 8m) and 3 orientations of the pillar set (0° , 22.5° , 45°), as illustrated in Figure 3.6.

After each TECHNIQUE, the participant filled out a questionnaire. At the end of the experiment, the participant also ranked the three TECHNIQUES according to their preference. The whole experiment lasted approximately 45 minutes.

Data Collection

I registered 864 trials: 3 TECHNIQUES \times 24 repetitions \times 12 participants. For each trial, I logged the following measures:

- *Task Completion Time (TCT)*: the total duration of a trial. The measurement started when the participant arrived at the starting point and ended when the red pillar was touched.

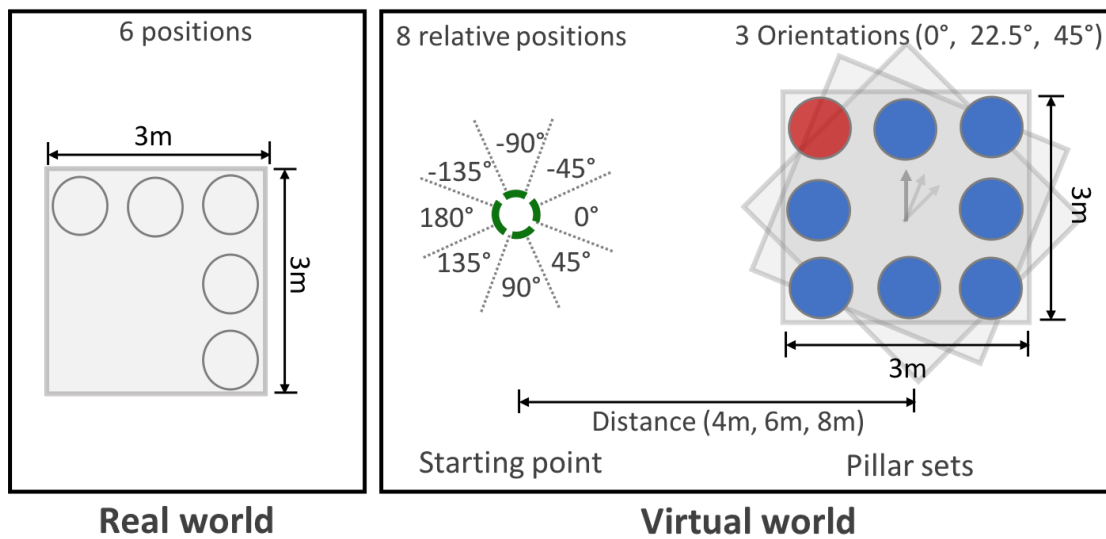


Figure 3.6 – Each starting position in the virtual scene positioned the participant at one of the 6 positions in the real space (left). The pillar set was located with 3 different orientations, in one of the 8 directions around the participant, and at one of the 3 distances from the participant (right).

- *Manipulation time*: the time used to enclose all the pillars. The measurement started when the virtual workspace representation collided with one of the pillars and ended when the participant triggered the teleportation.
- *Target identification time*: the time that the participant needed to reorient themselves to find the red pillar. The measurement started just after the teleportation, and ended when the eye gaze of the participant collided with the red pillar (measured by the eye-tracking system of the HTC Vive).

I used the NASA-TLX questionnaire [55] and also added two more questions about *anticipation* (Were you able to anticipate where you would be after teleportation?) and *disorientation* (Did you feel disoriented after teleportation?). Criteria were graded on a 21-point scale and later converted to a 100-point score.

Statistical Results

For each measure, I used normal QQ-plots and Shapiro-Wilk Tests to analyze data normality. *TCT*, *manipulation time* and *target identification time* were not normally distributed, so I applied a log-transformation to analyze them, as recommended by Robertson & Kaptein [88] (p. 316). To minimize the noise in my data, I averaged the 24 repetitions of each TECHNIQUE. I then ran a one-way ANOVA

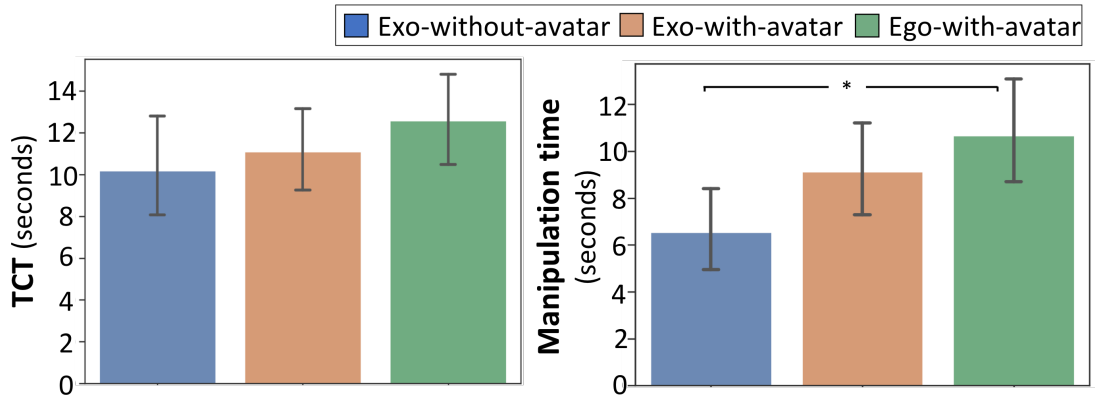


Figure 3.7 – Mean *TCT* (left) and *manipulation time* (right) by *TECHNIQUE*. Error bars show 95% confidence intervals (CI).

test and conducted post-hoc analysis with paired sample T-tests with Bonferroni corrections¹. Means (M) are reported with standard deviations.

For *TCT* (see Figure 3.7, left), I did not find a significant effect of *TECHNIQUE* ($F_{2,22} = 1.291$, $p = 0.295$), and all conditions had close mean values: *Exo-without-avatar* ($M = 10.18 \pm 4.21s$), *Exo-with-avatar* ($M = 11.09 \pm 3.43s$) and *Ego-with-avatar* ($M = 12.56 \pm 3.85s$).

For *manipulation time* (see Figure 3.7, right), I observed a significant effect of *TECHNIQUE* ($F_{2,22} = 4.683$, $p = 0.0202$). Pairwise comparisons showed that participants spent less time with *Exo-without-avatar* ($M = 6.54 \pm 3.32s$) than with *Ego-with-avatar* ($M = 10.66 \pm 4.07s$, $p = 0.0042$). No significant differences were found between *Exo-without-avatar* and *Exo-with-avatar* ($M = 10.66 \pm 4.07s$, $p = 0.132$), and between *Exo-with-avatar* and *Ego-with-avatar* ($p = 0.64$).

For *target identification time* (see Figure 3.8, left), I detected a significant effect of *TECHNIQUE* ($F_{2,22} = 17.40$, $p < 0.0001$). Pairwise comparisons showed that target identification time was significantly shorter with *Exo-with-avatar* ($M = 0.81 \pm 0.20s$, $p = 0.0021$) and *Ego-with-avatar* ($M = 0.77 \pm 0.38s$, $p = 0.0015$) than with *Exo-without-avatar* ($M = 1.79 \pm 1.06s$). No significant differences were found between *Exo-with-avatar* and *Ego-with-avatar* ($p = 0.57$).

For the subjective questionnaire, I used Friedman's tests and Wilcoxon signed-rank tests for post-hoc analysis in conformity with such non-parametric data. For cognitive load, I did not find a significant effect of *TECHNIQUE* ($\chi^2(2) = 1.721$, $p = 0.423$) on the NASA-TLX score (see Figure 3.8, right). However, I detected a significant effect of *TECHNIQUE* on *anticipation* ($\chi^2(2) = 19.19$, $p < 0.0001$) and *disorientation* ($\chi^2(2) = 21.80$, $p < 0.0001$). Post-hoc analysis showed that

¹All statistical analyses were performed with R and I used a significance level of $\alpha = 0.05$ for all tests.

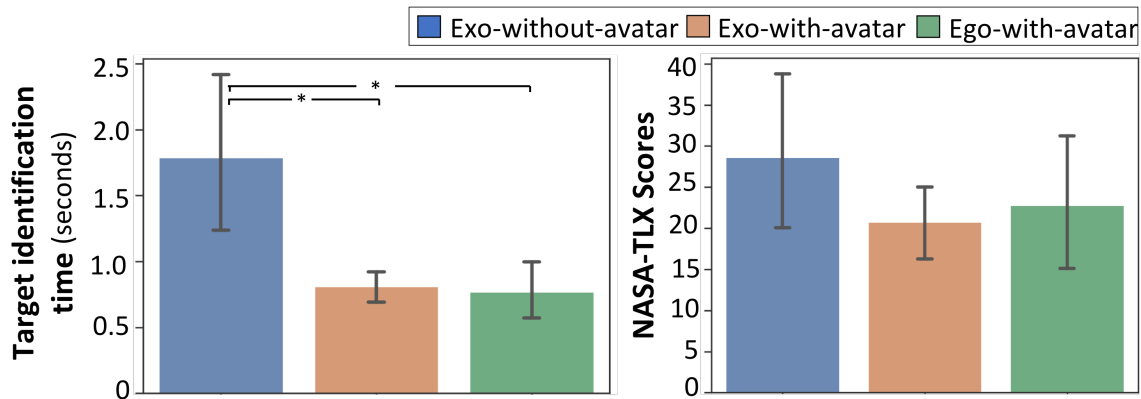


Figure 3.8 – Mean *target identification time* (left) and NASA-TLX score (right) by TECHNIQUE. Error bars show 95% CI.

Exo-with-avatar ($M = 16.67 \pm 12.67$, $p = 0.0057$) and *Ego-with-avatar* ($M = 15.00 \pm 12.06$, $p = 0.0061$) resulted in a significantly better anticipation (see Figure 3.9, left) compared to *Exo-without-avatar* ($M = 85.83 \pm 9.00$). It showed that significantly less disorientation (see Figure 3.9, right) was perceived by the participants with *Exo-with-avatar* ($M = 20.00 \pm 19.19$, $p = 0.015$) and *Ego-with-avatar* ($M = 16.08 \pm 19.08$, $p = 0.0099$) than with *Exo-without-avatar* ($M = 63.33 \pm 30.70$). In addition, 11 out of 12 participants preferred *Exo-with-avatar* and *Ego-with-avatar* over *Exo-without-avatar*, and 8 out of 12 participants ranked *Ego-with-avatar* as their favorite condition.

Discussion

Despite the non-significant difference in task completion time, I found that including a preview avatar significantly impacted manipulation time and target identification time. On the one hand, participants performed faster the manipulation task of the virtual workspace with *Exo-without-avatar* than with *Ego-with-avatar*. Manipulation with *Exo-without-avatar* also seemed slightly faster than with *Exo-with-avatar*, but the difference was not significant. On the other hand, the two conditions with avatar resulted in significantly less disorientation and thus a shorter target identification time, which supported **H1**. Even if the results could be predictable since the visual feedback directly showed where the user "land" in the VE, it was still interesting to measure its actual impact. While the user spent slightly more time on positioning the avatar, they could plan and better understand the upcoming teleportation. This reduced disorientation and the time needed to complete the task after the teleportation. In the conditions with the preview avatar, positioning the avatar increased the cognitive load but reduced the cognitive effort required to find the target. This can explain why the overall difference in cognitive load was not significant.

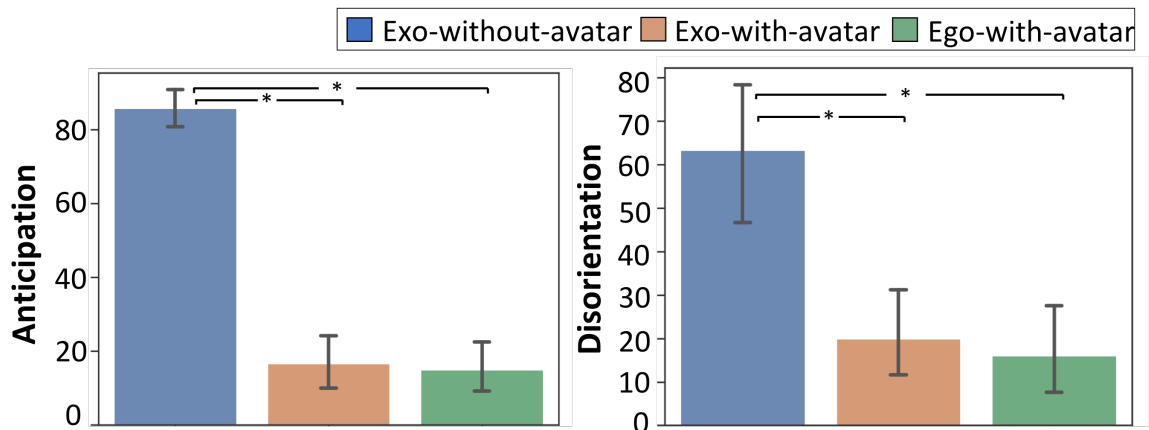


Figure 3.9 – Mean *anticipation* (left) and *disorientation* (right) score by TECHNIQUE. Error bars show 95% CI.

Contrary to my expectations, I was not able to find significant differences between exocentric and egocentric techniques in terms of user performance. For manipulation time, the difference was not significant, which did not support **H2**. For target identification time, no significant difference was found between *Exo-with-avatar* and *Ego-with-avatar*, which rejected **H3**. I also did not detect significant differences between *Exo-with-avatar* and *Ego-with-avatar* for cognitive load, anticipation and disorientation. However, participants preferred *Ego-with-avatar* to *Exo-with-avatar* according to the questionnaires. In particular, participants reported that *Ego-with-avatar* allowed them to "focus more on themselves" (P6) during the manipulation step, was "easier for positioning themselves" (P9), and was "easier for finding" (P3) the target objects after teleportation.

The two conditions with avatar seemed to reach close performance levels. However, I wanted to select one of them to compare it with the automatic positioning technique in the second experiment. Consequently, I decided to choose the *Ego-with-avatar* based on the user preferences.

3.3.2 Experiment 2: Positioning Technique Evaluation

The goal of this experiment is to compare the manual technique selected from the first experiment (i.e., *Ego-with-avatar*) and the automatic technique to a basic teleportation. I wanted to evaluate the benefits of spatial consistency recovery in terms of multi-object accessibility. In addition, I would like to compare the user task performance and subjective perception of the two positioning techniques in different layouts of virtual environments.

In this experiment, I set up a more realistic task similar to an escape room

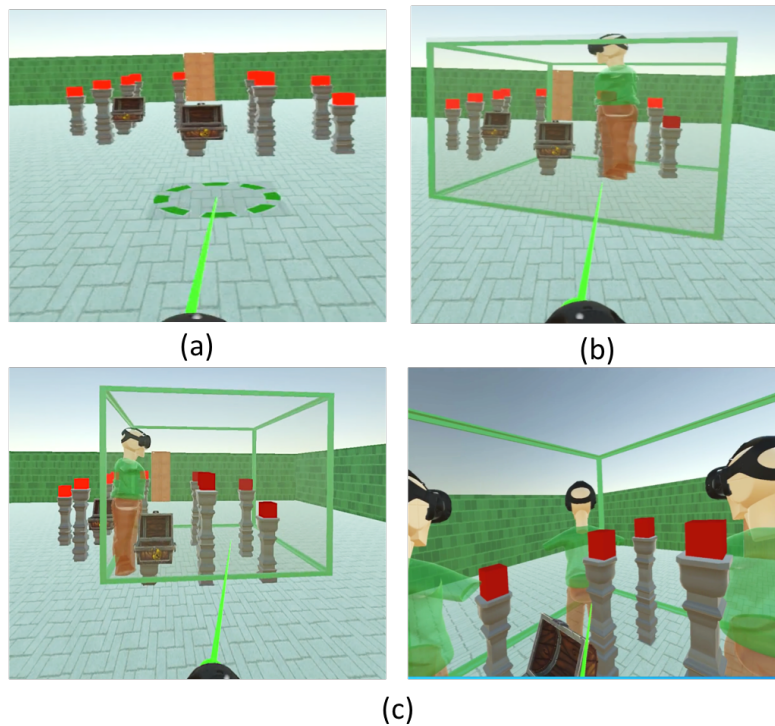


Figure 3.10 – Three conditions for TELEPORTATION: (a) *Basic* teleportation; (b) *Manual* technique allows the user to adjust their future virtual workspace’s position and orientation by manipulating its virtual representation; (c) *Automatic* technique enables the user to select their future virtual workspace among relevant options proposed by the system (left). In overlapping conditions, the user can teleport to an adjacent virtual workspace by selecting their relevant avatar (right).

game. The VE consisted of a series of virtual rooms. Participants needed to select multiple objects to escape each room and continue the exploration. They had to switch between large-scale navigation and multiple object selection tasks with different object layouts. The experiment followed a $[3 \times 2]$ within-subject design with the following factors:

- TECHNIQUE: *Basic*, *Manual* and *Automatic*,
- LAYOUT: *Overlap* and *No-overlap*.

For TELEPORTATION (see Figure 3.10), the three variations are:

- *Basic* is the basic teleportation technique used as a baseline. A virtual ray appeared when participants pressed the controller’s touch-pad. The teleportation position was determined by the collision point between the ray and

the virtual floor. It was represented by a green dotted circle. The participant activated teleportation by releasing the touch pad.

- *Manual* is the manual *Ego-with-avatar* technique described in Section 3.3.1. The participant used the virtual ray to manipulate the virtual workspace representation instead of the dotted circle used in the *Basic* technique. After determining the future workspace position and rotation, participants released the touch-pad to teleport to the pre-defined workspace. The recovered spatial consistency allowed them to reach the enclosed virtual objects by walking.
- *Automatic* is the automatic technique described in Section 3.2. The system used algorithm 1 to pre-calculate potential virtual workspaces based on the layout of objects in the VE. The participant used the virtual ray to select a virtual workspace from the relevant options. After being teleported to the desired workspace, the participant could get the desired virtual objects inside the workspace by walking.

For LAYOUT, two different object layouts were used:

- *No-overlap*: virtual objects were laid out in two separate areas. These areas are similar in size and shape to the user's real workspace and can therefore be included in the virtual workspace representation. For the *Automatic* technique, the system proposes a virtual workspace for each area.
- *Overlap*: virtual objects were spread in an area larger than the real workspace of the participants. Therefore, the required objects cannot be enclosed by a single virtual workspace representation. For the *Automatic* technique, the system proposes a set of virtual workspaces, each containing only a subset of objects.

The order of the TECHNIQUES was counter-balanced across participants using a balanced Latin square, and the order of the LAYOUT was also counter-balanced for each TECHNIQUE.

Hypothesis

In comparison to the basic teleportation, I expected that the manual and the automatic positioning techniques would allow the user to access more easily multiple objects using physical walking. As a result, the task could be completed faster and the user's sensation of presence can be enhanced. With the automatic technique, the user could select their future virtual workspace among the proposed ones and thus would be able to avoid the manipulation step required for positioning it. However, in a crowded virtual environment, i.e., with the *Overlap* layout,

a large number of suggested virtual workspaces could be confusing for the user. I, therefore, formulated the following hypotheses:

- H1** *Automatic* and *Manual* will result in better user performance, compared to the *Basic* teleportation.
- H2** *Automatic* and *Manual* will result in better sense of presence, compared to the *Basic* teleportation.
- H3** In *No-overlap*, *Automatic* will perform better than *Manual*.
- H4** In *Overlap*, *Manual* will perform better than *Automatic*.

Participants

I recruited 12 participants, aged between 25 and 32 (7 men, 5 women). 6 participants had VR experience. 8 out of 12 rated their everyday usage of head-mounted displays as very low.

Experiment Setup

The VR setup was the same as in Experiment 1 (see Section [3.3.1](#)).

Experimental Task

Participants traveled in a large virtual environment composed of nine rooms. In each room, they had to select multiple objects. Once participants completed the task in one room, they were guided to the next room via an opening door. When participants reached their real workspace limits, a warning sign appeared in their field of view with an alarm sound to ensure participants' safety.

The first room was used for the training task, and the other eight were set up for the evaluation: half with the *No-overlap* layout and half with the *Overlap* layout. The order of the two layouts could be reversed. Both types of layouts required participants to access ten target objects, grab them with the controller, and bring them back to one of two treasure boxes one by one (see Figure [5.6](#)).

With the *No-overlap* layout, the objects and the treasure boxes were located within two disjointed $3\text{m} \times 3\text{m}$ areas. Each area contained five targets and one treasure box located randomly on 6 of 9 positions. With the *Overlap* layout, the objects and the treasure boxes were placed randomly on 12 of 25 positions located in a single $5\text{m} \times 5\text{m}$ area. In *Automatic* condition of this layout, the algorithm computed four overlapping virtual workspace positions to cover the full area.

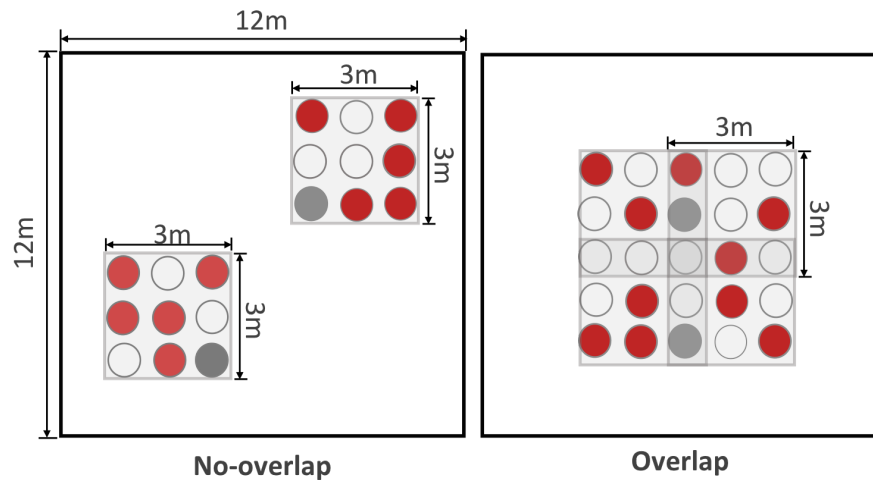


Figure 3.11 – Two object layouts were used: (left) *No-overlap* in which objects (red) and treasure boxes (gray) were randomly located in two disjointed $3\text{m} \times 3\text{m}$ areas; and (right) *Overlap* in which objects (red) and treasure boxes (gray) were randomly placed in a single $5\text{m} \times 5\text{m}$ area. The light gray rectangles represent the virtual workspaces computed in the *Automatic* condition.

Procedure

Each participant was welcomed, received instructions on the task, and signed an informed consent form. For each TECHNIQUE, the participant first completed the training task with eight targets and two treasure boxes located inside four $3\text{m} \times 3\text{m}$ areas (three overlapped and one not-overlapped). During this step, the experimenter was allowed to answer their questions, if any. Next, the participant completed eight trials (4 with *No-overlap* and 4 with *Overlap*, or vice versa).

After each TECHNIQUE, they filled out an Igroup Presence Questionnaire (IPQ) [86, 94] to measure the sense of presence and two NASA-TLX questionnaires [55] to assess the cognitive load of each LAYOUT. I used the color of the rooms to help the participant to differentiate the two LAYOUTS. The main color of *No-overlap* layout was blue, and the main color of *Overlap* layout was green. At the end of the experiment, the participant also ranked the three techniques according to their preference. The whole experiment lasted around 60 min.

Data Collection

I registered 288 trials: 3 TECHNIQUES \times 2 LAYOUTS \times 4 repetitions \times 12 participants. For each trial, I collected the following measures:

- *Task Completion Time (TCT)*: the total duration of a trial. The measure-

ment started when the participant entered a room and ended when all objects were put in the treasure boxes.

- *Warnings*: the number of times the participant triggered the warning sign.
- *Teleportations*: the number of teleportations performed.

Each question of the NASA-TLX was graded on a 21-point scale and converted to a 100-point score. Each question of the IPQ was graded on a 7-point Likert scale (from 0 to 6).

Statistical Results

To minimize the noise in my data, I averaged the 4 repetitions of each TECHNIQUE \times LAYOUT. Means (M) are reported with standard deviations.

For *TCT*, I used normal QQ-plots and Shapiro-Wilk Tests to analyze data normality. The data was not normally distributed, so I applied a log-transformation to analyze it following statistical recommendations [88]. A two-way repeated measures ANOVA with the model TECHNIQUE \times LAYOUT revealed a significant effect of TECHNIQUE ($F_{2,22} = 11.08$, $p = 0.0005$) and interaction effect ($F_{2,22} = 4.79$, $p = 0.019$), but no significant effect of LAYOUT ($F_{1,11} = 2.13$, $p = 0.17$) was found. For TECHNIQUE, post-hoc Tukey HSD tests indicated that performing the task with *Manual* ($M = 45.70 \pm 9.65s$, $p = 0.0019$) and *Automatic* ($M = 45.40 \pm 9.46s$, $p = 0.0011$) was significant faster than with *Basic* ($M = 61.70 \pm 20.19s$) For TECHNIQUE \times LAYOUT (see Figure 3.12, left), post-hoc Tukey HSD tests shown the task with the *No-overlap* layout was significant faster to achieve with *Manual* ($M = 43.75 \pm 10.63s$, $p = 0.0005$) and *Automatic* ($M = 39.80 \pm 8.75s$, $p < 0.0001$) than with *Basic* ($M = 64.02 \pm 20.60s$). For the task with the *Overlap* layout, *Basic* ($M = 58.99 \pm 19.23s$) was significantly different from *Manual* ($M = 46.97 \pm 10.86s$, $p = 0.044$), but not from *Automatic* ($M = 49.87 \pm 13.75s$, $p = 0.17$). In all cases, no significant differences were found between *Manual* and *Automatic*.

For *Warnings*, I used non-parametric tests in conformity with the nature of count data. I first aggregated the data by TECHNIQUE and a Friedman test revealed a significant effect of TECHNIQUE ($\chi^2(2) = 11.51$, $p = 0.0032$). Wilcoxon Signed Rank tests² shown that participants triggered significantly more *Warnings* with *Basic* ($M = 3.38 \pm 3.32$) than with *Manual* ($M = 1.50 \pm 1.11$, $p = 0.041$) and *Automatic* ($M = 0.90 \pm 0.67$, $p = 0.034$). No significant differences were found between *Manual* and *Automatic*. I then split the data by LAYOUT and ran a Friedman test for each LAYOUT (see Figure 3.12, right). For *No-overlap*, it indicated a significant effect of TECHNIQUE ($\chi^2(2) = 14.28$, $p = 0.0008$). Wilcoxon Signed

²In this experiment, all Wilcoxon Signed Rank tests were performed with Holm-Bonferroni corrections.

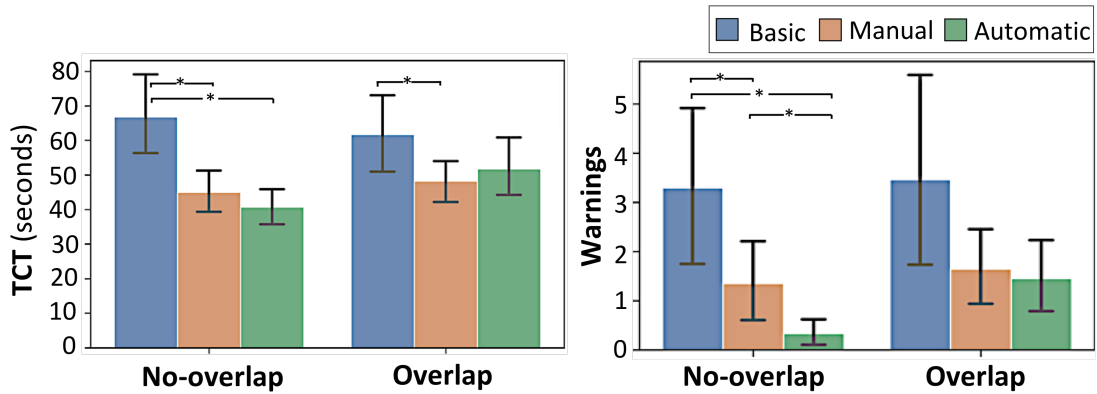


Figure 3.12 – Mean *TCT* (left) and *warnings* (right) by TECHNIQUE \times LAYOUT. Error bars show 95% CI.

Rank tests shown that participants triggered significant more *Warnings* for the *No-overlap* layout with *Basic* ($M = 3.29 \pm 2.91$) than with *Manual* ($M = 1.35 \pm 1.41$, $p = 0.029$) and *Automatic* ($M = 0.33 \pm 0.44$, $p = 0.011$). *Manual* was also significantly different than *Automatic* ($p = 0.032$) for *No-overlap*. For *Overlap*, no significant effect of TECHNIQUE was found ($\chi^2(2) = 4.95$, $p = 0.084$).

For *Teleportations*, I also used non-parametric tests. I first aggregated the data by TECHNIQUE and a Friedman test revealed a significant effect of TECHNIQUE ($\chi^2(2) = 19.50$, $p < 0.0001$). Wilcoxon Signed Rank tests showed that participants teleported significantly more with *Basic* ($M = 19.00 \pm 17.49$) than with *Manual* ($M = 3.00 \pm 0.85$, $p = 0.0050$) and *Automatic* ($M = 3.53 \pm 0.90$, $p = 0.0015$). No significant difference was found between *Manual* and *Automatic*. I then split the data by LAYOUT and ran a Friedman test for each LAYOUT (see Figure 3.13). For both LAYOUTS, I had similar results to that of the aggregated data, pointing out that there was probably no interaction effect of TECHNIQUE \times LAYOUT.

For the NASA-TLX questionnaires, I aggregated the data by TECHNIQUE and did not detect a significant effect of TECHNIQUE ($\chi^2(2) = 2.426$, $p = 0.2974$). I also aggregated the data by LAYOUT and observed that the *Overlap* layout ($M = 42.22 \pm 21.72$) induced a significantly higher cognitive load than the *No-overlap* layout ($M = 38.75 \pm 19.76$, $p = 0.0050$). Further analysis on the data split by LAYOUT revealed that a significant higher cognitive load was required with *Automatic* ($M = 32.98 \pm 18.76$) than with *Manual* ($M = 28.96 \pm 17.95$, $p = 0.031$) for the *Overlap* layout.

For the IPQ questionnaire (see Figure 3.14), a Friedman test revealed a significant effect of TECHNIQUE ($\chi^2(2) = 19.63$, $p < 0.0001$). Wilcoxon Signed Rank tests reported a significantly better presence with *Manual* ($M = 3.89 \pm 0.47$, $p = 0.0025$) and *Automatic* ($M = 4.80 \pm 0.53$, $p = 0.0025$) than with *Basic* ($M = 4.75 \pm 0.69$).

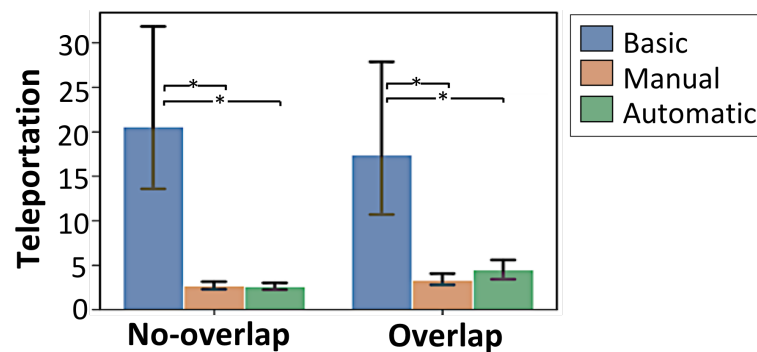


Figure 3.13 – Mean *Teleportations* by TECHNIQUE × LAYOUT. Error bars show 95% CI.

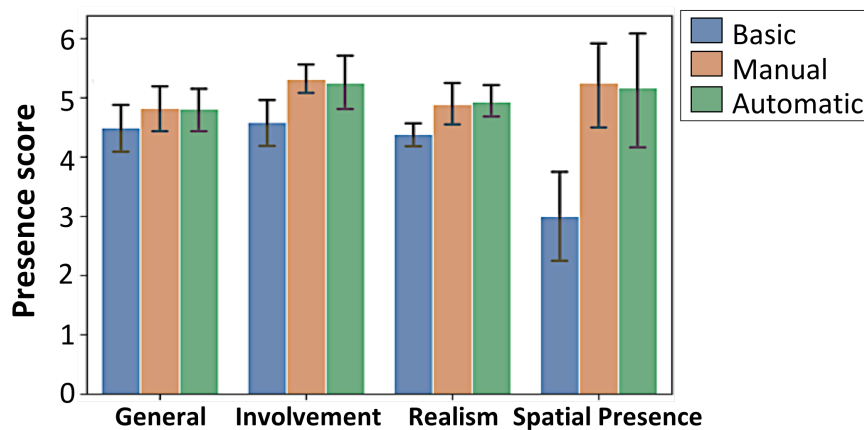


Figure 3.14 – Results from the IPQ questionnaire by TECHNIQUE × LAYOUT. Error bars show 95% CI.

Finally, 11 out of 12 participants preferred *Manual* and *Automatic* for both tasks over the *Basic* condition. For the *No-overlap* layout, 6 out of 12 participants ranked *Automatic* as their favorite, and 5 participants preferred *Manual*. For the *Overlap* layout, 6 out of 12 participants preferred *Manual*, and 5 participants preferred *Automatic*.

Discussion

The results provide evidence that the *Manual* and *Automatic* techniques outperformed the *Basic* teleportation. In particular, participants completed the task significantly faster when they were able to recover spatial consistency within the selected area compared to the *Basic* teleportation. This supports **H1**. It can be

explained by the fact that the recovered spatial consistency allowed participants to easily reach multiple virtual objects by physically walking, avoiding unnecessary teleportations. It is also confirmed by the significantly smaller number of teleportations executed with *Manual* and *Automatic* compared to *Basic*.

In addition to a better performance, the *Manual* and *Automatic* techniques also resulted in higher sense of presence compared to the *Basic* teleportation, according to the IPQ questionnaire. This supports **H2**. Basic teleportation usually neglects the user's real surrounding workspace, and the user gets warnings only when they approach the tracking space limits. With *Basic* teleportation, since the user "cannot imagine the accessible area" (P3) and "cannot determine if an object is accessible" (P7), a larger number of warnings were triggered while performing the task, compared to *Manual* and *Automatic*. Excessive warnings often lead the user to distrust the VR system and break the immersion. For example, participants "feel fear" (P4) and were "afraid to move" (P5) with *Basic* teleportation. The fact that the user performs a more significant number of teleportations and walks less with the *Basic* teleportation is also detrimental to their immersion.

For the task with the *No-overlap* layout, no significant differences in *TCT* were found between *Manual* and *Automatic*, which does not support **H3**. However, significantly more warnings were detected with *Manual* condition than with *Automatic*. The *Manual* technique requires the user to position the virtual workspace manually, and they may sometimes make mistakes. For example, the user-defined future workspace cannot include all the virtual objects needed or make them too close to the boundary of the workspace. As a result, the user may easily trigger warnings when they try to access these objects. However, the non-significant difference in *TCT* also revealed the fact that the user seems to be able to quickly re-position the virtual workspace when facing such problems using *Manual* technique. Consequently, both techniques are suitable in a virtual environment with no-overlapping interaction areas. However, the *Automatic* technique seems more appropriate in such a context since fewer warnings are triggered, thus avoiding immersion breaks.

For the task with the *Overlap* layout, no significant differences in *TCT* were found between *Manual* and *Automatic*, which does not support **H4**. However, while the task was significantly faster to achieve with *Manual* compared to *Basic*, similar results were not reported for *Automatic*, suggesting that a small difference could exist between *Manual* and *Automatic*. In addition, the score from the NASA-TLX showed that *Manual* significantly reduced the cognitive load, compared to *Automatic*. As the virtual workspaces proposed by the system can be numerous and overlapped each other, the user sometimes has to pass through an intermediate virtual workspace to reach the one behind, which can be time consuming and increase the cognitive load. Users also felt "constrained" (P2, P7) as

they needed "to adapt to a previously defined position" (P5). Consequently, the *Manual* technique seems more appropriate than the *Automatic* one when the VE is crowded with many objects in the same area.

3.4 Conclusion

This chapter presents two generic solutions for defining spatial consistency areas in virtual environments on run time. These techniques use a virtual representation of the user's physical workspace in the VE. By teleporting into such virtual workspace, the user can recover the one-to-one position mapping between real and virtual worlds. The resulting spatial consistency allows the user to access virtual objects within this area by physical walking and natural gestures. To enable the user to position their future virtual workspaces in VE, two different interactive techniques are investigated. The *manual* technique allows the user to adjust the position and orientation of the future virtual workspace by themselves. The *automatic* technique uses algorithms to automatically generate possible virtual workspaces based on VE layouts, and the user can choose one of them as their future workspace.

To evaluate these techniques, two experiments were conducted. A first experiment compared the three manual positioning techniques. It demonstrated that using an avatar to represent the user's future position in the virtual workspace reduces disorientation and thus the time needed to locate targeted objects after teleportation. It also showed that exocentric and egocentric techniques with an avatar resulted in a close performance level, but the egocentric technique seemed to be preferred by users.

A second experiment compared the egocentric manual technique with an avatar and an automatic technique to basic teleportation. The results demonstrated the benefits of the virtual workspace positioning approaches over the basic teleportation. The manual and automatic positioning techniques outperformed the basic teleportation in terms of efficiency and immersion. Although these two positioning techniques reached equivalent performances, each one seemed to have its advantages depending on the layout of the virtual environment. Compared to the manual technique, the automatic one caused fewer collisions with the real workspace limits in sparse virtual object layouts, but it induced a higher cognitive load for crowded scenes. Moreover, the manual technique was better suited for open-ended tasks, where the user can interact anywhere in the VE.

Although these virtual workspace positioning techniques can be applied to most VR systems and applications, they are not suitable for certain applications with special design needs. For example, tangible interactions allow the user to access the real-world object and its virtual counterpart simultaneously. The required

one-to-one mapping in position imposes limitations on the positioning of virtual workspace in the VE. Therefore, the positioning techniques described above should be further improved to fit such constraints. To address this issue, the next chapter describes different solutions that allow the user to position their future virtual workspace in an appropriate position when tangible objects are integrated into the scenario. As a result, the one-to-one position mapping can be recovered to support tangible interaction when necessary.

Consistency for Tangible Interaction

4

The position and orientation of spatial consistency areas in the virtual environment can be determined by the user or calculated by the system using algorithms. These approaches are applicable to most VR applications and systems but do not meet some specific design requirements. Particularly, tangible interactions highly rely on a one-to-one 3D mapping between the real object and its virtual counterpart, limiting the user's virtual workspace positioning during the spatial consistency recovery process. Targeting these issues, this chapter presents three interactive techniques to help the user recover the required one-to-one mapping for tangible interactions during teleportation.

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4.1 Introduction

Haptic technology is one of the VR technologies whose objective is to enhance the realism and immersion of user experience with a sense of touch [56]. As opposed to dedicated VR setups found in academic labs or big companies, most haptic devices on the market are not always available at home or in SME offices, and they are quite expensive for the general public. Therefore, tactile and kinesthetic feedback based on such technology is usually absent in home-based VR applications (see more details in Section 1.1.1).

As an alternative solution, some previous works propose to integrate everyday objects into a virtual environment by pairing them with virtual counterparts [95, 33]. The main idea is to employ some tangible objects in the real working space, which provide passive haptic feedback [56] realistic enough in terms of tactile-kinesthetic sensation. Therefore, the user can perceive a haptic feeling when touching the virtual objects. Adding physical qualities to virtual objects is a cost-effective and straightforward approach that can enhance the perception of virtual object affordances [50], improves the user's sense of presence, and contributes to a more compelling VR experience.

In response to enabling such tangible interaction, this chapter proposes three interactive techniques to help the user recover the one-to-one mapping between the real and the virtual objects during teleportation. By teleporting either the user, the virtual object, or both of them to a new position and/or orientation, these techniques align the spatial configuration in the virtual environment to the one in the real world. As a result, the user can find and touch the object again each time a tangible interaction is required after teleportation navigation. The following sections of this chapter will describe in detail the design as well as the implementation of these three advanced teleportation techniques. This chapter is based on work published at IEEE VR Workshop 2021 (see Publications (c)).

4.2 Tangibility Supported by Teleportation

Enabling the user to "touch" a virtual object highly relies on a consistent spatial relationship between the user, the tangible prop, and its virtual counterpart. The required one-to-one position mapping between real and virtual objects imposes additional constraints and challenges on the positioning of spatially consistent areas in the virtual environment.

4.2.1 Problematic

When tangible interaction is not involved, the positioning of spatial consistency areas depends on the configuration of the virtual objects in the VE (see more details in Chapter 3). Therefore, the resulted configurations can be various. However, in situations involving tangible interactions, the possible configurations are limited since the real-world object needs to be mapped to its virtual counterpart. The number of possible configurations can be related to the shape of the physical prop used. For example, if we pair the ball suspended from a long pendulum with a virtual flying droid as in the iTurk system [33], the number of possibilities to position the user near the ball in the virtual environment tends to be infinite. In cases where the user needs to access two or more objects in the physical workspace, the possible configuration is unique. Such as, for the Substitutional reality system [95], there is only one possible mapping since every architectural feature should pair to its virtual object.

4.2.2 Proposed Approaches

To address this issue, the basic idea of my techniques is to teleport either the user, the virtual object, or both of them to a new position calculated based on the spatial configuration of the user's physical workspace. Therefore, the spatial relationship between the user's avatar and the virtual object can be consistent with the spatial arrangement between the user and the tangible prop. When tangible interaction is not required, such as during basic teleportation navigation, the surrounding real objects are not aligned with any visual objects. Under such circumstances, those real-world tracking objects can be considered as invisible obstacles to the user. Potential collisions between the user and those objects can be avoided by deploying specific visual feedback [68].

As an example of possible applications of these teleportation techniques, I designed a VR environment that incorporates a tracked physical chair in the real world to allow the user to rest on it. This chair also has a virtual counterpart with which the user can interact in the virtual world. However, the use cases associated with each technique can be extended into more general situations in everyday VR applications with different physical objects involved.

The VR setup of my proof-of-concept implementation consisted of an HTC Vive headset and two controllers. The virtual environment was rendered using Unity 2019.4.2f1 with a resolution of 1080×1200 pixels per eye at 90 Hz. The room supported a 3m x 5m tracking area, and the real chair was tracked using one Vive Tracker.

Depending on the working context in the virtual environment, the user can select from a virtual menu at runtime the teleportation technique they want to

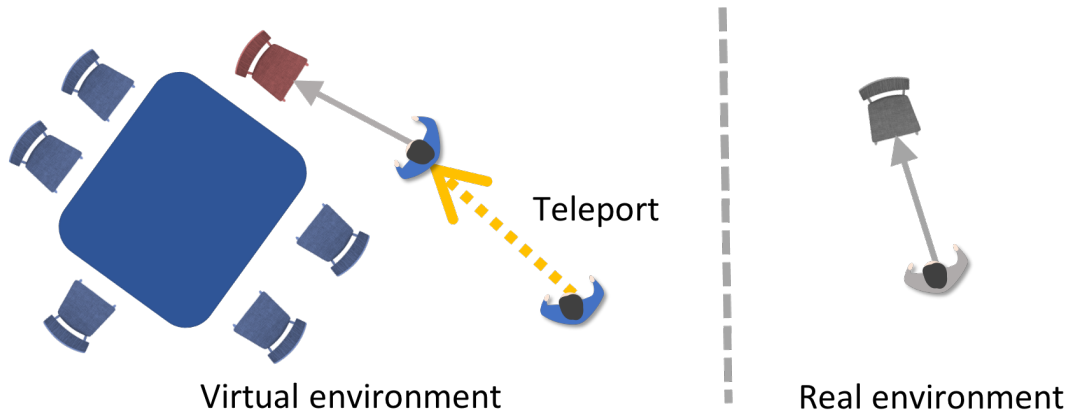


Figure 4.1 – Teleportation of the user in the virtual world towards the targeted virtual object's (brown chair) position illustrated from the bird-eye view. Their new positioning recovers the spatial relationship between them and the object's physical counterpart (black chair).

use to connect virtual objects with their tangible counterparts. For instance, to interact with the virtual object and its physical counterpart in its current virtual context, the user can teleport himself close to the targeted object. On the contrary, if the current interaction context is not important to the user and the task at hand, the second technique can be applied to bring the object close to the user. Finally, if the user wants to use a virtual object at another place in the virtual environment, the hybrid technique can be activated.

4.3 Teleportation of the User

In this technique, the selected virtual object becomes an anchor of the teleportation. The system will calculate the user's avatar future position and orientation to reflect their actual positioning related to the physical object in the real world (see Figure 4.1). After teleportation, the user can reach and interact with the real object using its virtual counterpart with the recovered spatial consistency.

As highlighted in Section 4.2.1, to preserve the existing spatial relationship in the real world, the number of the possible future positioning for the user's avatar in the virtual environment is decided by the number of the physical props integrated as well as their shapes and potential mobility. Besides, the possible future positioning of the user's avatar also depends on the actual context of the virtual scene if the system wants to maintain a semantic coherence. For example, the system can help prevent the user from being positioned behind a virtual obstacle or in the middle of surrounding virtual object after the teleportation.

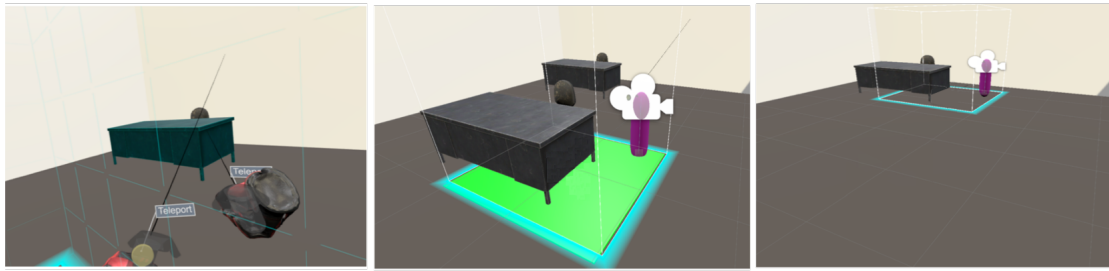


Figure 4.2 – **Left:** Targeting the tangible object. **Middle:** Showing a live preview of the contexts after teleportation to guide the user to a more appropriate position to avoid overlap. **Right:** Resulting configuration after teleportation with the tangible object accessible to the user.

Although the user has the possibility to select an appropriate positioning among multiple options computed by the system, it is sometimes unavoidable when the user has no choice but to teleport into a virtual object to maintain the spatial relationship. In particular, it often happens when many virtual objects surround the target one. However, teleporting the user inside or in the middle of a virtual object can break the user's immersion and affect the realism of the virtual environment and VR experience. In order to overcome this issue, the system can show the user's future positioning while highlighting the objects currently overlapping with them. The system then guides the user to physically move to a more appropriate positioning in the real world before triggering the teleportation.

In my implementation, the virtual object with potential tangibility (i.e., the chair) will be highlighted with a different color when the user hovers the virtual ray over it (see Figure 4.2 left). The user can select the virtual object with the pointer and *soft trigger* the teleportation by pressing the "Grab" button on the Vive controller. Due to the shape of the chair (with backrest), the user has only one possible mapping position for the teleportation.

If the user's future position of teleportation overlaps with the nearby virtual objects (e.g., the table), the user needs to physically move (i.e., walk) to a more appropriate position and orientation in the real world to be able to complete the teleportation. To achieve this, the system will display a clone of the distant context (the chair and the table that currently overlaps with the user's future position) around the user's current position to simulate the scene after teleportation (see Figure 4.2 middle). The available area where the user can physically walk turns green, guiding the user to move to a position and/or orientation to avoid any overlapping. Once the user physically reach a position and/or orientation which is free of obstacles, the teleportation can be *hard triggered* by pressing the "Squeeze" button and the user will be teleported nearby the targeted tangible object while avoiding teleporting into the surrounding obstacles (see Figure 4.2 right).

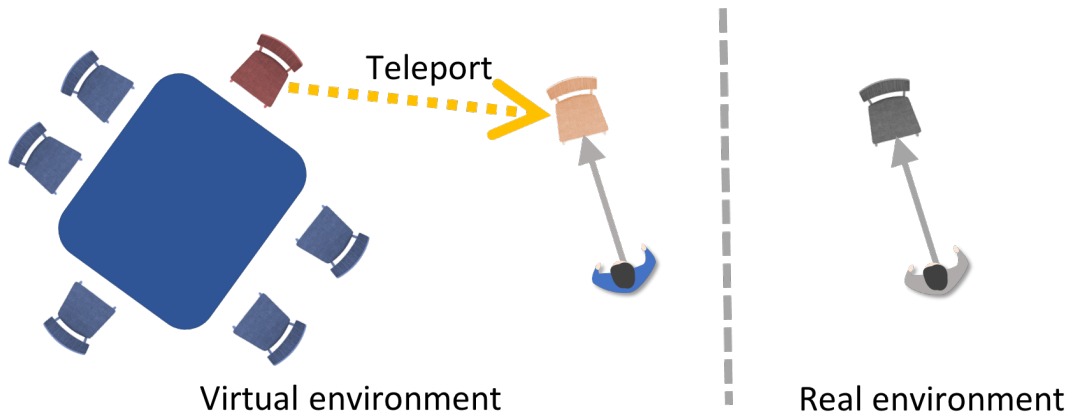


Figure 4.3 – Teleportation of the targeted virtual object (brown chair) towards to the user’s actual position illustrated from the bird-eye view. Its future position recovers the spatial relationship between the user and the object’s physical counterpart (black chair).

4.4 Teleportation of the Object

Instead of moving the user towards the virtual object as mentioned in Section 4.3, it is also possible to bring the targeted virtual object to the user to recover the spatial relationship relating to the tangible object. Based on the actual position and orientation of the user’s avatar in the virtual environment, we can compute the virtual object’s future positioning in relation to its tangible prop (see Figure 4.3). Different from the first technique which teleports the user’s avatar, the resulted positioning is unique in this case. However, this position can probably be occupied or occluded by other virtual obstacles (e.g., a virtual wall) surrounding the user (see Figure 4.4 left where the chair is inside the blue hexagonal object). In this case, the system detects post-teleportation interference and computes a new positioning to which the user has to teleport themselves before completing the object-based teleportation operation.

To compute this new position and orientation, the system first finds a position for the targeted virtual object outside the obstacle. A basic approach is to use the point on the obstacle’s collider that is closest to the current teleportation destination of the virtual object. Then, based on this new positioning of the targeted virtual object, the system computes the corresponding new position for the user’s avatar in relation to their physical position in the real world (see Figure 4.4 left, the green avatar). Consequently, the targeted virtual object will no longer overlap or be blocked by other virtual objects after the teleportation. However, in some crowded virtual environments, the resulted user’s positioning computed from this basic approach can also be occupied by other obstacles in the scene. In this case,

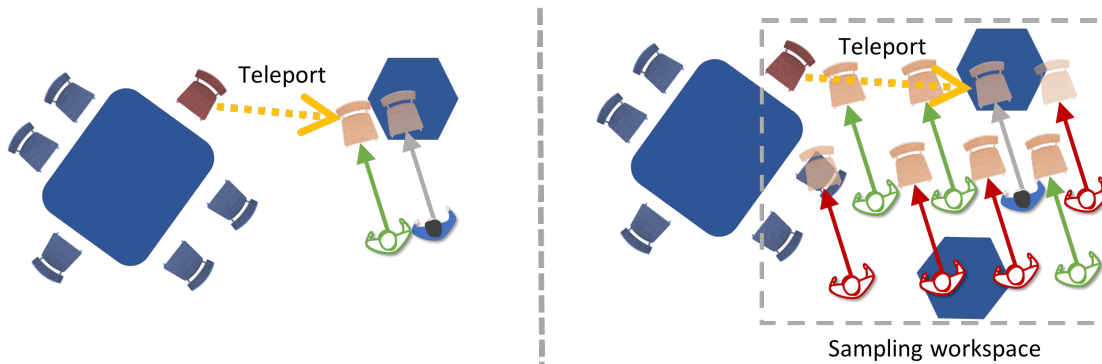


Figure 4.4 – **Left**: Basic approach to compute a valid teleportation destination for the user in the case of the object appearing in a virtual obstacle using *Collider.ClosestPoint* function of Unity3D. **Right**: Computation of possible teleportation destinations (in green) using the PRM-based sampling approach on the couple of the virtual chair and the avatar of the user.

another configuration for the couple of the virtual chair and the avatar of the user can be computed using the Probabilistic RoadMap (PRM) sampling approach [60] (see Figure 4.4 right).

Similar to the first technique, my implementation allows the user to select the targeted virtual object (i.e., the chair) and teleport the object towards the user. By pressing the “Grab” button on the controller, the user can *softly trigger* the teleportation. The system will show a clone of the targeted object at the computed positioning to inform the user of its future position (see Figure 4.5). If the virtual object destination is occupied or blocked by other virtual objects, those obstacles will be highlighted. In this case, the user is then asked to teleport himself to a new positioning (presented as a green zone on the ground) in the virtual world before teleporting the object. After reaching such suitable virtual positioning, the user can *hard trigger* the teleportation of the object with the “Squeeze” button. The targeted virtual object then will be teleported nearby the user.

4.5 Hybrid Teleportation Technique

As the name suggests, the hybrid technique is an ultimate approach to resolve the spatial consistency recovery problem by combining the first two techniques mentioned in Section 4.3 and 4.4. Similar to group teleportation [110], this technique allows the user to teleport the targeted virtual object and themselves simultaneously to support a tangible interaction at a specific destination in the virtual world. However, their spatial relationship needs to be recomputed with regard to the spatial arrangement between the user and the physical prop (see Figure 4.6).

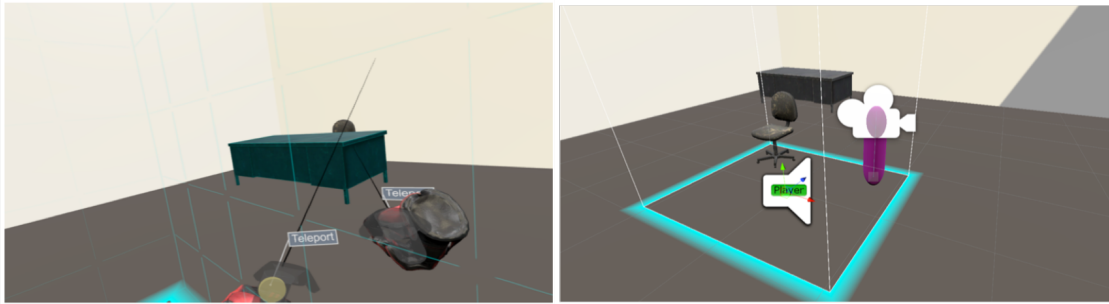


Figure 4.5 – **Left:** the user selects the targeted virtual object (brown chair) to *soft* triggers the teleportation of the object. **Right:** a clone of the virtual object is shown in the surroundings of the user (purple avatar). The targeted virtual object is teleported toward to the user after the user *hard* triggers the teleportation.

The hybrid technique deploys a virtual representation that couples the teleportation destinations of the user and the virtual object according to the current relative positioning between the user and the tangible object. By manipulating such virtual representation's position and rotation, the user can simultaneously define the teleportation destination for the targeted virtual object and themselves. Thus, the user can customize the teleportation for different virtual contexts, optimizing the obstacle-related situations (e.g., obstruction, overlapping). At the same time, the teleportation provides tangible interactions for the user.

Unlike the other two implementations, the user *soft* triggers the teleportation with the "Pinch" button after selecting the targeted virtual object (i.e., the chair). The user can define their future position using a virtual ray. Based on this position, the system will calculate the corresponding position of the virtual object to maintain the spatial relationship between the physical object and the user, and display a clone of the target virtual object at the resulting position (see Figure 4.7). By pressing the "Touch left" and "Touch right" buttons of the other controller, the user can rotate the clone object around their future positioning to make sure that the user or the object will not teleport into any other obstacles afterwards. Finally, by pressing the "Pinch" button again, the user and the virtual object can be teleported to the predefined positioning with a recovered spatial relationship.

4.6 Conclusion

Allowing a user to touch or hold virtual objects can enhance immersion and contributes to a greater sense of presence. Passive haptic is a simple and cost-effective solution to compensate for the lack of haptic feedback in everyday use of virtual reality. However, it requires a one-to-one mapping between tangible props and

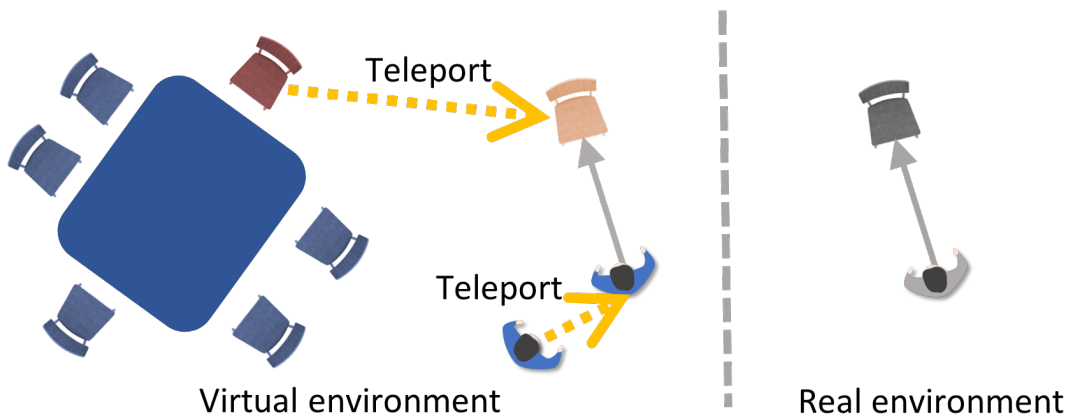


Figure 4.6 – Hybrid teleportation of both the user and the targeted virtual object (brown chair) to their new positions defined by the user while preserving spatial relationship between them.

their virtual counterparts, introducing additional constraints when defining areas in the VE to recover spatial consistency. To overcome this issue, I propose three techniques to help the user to recover the spatial mapping between the real-world object and its virtual counterpart after teleportation: *teleportation of the user*, *teleportation of the object* and *hybrid teleportation*.

Determined by the virtual object’s positioning, the *teleportation of the user* technique teleports the user to a position near the virtual object. In such a way, the virtual object and its corresponding tangible object are spatially consistent for the user. Different positioning can be proposed to the user according to the shape, size, and number of integrated tangible props. Conversely, *teleportation of the object* technique teleports the virtual object to the positioning of its tangible prop, to create the expected spatial consistency. This positioning is, in theory, unique and can be occupied or occluded by other obstacles present in the virtual scene. Therefore, additional procedures based on collision detection or the probabilistic road map (PRM) approach complement this technique. Finally, *hybrid teleportation* approach combines these two techniques and allows the user to define a new teleportation destination for both the object and themselves while restoring the spatial consistency.

These different techniques can be applied in different scenarios according to the targeted object’s features. For example, *teleportation of the user* can be more appropriate than *teleportation of the object* or *hybrid teleportation* to allow the user to touch virtual objects that are considered non-movable in the scene. On the other hand, *teleportation of the object* or *hybrid teleportation* may be more suitable for the user to interact with small objects or tools to perform a task at a specific location in the virtual environment.

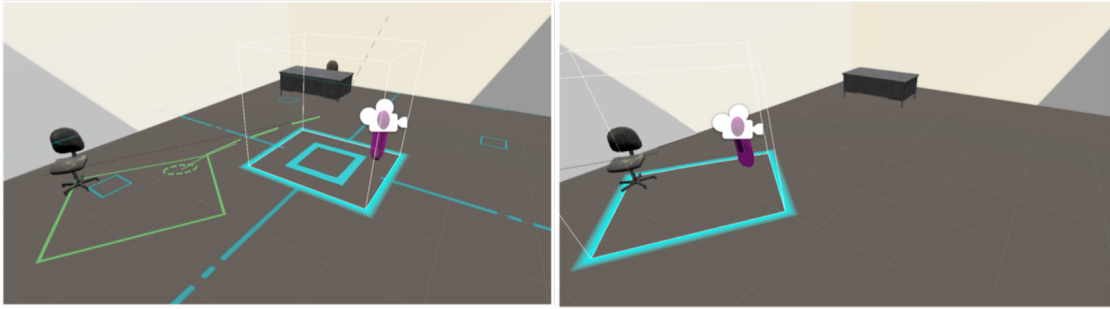


Figure 4.7 – **Left**: when the user *soft* triggers the technique, the system displays a clone object at a location calculated based on the user-defined teleportation position. The user has all the freedom to manipulate the future position and orientation of the user and object as a set. **Right**: when the user *hard* triggers the technique, both the user and the object arrive at the predefined positioning with a recovered spatial relationship.

Each of these techniques also has its advantages and disadvantages. For example, *teleportation of the user* and *teleportation of the object* require additional strategies to prevent the user or the object from being teleported inside or behind other virtual objects. *Hybrid teleportation* solves this problem by enabling the user to manage the teleportation location themselves. Nevertheless, this technique might be time-consuming and cognitive-challenging to use. Therefore, it would be interesting to evaluate these methods in user studies using virtual objects of different shapes, sizes and potential mobility in various virtual scenarios. It would also be interesting to verify whether experiencing tangible interactions affects users' sense of presence and changes their behavior when interacting with purely virtual objects.

These spatial consistency recovery techniques allow the user to find and touch tangible objects after teleportation navigation. These methods can also be extended to collaborative contexts by replacing the real-world object with a second user. If the spatial configuration between the co-located users in the virtual environment can be aligned with the one in the real world, users can directly interact with each other without mediation, such as performing a handshake. Moreover, a tangible prop can also be integrated into the scenarios, for instance, to coordinate the users' movement in collaborative manipulation tasks. However, unlike the single-user case, positioning a spatial consistency area shared by multiple users in a virtual environment can be challenging, as users may have different ideas about the position of this area. To address this issue, the next chapter proposes two different approaches that combine the actions of two users and allow them to define together a spatial consistency area in the virtual environment.

Multi-user Spatial Consistency Recovery

5

This chapter addresses spatial consistency issues when using HMD technologies for immersive collaboration with co-located users. In the context of such a collaborative setup, I propose two different interactive approaches that allow pairs of users to define together a shared spatial consistency area in the virtual environment. Once the spatial configuration in the virtual world matches the one in the real world, users can have physical and tangible interaction together, such as performing a handshake. In this chapter, I first detail the design and implementation of these two techniques. Then, I describe the experiment that I carried out to evaluate these two methods. Finally, I present the results and conclude this chapter by discussing some open problems of this contribution.

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5.1 Introduction

Computer-supported collaborative work (CSCW) tools allow groups of users to communicate, interact with each other, and coordinate their activities to solve collaborative tasks. Group interaction can be categorized according to a time/location matrix, in which distinctions are made between same-time (synchronous) or different-time (asynchronous) interaction, as well as same-location (co-located) or different-location (remote) interaction [39]. In this chapter, I investigate co-located synchronous teamwork using head-mounted displays (HMDs), where multiple users share the same physical workspace while immersed in a collaborative virtual environment (CVE).

In many collaborative VR applications, users' relative position in the VE matches their position in the real world. As highlighted in detail in Section 1.3, this spatial consistency has many interests, but also imposes some limitations or constraints. Basically, spatial consistency enriches the VR experience by allowing, for example, a direct physical interaction between them [79] as well as the integration of shared tangible props in the scene [90, 32, 7]. However, these applications usually do not support users with individual navigation capability, as it can break the spatial relationship between the users. As a result, users' accessible area in the VE is often limited, and users can only explore the VE whose size is similar to the size of their physical workspace. In addition, allowing individual navigation for co-located users often increases the risk of the user collisions because of the lack of awareness of the others' position in the real world [68]. Moreover, the dual presence of real and virtual audio stimuli generates perceptual conflicts and impacts user performance on their task [29].

Targeting these issues, this chapter explores techniques to help co-located users to recover spatial consistency after individual teleportation. Such spatial consistency recovery techniques can be useful in many scenarios, especially for a complete workflow of individual and collaborative sub-tasks. This is usually the case for complex virtual assembly simulations, where the users often have to perform a continuous virtual activity including individual and collaborative sub-tasks at different times, depending on the actual operation at hand. To achieve this, I use a virtual representation of the user shared physical workspace in the VE. Two techniques are proposed for users to position such a virtual workspace in the VE while taking into account the requirements of the subsequent collaborative task. The first technique enables one of the users (*leader*) to control the virtual workspace in the VE, and the other user (*follower*) can only express their need in terms of the workspace's position and orientation using verbal communication. The second uses a spring-damper system to integrate the input from both of the users, enabling concurrent co-manipulation of the virtual workspace.

This chapter details the design and implementation of these multi-user spatial consistency recovery techniques. It then describes the controlled experiment that I conducted to evaluate the performance differences between these two techniques. From the results obtained, I discuss the open problems of this contribution.

5.2 Multi-user Spatial Consistency Techniques

The multi-user recovery techniques incorporate a virtual description of user physical workspace in the VE, which is similar to the one used for individual spatial consistency recovery (see Chapter 3). The virtual workspace representation includes a 3D volume possessing the same shape and size as the real workspace shared by the co-located users. In addition, I represented the current group configuration by adding preview avatars [118, 111, 110] in the 3D volume to directly show how each user will be positioned after teleportation. These avatars have different colors that correspond to the users' avatar color in the VE.

By positioning the virtual workspace in the VE, users can define an area to recover spatial consistency regarding different scenarios and tasks. As collaborative interaction in the VE can be symmetric or asymmetric, I propose two different strategies to allow users to control the position and orientation of the virtual workspace: *Leader and Follower* and *Co-manipulation* techniques. Both of the techniques will be described for a pair of co-located collaborators but they can be extended to a bigger teamwork.

5.2.1 Leader and Follower Technique

My first technique allows one of the users (named the *leader*) to position the virtual workspace, while the other user (named the *follower*) can only communicate verbally to the leader their requirements (see Figure 5.1). When approaching an area that requires spatial consistency for performing collaborative tasks, the leader can press the HTC Vive controller's touch-pad to trigger the control of the virtual workspace (see Figure 1.1.1). It displays the virtual workspace for both users. The intersection point between a virtual ray and the virtual ground determines the future position of the leader.

Based on this position and the actual spatial relationship between both users in the real world, the future position of the virtual workspace with the follower's position inside is computed. The leader can also rotate the virtual workspace around the vertical axis of their preview avatar by sliding their finger in a circle on the touch-pad with a one-to-one mapping. Such a design is chosen based on the results of the first user study of Chapter 3. The egocentric cues provided by this design can help the user gather self-related information and estimate distance more

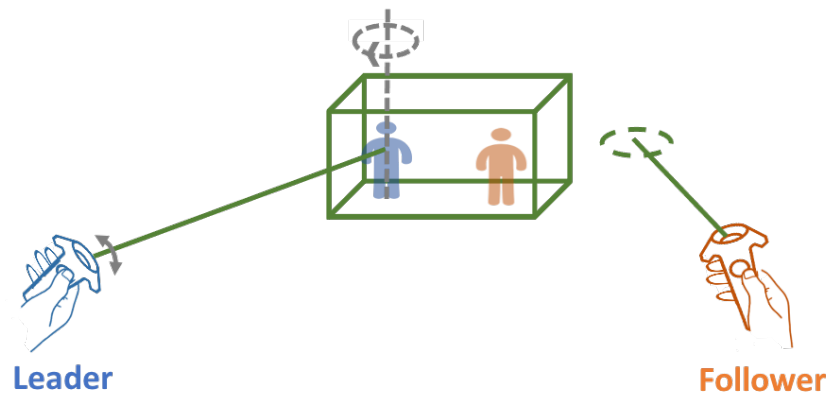


Figure 5.1 – Leader and Follower technique: the leader controls the position and orientation of the virtual workspace and once it is configured, the follower can teleport directly into this space to recover the spatial consistency. The users can observe their future position within this workspace by looking at their preview avatars.

accurately [72]. The leader can release the touch-pad to end the manipulation once the future position of the virtual workspace is satisfactory to both of the users. The leader is then teleported to this newly positioned workspace. The follower can use their ray to select the leader-defined virtual workspace and releases the touch-pad to teleport inside that workspace. The spatial consistency among users is thus restored. Instead of having the leader teleporting the two users at the same time, this process is split into two steps to avoid unwanted teleportation of the follower which can create frustration and disorientation.

5.2.2 Co-manipulate Technique

Unlike the first technique in which only one user (leader) can position the virtual workspace, my second approach allows both users to simultaneously control the virtual workspace representation in the VE (see Figure 5.2). To achieve this goal, I considered different interaction techniques which have been proposed in the literature to enable multiple users to simultaneously manipulate a shared object. Indeed, collaborative object manipulation is one of the most important interaction tasks in CVE. One plausible solution is to average the translation and rotation of the user movements to obtain the final movement of the shared object [90, 48, 93, 49, 6]. In addition, the user input can be asymmetrically integrated by assigning different degree-of-freedom (DOF) control of the shared object to the users [7, 83].

In the context of teleportation, the users define a remote targeted point using a pointing technique. To avoid introducing additional inputs, I propose a novel

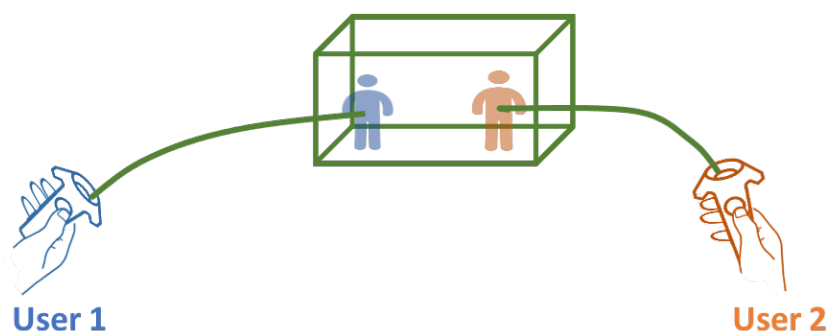


Figure 5.2 – Co-manipulate technique from the front view: the two users will concurrently manipulate the workspace using a bending ray.

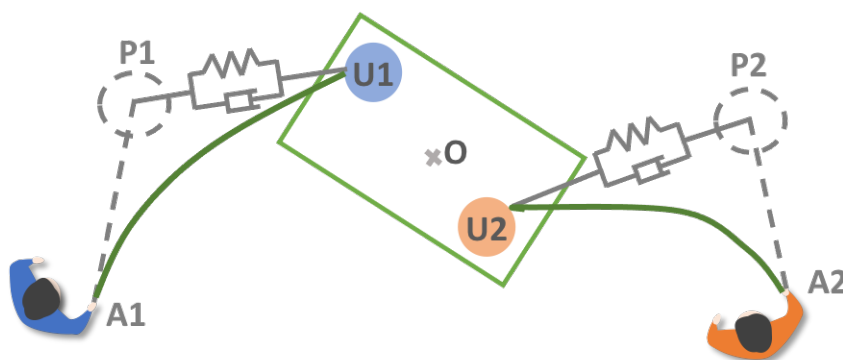


Figure 5.3 – Co-manipulate technique from the top view: the position and orientation of the workspace are calculated from a physically-based approach using a mass-spring-damper system.

interaction technique that allows users to move and rotate the virtual workspace representation together based on the translation motion of targeted points on the virtual ground. In order to pull the virtual workspace towards the users' desired configuration, I consider that the user-defined targeted positions and the users' preview avatars are connected by a mass-spring-damper system (see Figure 5.3). Similar physically-based approaches have been used to produce realistic virtual object grasping [18] or simulate collision during object manipulation [52].

At each time step, the translational force coming from each user is first computed. If we assume that U_1 and U_2 are users' preview avatar positions inside the virtual workspace, P_1 and P_2 are the targeted positions defined by the users, then the force coming from *User 1* and *User 2* can be computed as follows:

$$\vec{F}_1 = k \cdot (P_1 - U_1) + b \cdot \vec{V}_{p1} \quad (5.1)$$

$$\vec{F}_2 = k \cdot (P_2 - U_2) + b \cdot \vec{V}_{p2} \quad (5.2)$$

$$\vec{F} = \vec{F}_1 + \vec{F}_2 \quad (5.3)$$

where k and b are respectively the spring and damper coefficients, \vec{V}_{p1} and \vec{V}_{p2} are the velocity of the targeted point for *User 1* and *User 2*, respectively. The spring and damper coefficients were empirically set to 3.14N/m and 9.85N.s/m to maintain the critical damping of the system. Finally, I symmetrically integrate the user input by adding up the forces that come from both of them (Equation 5.3) and applying the total force to the point O , the center of gravity of the virtual workspace.

To allow users to simultaneously control the virtual workspace rotation, I sum the torque coming from each user by using the following formula:

$$\vec{T} = U_{1O} \times \vec{F}_1 + U_{2O} \times \vec{F}_2 \quad (5.4)$$

where the U_{1O} and U_{2O} are the vectors from the point U_1 and U_2 to the center of gravity of the virtual workspace, respectively.

Providing the users with appropriate feedback to show the current state of the shared object's position and orientation is critical in a collaborative manipulation task. Inspired by the Bent Pick Ray technique [87], I use a similar bending ray to continuously inform users about their mutual actions during the whole co-manipulation of the virtual workspace (see Figure 5.3). The curved ray starts at each user's virtual hand position (A_1 or A_2) and ends at the position of their preview avatar (U_1 or U_2). The user-defined targeted destinations (P_1 or P_2) serve as an additional control point to define a Bézier curve of the 2nd degree (i.e., parabolic curve segment). The deformation of the curved ray indicates the direction and intensity of the user's drag on the virtual workspace.

The co-manipulation of the virtual workspace is triggered when the distance between two targeted points defined by the users is less than a specific value (e.g., the length of the diagonal of the virtual workspace). This threshold is set to avoid the situation when one user wants to perform a simple individual teleportation and accidentally activates the co-manipulation mode of the virtual workspace. When reaching an agreement on the configuration of the virtual workspace, either of the two users can end the co-manipulation by releasing the touch-pad. They will then be teleported to the newly defined workspace, and the spatial relationship among them will thus be recovered. However, by giving both users the ability to end the co-manipulation on their own, there is a risk that users can accidentally trigger this process due to misunderstandings in communication. To overcome this issue, alternative solutions to end the co-manipulation can be explored, such as locking

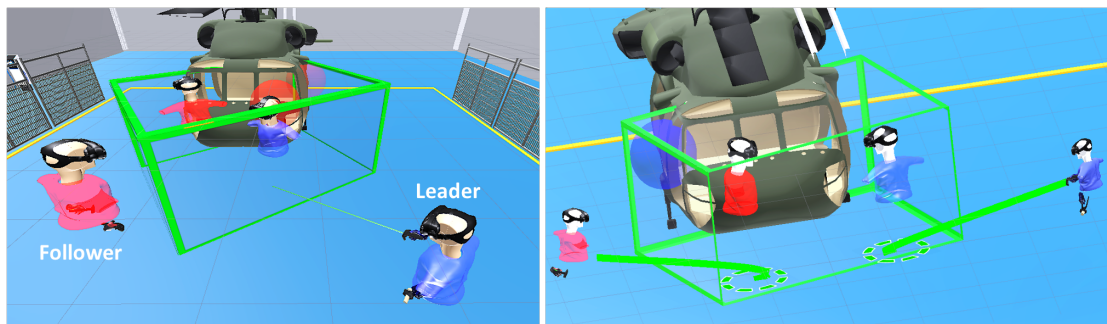


Figure 5.4 – Two virtual workspace positioning techniques to help co-located users to recover their spatial consistency after a teleportation. The 3D volume framed in green represents the virtual representation in the VE of the user shared physical workspace. While positioning this virtual workspace, the users can predict their future position and orientation after the teleportation by observing their preview avatars (each user is represented by a distinct color). *Left: Leader-and-Follower* technique which allows one of the users to fully manipulate the position and orientation of the virtual workspace. The other user can only communicate their own requirements for this manipulation. *Right: Co-manipulation* technique which integrates the inputs from both of the users, allowing concurrent positioning.

the virtual workspace manipulation when one of the users is satisfied with the current configuration and waiting for a confirmation from the other. However, such a design may take a longer time and introduce unbalanced control over the positioning of the virtual workspace.

Finally, if users want to stop the co-manipulation and return to the basic individual teleportation state, they can intentionally increase the distance between the two targeted points and exceed the predefined threshold. The threshold values used for starting and stopping the co-manipulation can be parameterized. For example, the stopping value can be greater than the starting one to allow users to manipulate the virtual workspace over a broader range. In addition, an additional threshold can be set between these two values. For example, when the distance between the two separate target points is about to reach this threshold, the curved rays will turn red, informing users in advance that the co-manipulation is about to end and that the virtual workspace is about to disappear.

5.3 User Study

I conducted a controlled experiment to compare the two spatial consistency recovery techniques presented in the previous section. I did not compare these two techniques with a baseline condition with which the users have to perform indi-

vidual teleportation without any assistance to recover the spatial consistency. It is due to the fact that for such baseline condition, it is nearly impossible for the users to recover their spatial consistency without removing their HMDs from time to time, to verify their spatial relationship in the real world, and to apply it to the virtual world.

In this experiment, I set up a virtual riveting task in which the co-located participants were asked first to complete an individual task, and then return to a designated area to achieve together the riveting of a helicopter shell. Participants had to position the virtual workspace representation according to the current riveting task location. The restored spatial consistency inside the newly defined workspace allows participants to interact directly with each other during the riveting process. The experimental protocol has been approved by the ethics committee of university.

The experiment followed a within-subject design and assessed the two following TECHNIQUES (see Figure 5.4):

- *Leader-and-Follower* allows only one of the users (leader) to control the position and orientation of the shared virtual workspace. The other user (follower) can help the leader to better position the virtual workspace by verbal and gestural suggestions. Spatial consistency is recovered after the follower selects the virtual workspace defined by the leader and teleports into this space.
- *Co-manipulation* enables both of users to position the virtual workspace simultaneously in the VE. The user inputs are symmetrically integrated into a co-manipulation of the shared virtual workspace based on a mass-spring-damper model. The spatial consistency is recovered when either of the two users ends the co-manipulation.

5.3.1 Hypothesis

I assumed that *Co-manipulation* would help users to better position the workspace as their intention can be directly conveyed by the manipulation of the virtual workspace, and thus avoiding possible misunderstandings which can occur during the verbal communication in *Leader-and-Follower*. Moreover, I expected to find imbalance negotiation between the participants and differences in their respective contribution to the task in the *Leader-and-Follower* as it implies an asymmetric role assignment in the virtual workspace positioning process. Therefore, the following hypotheses are formulated:

- H1** *Leader-and-Follower* will require more time to discuss and negotiate the future workspace position compared to *Co-manipulation*.

H2 *Co-manipulation* will induce better workspace positioning resulting in a better performance for the riveting task.

H3 *Leader-and-Follower* will be more challenging for the leader.

5.3.2 Participants

I recruited 24 participants, aged between 21 and 50, with normal or corrected-to-normal vision. Pairs were formed at the time of recruitment resulting in eight male-male and four female-male groups. 18 out of 24 participants had previous VR experience and 10 of them rated their everyday usage of HMDs as very low.

5.3.3 Experiment Setup

The VR setup consisted of two HTC Vive Pro headsets with position and orientation tracking. User inputs were obtained through the two Vive handheld controllers that were used by for each user. Two workstations were linked together via the network and shared the same tracking space calibration. The tracking spaces of the two users are aligned to a common coordinate system by a calibration procedure [112]. The experiment room supported a $3\text{m} \times 4\text{m}$ tracking area. The virtual environment was rendered using Unity (released 2019.4.21) with a resolution of 1440×1600 pixels per eye at 90 Hz. An end-to-end average latency¹ of 5 ms was measured.

5.3.4 Experiment Task

Before the experiment, each participant of a pair was asked to walk to their respective starting points presented by dashed circles on the virtual floor. Each participant was equipped with two controllers, one for teleportation and the other for the riveting task. The latter was presented in the VE as a hammer or a riveting pliers, depending on the participant's role. To ensure the safety of participants, warning signs appeared in their field of view with alarm sounds when they reached the limit of their physical working space, or stayed too close to each other and were about to collide [36, 68, 108].

Each participant first performed an individual task to prepare the team riveting task. As illustrated in Figure 5.5, the participant with the hammer had to teleport close to the charging station to charge it, while the other participant needed to teleport near a shelf to grab the rivets with the riveting pliers. After the participants finished their own individual tasks, they needed to return to the team

¹The average time from when a message is sent from one headset till it is received by the other headset.

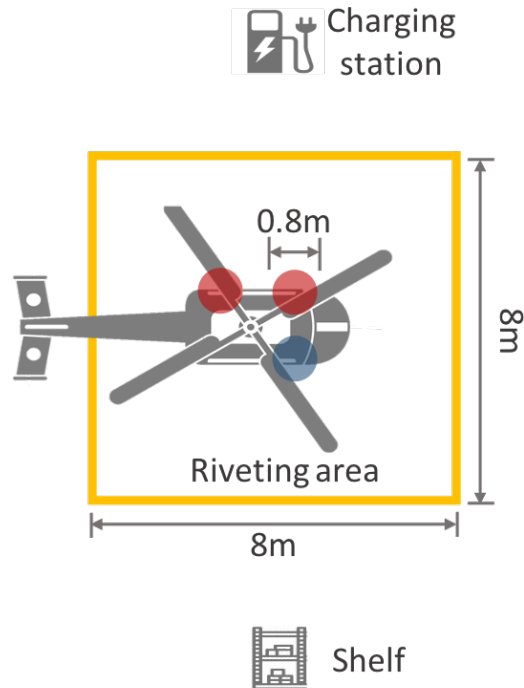


Figure 5.5 – Top view of the VE implemented for the user study: a riveting area (including semi-transparent spheres presenting three predetermined riveting positions) as the shared working area, and two separate areas (including the charging station and the shelf) for individuals tasks.

riveting area indicated by the yellow frame on the ground. Then, participants had to position their virtual workspace to enclose three riveting positions required by the collaborative task.

Individual criteria for the future virtual workspace position were provided differently to the participants: one participant was informed of a part of the required riveting positions, while the other was informed of the remaining positions. Such design is based on the fact that each worker may have a different sequence workflow in an actual riveting process according to their expertise and preference. In addition, the negotiation is encouraged during the virtual workspace positioning stage to mitigate the imbalance of control in *Leader-and-Follower* condition.

The predetermined riveting positions were enclosed in a semi-transparent sphere ($d = 0.8\text{m}$) and displayed to the participants. There were three spheres in total in each operation and each sphere includes two riveting points. Each user was randomly assigned to see one or two of the three spheres either in red or blue. For example, in the case shown in the Figure 5.5, one user can see the two spheres in red, while the other can see the remaining one in blue. To help the participants

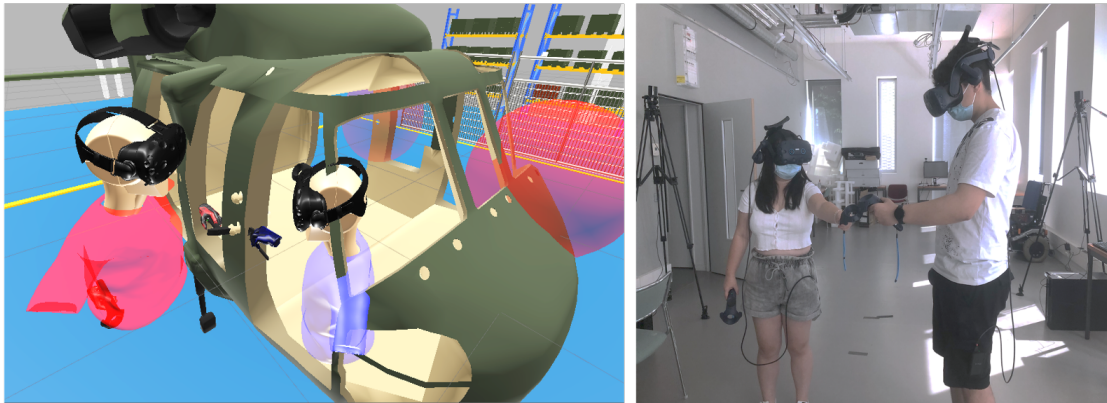


Figure 5.6 – The collaborative riveting task requires that the two controllers of the users (which are displayed as a hammer or a riveting pliers depending on the role of the user) come into direct contact to perform the riveting. The users can feel the hit when hammering the rivet, which provides them passive haptic feedback for the collaborative task. *Left:* bird-eye view of the virtual environment. *Right:* view of the shared real environment.

better determine the position and orientation of the virtual workspace, the color of the sphere is darkened when it is completely enclosed by the workspace.

After the participants configured the position and orientation of the virtual workspace and arrived at this newly positioned workspace with a recovered spatial consistency, the team riveting task began. The participant with the riveting pliers had to place the rivet in the drilled hole of the helicopter shelf, while the other completed the riveting by tapping the end of the rivet with the hammer. The rivet end and the hammer were respectively mapped to the upper area of the controllers held by the participants. As a result, they could feel the hit as they hammered the rivet, which provided them with passive haptic feedback for the collaborative riveting (see Figure 5.6). When the two riveting points inside one sphere were filled, the color of this sphere faded to gray, prompting the participants to walk to the next riveting position.

Based on the size of the physical workspace and the riveting area, the co-manipulation starting and stopping values are set to 3m and 10m, respectively, and the stopping warning threshold was set to 8m.

5.3.5 Procedure

After arriving at the laboratory, each pair of participants received instructions on the task, signed an informed consent form, and filled out a demographic questionnaire. At the beginning of each condition, the participants received a training trial. During this training, the experimenter was allowed to answer the partici-

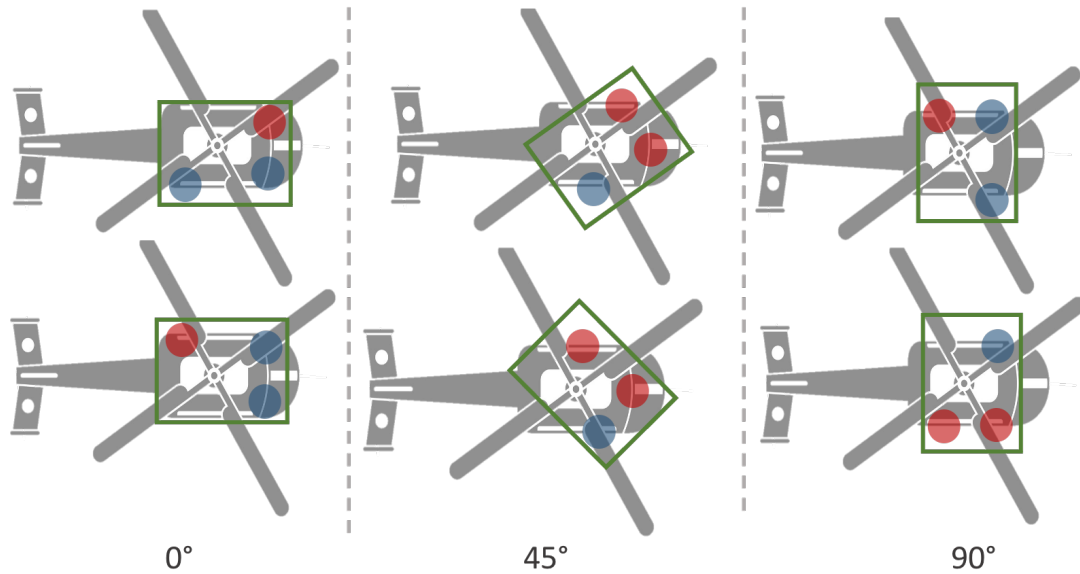


Figure 5.7 – The six optimal virtual workspace positions for the six variations the riveting task. These variations included three types of rotations (0° , 45° , 90°) and different riveting positions.

pants' questions, if any. Then, the participants completed six trials in a randomized order with different targeted riveting positions, resulting in six optimal virtual workspace positions with three different rotations (0° , 45° , 90°), as illustrated in Figure 5.7. Participants filled out a questionnaire after each technique. At the end of the experiment, participants ranked the two techniques according to their preference. The whole experiment lasted approximately 45 minutes.

5.3.6 Data Collection

I registered 144 trials: 2 TECHNIQUES \times 6 repetitions \times 12 pairs. For each trial, I logged the following measures:

- *Task Completion Time (TCT)* is the total time spent by the participants completing one trial. Measurements began at the start of the individual task and ended when the six rivets were installed.
- *Workspace positioning time* is the time spent by the participants positioning the virtual workspace. The measurement started when both of the participants entered the riveting area and ended when they teleported inside the newly defined workspace (by releasing the touch-pad of their controller). For each of these measurements, I summed the values if more than one workspace positioning operation was required during the trial.

- *Riveting time* is the time spent by the participants completing the riveting task. The measurement began when the participants were first teleported into the shared workspace and continued until all six rivet placements were completed.
- *Number of positions* is the number of times the participants positioned the virtual workspace in one trial to complete the installation of the six rivets.
- *Position offset* is the position offset between the virtual workspace defined by the participants and the optimal one. The measurements are averaged if there are several workspace manipulation attempts in one trial.
- *Rotation offset* is the rotation offset between the virtual workspace defined by the participants and the optimal one. The measurements are averaged if there are several workspace manipulation attempts in one trial.
- *Number of warnings* is the number of the warnings triggered by the participants due to a collision with the workspace borders during the team riveting.

I used the NASA-TLX questionnaire [55] to assess the cognitive task load. Participants were also asked to evaluate their leadership ("Who was the leader, you or your partner?"), contribution ("To what extent did you and your partner contribute to positioning the workspace?"), and talkativeness ("Who talked the most, you or your partner?"). Several previous studies have used similar questions to investigate leadership in collaborative tasks [100, 114]. Criteria were graded on a 21-point scale and later converted to a 100-point score.

5.3.7 Statistical Results

I averaged the 6 repetitions of each technique to minimize the noise in the data. All statistical analyses were performed in R with a significance level of $\alpha = 0.05$ for all tests. Means (M) are reported with standard deviations.

For *TCT* (see Figure 5.8, left), I used Shapiro-Wilk test and QQ plots to analyze data normality. The data did not conform to normal distribution, so I applied a log transformation to it following the statistical recommendations [88] (p.316). The Kolmogorov's D-test then showed its goodness-of-fit to the log-normal distribution. I thus ran the analysis using the log-transform of *TCT*. The paired sample t-test revealed that the participants achieved the task significantly faster with *Co-manipulation* ($M = 90.90 \pm 17.95s$) than with *Leader-and-Follower* ($M = 112.81 \pm 34.00s$, $p = 0.037$).

Regarding *workspace positioning time* (see Figure 5.8, right), I followed the same analysis procedure as applied to *TCT* and observed a significant difference of TECHNIQUES in the paired samples t-test ($p = 0.008$). It was shown that the

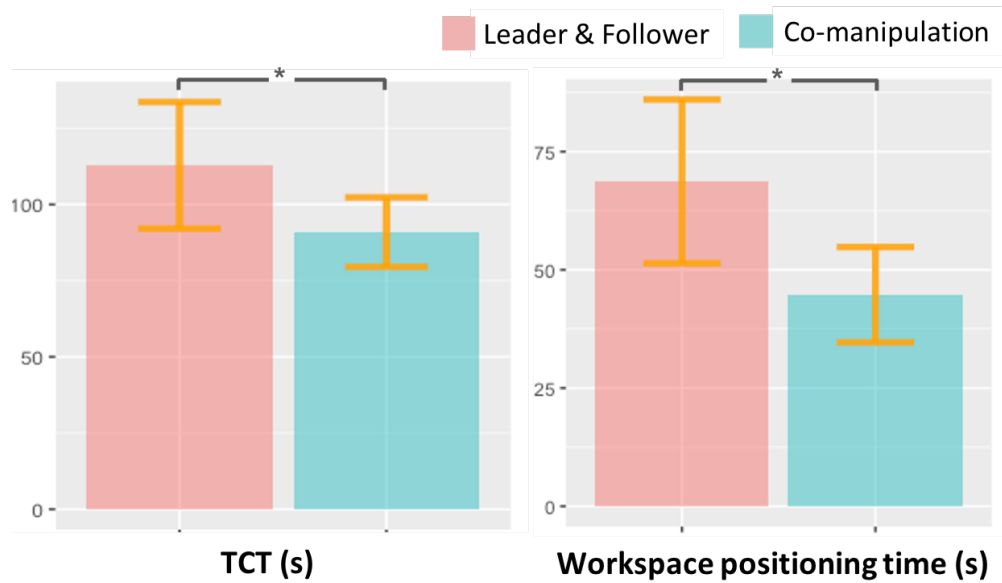


Figure 5.8 – Mean *TCT* (left) and *workspace positioning time* (right) by technique. Error bars show 95% confidence intervals (CI).

participants spent significantly longer time positioning the workspace with *Leader-and-Follower* ($M = 68.70 \pm 28.46s$) than with *Co-manipulation* ($M = 44.74 \pm 15.87s$).

Concerning *riveting time* (see Figure 5.9, left), a paired sample t-test was used as the data was normally distributed. I did not find any significant difference between *Co-manipulation* ($M = 29.48 \pm 5.58s$) and *Leader-and-Follower* ($M = 35.66 \pm 11.59s$, $p = 0.075$).

For *number of positions* (see Figure 5.9, right), I used a non-parametric test in conformity with the nature of count data. Wilcoxon signed-rank test revealed that the participants positioned the workspace significantly more often with *Leader-and-Follower* ($M = 1.22 \pm 0.32$) than with *Co-manipulation* ($M = 1.04 \pm 0.10$), $p = 0.025$).

From the *position offset* and *rotation offset* results (see Figure 5.10), I also used non-parametric test as the data was not normally or log-normally distributed. For *position offset*, a Wilcoxon signed-rank test did not reveal any significant difference between *Leader-and-Follower* ($M = 0.77 \pm 0.37m$) and *Co-manipulation* ($M = 0.67 \pm 0.25m$, $p = 0.259$). Similarly, no significant difference was found in *rotation offset* between *Leader-and-Follower* ($M = 41.67 \pm 9.32^\circ$) and *Co-manipulation* ($M = 44.71 \pm 12.79^\circ$, $p = 0.791$).

For *number of warnings* (see Figure 5.11, left), I used a non-parametric test for post-hoc analysis in conformity with this type of data. Wilcoxon signed-rank test

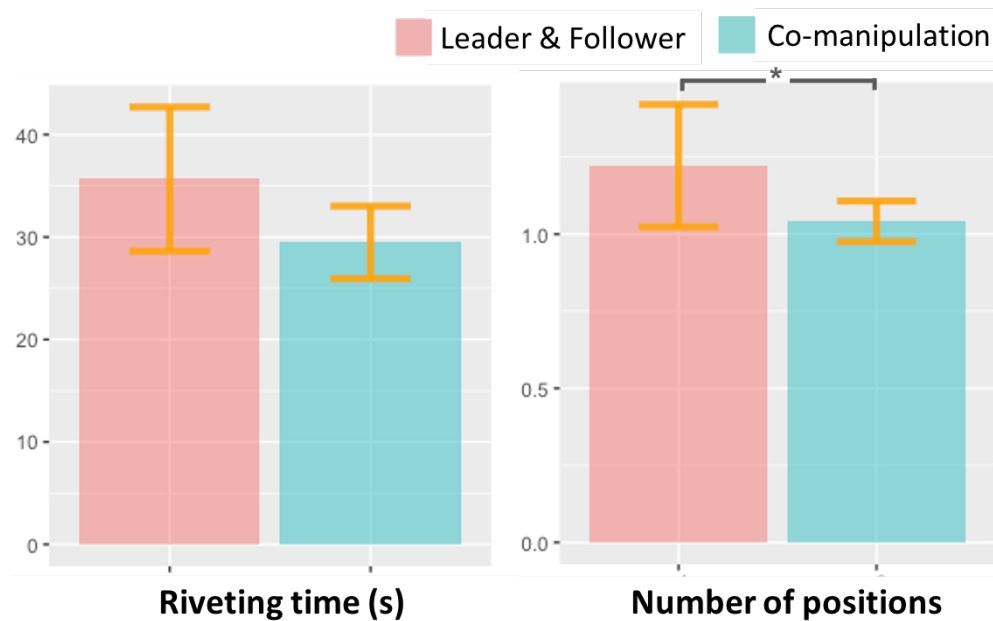


Figure 5.9 – Mean *riveting time* (left) and *number of positions* (right) by technique. Error bars show 95% CI.

showed that the participants detected significantly more the warnings with *Leader-and-Follower* ($M = 0.85 \pm 0.50$) than with *Co-manipulation* ($M = 0.58 \pm 0.46$), $p = 0.034$).

Regarding the subjective questionnaire, I used non-parametric Wilcoxon signed-rank tests for post-hoc analysis. For NASA-TLX score, I did not find any significant difference on cognitive task load between *Leader-and-Follower* ($M = 43.09 \pm 12.32$) and *Co-manipulation* ($M = 42.47 \pm 11.75$), $p = 0.99$). In *Leader-and-Follower*, no significant differences in talkativeness were found among participants in the leader role ($M = 42.92 \pm 16.71$) and follower role ($M = 48.33 \pm 18.50$), $p = 0.506$). Leaders ($M = 50.00 \pm 11.48$) were also found to have no significant differences in the level of contribution as followers ($M = 52.50 \pm 5.84$, $p = 0.792$). However, I detected an imbalance of leadership in *Leader-and-Follower* condition, with higher value for leaders ($M = 40.00 \pm 14.61$) compared to followers ($M = 57.92 \pm 17.64$), $p = 0.015$). Finally, 14 out of 24 of participants preferred *Co-manipulation* than *Leader-and-Follower*. Six participants out of 10 who preferred *Leader-and-Follower* took a leadership role in the experiment.

5.3.8 Discussions

The results provide evidence that *Co-manipulation* was more efficient than the *Leader-and-Follower* for workspace positioning. In *Co-manipulation*, the partici-

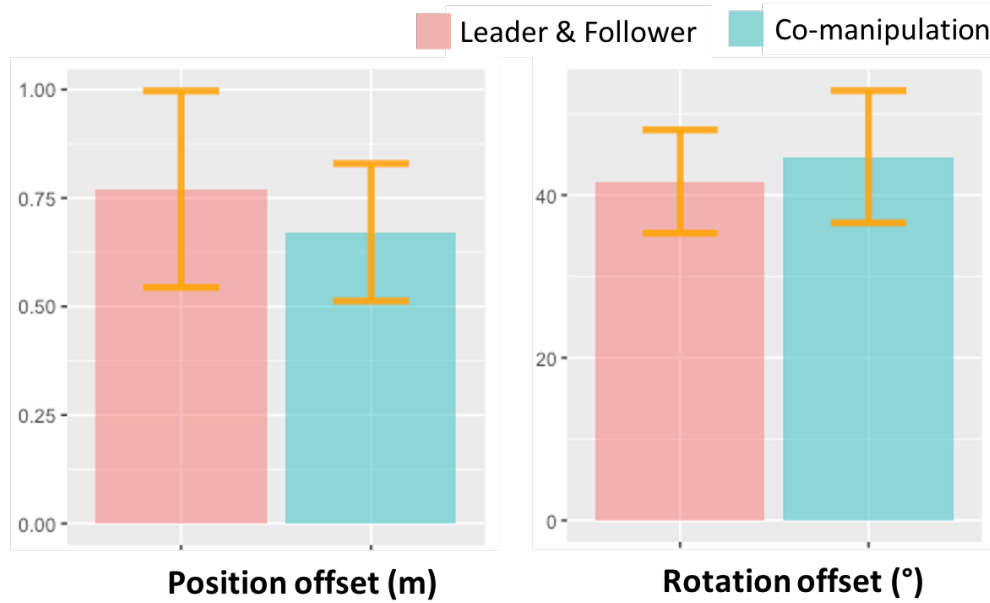


Figure 5.10 – Mean *position offset* (left) and *rotation offset* by technique. Error bars show 95% CI.

pants spent significantly less time on completing the task. In particular, the time used for negotiation and positioning the workspace was significantly decreased when both participants were able to manipulate the workspace, compared to the *Leader-and-Follower*. It therefore supports **H1**. This can be explained by the fact that each participant could adjust the position of the workspace according to the individual criteria provided to them. Besides, the participants' desired positions and intentions could be communicated implicitly through the manipulation of the workspace. In the *Leader-and-Follower*, communicating the desired positions could be difficult, and I observed three different approaches that the participants used to achieve this. The participants could either (i) teleport themselves close to the required riveting point, (ii) use a ray to point to the target position, or (iii) use a virtual object (e.g., helicopter or avatar) as a reference to verbally describe its position. However, the use of additional teleportation or pointing, as well as the potential misunderstandings that could arise from the verbal communication, resulted in the need to use more time to exchange the information on riveting positions between the participants.

Contrary to my expectations, I was not able to find any significant difference between *Co-manipulation* and *Leader-and-Follower* in terms of positioning accuracy. These two TECHNIQUES produced similar position and rotation offsets, which does not support **H2**. However, I found that the participants triggered significantly more warnings and executed a significantly larger number of workspace position-

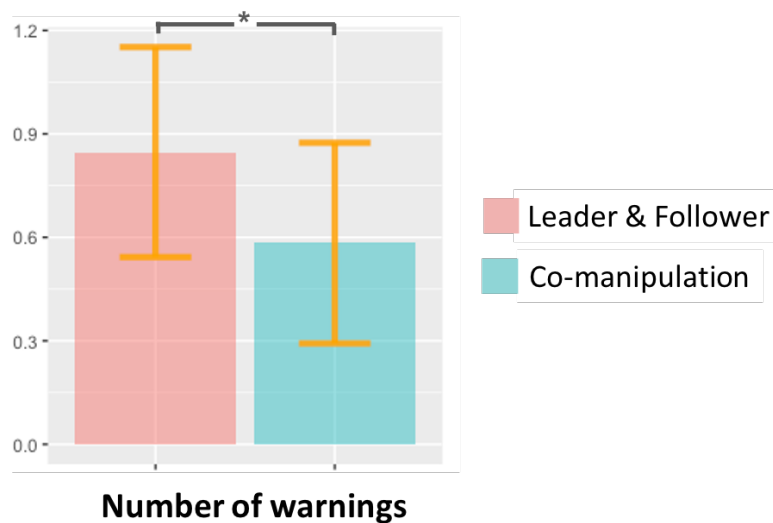


Figure 5.11 – Mean *number of warnings* by technique. Error bars show 95% CI.

ing operations in *Leader-and-Follower* during the riveting process. Although the difference was not significant, an increase of *riveting time* in *Leader-and-Follower* was also observed. Indeed, the accuracy of the workspace positioning affects the performance of the subsequent riveting tasks. If the user-defined workspace does not include all the required rivet positions, warnings will be triggered when users attempt to access to a rivet outside the workspace. The virtual workspace then needs to be re-positioned to complete the task. Therefore, some minor accuracy differences may still exist between these two techniques and *Co-manipulation* may lead to a better accuracy in position. The lack of significant differences could maybe be explained by the fact that I averaged the measurements when there were several workspace manipulations in one trial, which consequently reduced the bias.

Participants agreed that it was the leader who directed the workspace positioning in *Leader-and-Follower*. However, no significant difference in levels of verbal activity and contribution was found, which rejects **H3**. This can be explained by the fact that the individual position criteria were provided to the follower which required them to actively join the workspace positioning task. I also did not detect any significant difference between *Leader-and-Follower* and *Co-manipulation* for cognitive task load. Although the *Co-manipulation* can be more efficient, a few participants also felt "out of control" (P4) in such a condition as the simultaneous manipulation inevitably produced "conflicts" (P11) during the virtual workspace positioning. This may also explain why a significant number of participants, especially those in the leader role, preferred to use the *Leader-and-Follower* technique.

5.4 Conclusion

This chapter proposes and evaluates two interactive techniques that can help co-located users to recover spatial consistency between their real and virtual workspace after individual teleportation, when using HMD technologies. Such interactive techniques can be interesting in complex collaboration scenarios where the users need to perform individual activities and collaborative sub-tasks at different times in a full workflow. During the collaborative phase, the recovered spatial consistency allows the users access to surrounding virtual objects through physical movements. Moreover, it enables direct physical interaction between the users and prevents perceptual conflicts due to the dual presence of the users and their avatars in the virtual scene.

These multi-user consistency recovery techniques use a virtual representation of the user shared real workspace. Users are provided with two different interactive approaches to position this virtual representation in the VE by taking into account the requirements of the subsequent collaborative tasks. In the *Leader-and-Follower* technique, only one of the users can manipulate the virtual workspace, while the other users have to communicate their needs with verbal suggestions or other communication cues. The *Co-manipulation* technique integrates all of the users' inputs equally, thus enabling simultaneous positioning of the virtual workspace. For this technique, I design and implement a novel concurrent manipulation technique using physically-based approaches with a mass-spring-damper system and bent-ray control. This co-manipulation technique takes into account the translational force coming from each user and uses bent rays to provide continuous visual feedback to each user for collaborative manipulation. The deformation of the curved ray indicates the direction and intensity of the user's drag on the virtual workspace.

I conducted a controlled experiment to evaluate the performance of the two techniques in a collaborative virtual riveting task. The results showed that the positioning of the virtual workspace can be significantly faster with *Co-manipulation* than with *Leader-and-Follower*. In *Co-manipulation*, the user intents can be directly communicated by manipulating their future virtual workspace, shortening the time it takes to communicate its correct position allowing an efficient subsequent collaborative task. In addition, significantly more attempts to reposition the virtual workspace and more warnings given when the users collided with the workspace borders during the collaborative task were measured in *Leader-and-Follower*. This result suggests that *Co-manipulation* may lead to better positioning accuracy. However, despite a better performance of the *Co-manipulation*, it also introduces conflicts in the way to position the virtual workspace. Moreover, it is sometimes difficult for users to understand their impact on controlling the final position and orientation of the workspace during the co-manipulation.

Nevertheless, *Leader-and-Follower* may be a relevant technique to reach the spatial consistency when one of the users is well aware of all the requirements of the subsequent collaborative tasks. For example, in training or education application, the trainer may be responsible for placing the workspace to include all the required training contents for the following tasks. Moreover, this technique can also be applied for asynchronous collaborative interaction. In a collaborative system that uses tangible interaction, a user can define a workspace and leaves a tangible prop in it. When other users arrive to the scene, they can continue to use that same prop within the workspace configured by the previous user.

Both of these techniques can be extended to collaborative tasks involving more than two users. However, some improvements are necessary to adapt the workspace positioning techniques, especially for concurrent manipulation done by more than two users. One of the possible approaches that I envision is to display the targeted positions for the users, i.e., the P_1 and P_2 in Figure 5.3, so that they can explicitly convey their desired position during *Co-manipulation*. However, such additional visual cues would also increase the cognitive load during the workspace positioning phase. In addition, further investigation is needed to determine which technique is the most appropriate with different numbers of users and in various collaboration scenarios.

Last but not least, the spatial consistency recovery can be more complex in a context of remote collaboration. Defining a shared virtual workspace with recovered spatial consistency allows remote users to exchange spatial information using the same coordinate system. In addition, the beforehand positioning of the virtual workspace avoids cognitive overload for users. Since in the case of spatial desynchronization, they need to use navigation metaphors to manage the accessibility of virtual objects and perform collaborative tasks simultaneously. However, in remote collaboration, users can use different VR systems with motion tracking areas of different shapes and sizes. In addition, the navigation metaphors used by users can also vary depending on the system used. These issues introduce additional constraints in defining spatial consistency areas and create additional challenges for the compatibility of recovery techniques.

Conclusion

The design of many virtual reality applications relies on complete position and orientation matching between the user real and virtual workspaces. The spatial consistency provided by such matching allows the user to take advantage of the complete tracking area to walk and interact intuitively with the virtual surroundings. In addition, such one-to-one mapping allows real-world objects presented in the scene to provide tangibility to associated virtual objects, overcoming the lack of haptic feedback in everyday use of virtual reality.

In collaborative virtual reality systems, maintaining a consistent spatial configuration between the real and virtual environments allows users to interact with each other as if they were in the real world. Besides, the spatial consistency prevents mutual collision and perceptual conflicts which could occur when user positions in the real world differ from their avatar positions in the virtual world. The latter situation, also known as spatial desynchronization, can usually be found in scenarios where individual navigation capabilities are provided to the user. The virtual navigation technique allows the user to explore a virtual environment larger than their real workspace. However, it breaks the spatial configuration between the real and virtual workspaces.

Contributions

This dissertation describes my efforts to make spatial consistency compatible with large-scale virtual environments. My goal is to provide a seamless transition to help the user to recover the one-to-one mapping in certain areas of the virtual environment after individual virtual navigation. **I identify four factors in designing the spatial consistency recover technique, including the system and the virtual navigation metaphor employed, as well as the tangibility and number of users involved.** My research work is then organized around these factors.

To help the user to recover this one-to-one mapping after individual navigation, I am interested in designing efficient and valid interactive techniques. However, spatial consistency recovery depends on the navigation metaphor, and thus I decide to focus on the teleportation. I choose this metaphor since it is one of the most commonly used navigation techniques. In addition, compared to other navigation techniques, instantaneous transitions reduces the user's simulator sickness caused by sensory conflicts between the visual and vestibular systems.

Based on the proposed design space, this thesis explores appropriate spatial consistency techniques in different immersive environments (CAVE vs. HMD) and various interaction contexts (individual interaction, tangible situations, and co-located collaboration), and validates them using experimental studies.

For virtual reality systems with predetermined shapes and sizes, such as CAVE-like systems, I propose two interactive techniques that allow users to recover spatial consistency in pre-defined areas of the virtual environment (see Chapter 2). **The first technique allows users to quickly restore spatial consistency through two steps: selection and activation. The second technique has an additional visual feedback of the user arrival destination improving the user spatial awareness and performance in the subsequent task.** I conducted a controlled experiment to compare these two recovery techniques with a basic teleportation condition to verify if the recovered spatial consistency can improve the accessibility to multiple virtual objects. The results showed that restoring spatial consistency during virtual navigation led to higher task performance, and the additional visual feedback appeared to provide the user with a better understanding of the resulting spatial configuration.

However, during the design of real VR applications, the size and shape of the user real workspace are usually unknown for the designer, especially when applications use head-mounted devices. To solve these problems, I propose two more generic solutions to define these areas in the virtual environment to restore the spatial consistency (see Chapter 3). **The first technique allows users to manually adjust the positioning of their future workspaces in the virtual environment. The second technique uses clustering techniques to automatically generate a range of possible virtual workspaces based on the VE layout and recommend them to the users.** I conducted two controlled experiments to evaluate these two approaches with different virtual environment layouts. The results demonstrated the benefits of the virtual workspace positioning approaches over a basic teleportation. Automatic generation of possible future workspaces seemed to be better suited for sparse virtual environment layouts, while manual positioning might be preferable in crowded scenes.

Application requirements often bring additional limits when defining spatial consistency areas in a virtual environment. For example, passive haptic inter-

action requires a strict one-to-one mapping between the tangible prop and its virtual counterpart. To address this limitation, **I propose three interactive techniques that allow users to explore large virtual environments while obtaining passive haptic feedback through real-world objects (see Chapter 4)**. By teleporting the user, the object, or both accordingly to a new position, these methods correct the spatial mismatch between real and virtual objects during teleportation navigation, thus enabling tangible interaction.

In addition to tangible interactions, the presence of other users in the real workspace can also impose limitations when defining spatially consistent areas. It is thus crucial to provide users with an effective way to communicate their future workspace positioning, taking into account their different intentions. Targeting these issues, I propose two strategies to allow users to manage and recover the spatial consistency for a subsequent collaborative task (see Chapter 5). **The first technique allows one of the users to define the area to recover spatial consistency, and the other user can only select the area previously specified by the first user. The second technique allows both users to contribute equally to define the spatial consistency area using spring-damper system.** I run a controlled experiment to evaluate these two techniques. The results showed that the co-manipulation method significantly reduced the time spent negotiating the position of the future workspace. However, the inevitable conflicts in simultaneous collaborative manipulation can also be confusing to them.

Future Work

In this thesis, I discuss spatial consistency related issues and propose different spatial consistency recovery techniques for teleportation navigation in the face of different systems and application requirements. However, the proposed solutions still have limitations that lead us to some new future research directions.

Other Navigation Metaphors

This thesis presents different interactive techniques applicable to the teleportation metaphor. These techniques allow users to move to the corresponding destination immediately after initiating the consistency recovery process. As mentioned in Chapter 2, one can continue to work on spatial consistency recovery techniques for other navigation metaphors, such as steering techniques. Referring to "continuous control of the direction of motion by user" [20], steering techniques allow users to gather more spatial information about the integration of the path and retain the sensation of movement. Such techniques usually map user input to velocity or acceleration control of the user motion in the virtual environment. The corre-

sponding recovery techniques can be thus designed according to the characteristics of the steering metaphors used.

For those velocity-based metaphors, for example, the consistency recovery can be achieved by smoothly joining the user to the targeted destination following a path computed by the system using pathfinding algorithms. However, since the user does not have control over their movements during the recovery phase, the loss of control may frustrate them and trigger motion sickness. Also, depending on the pathfinding algorithm used, users may risk crossing the virtual obstacle presented on the path, affecting the virtual experience authenticity. For acceleration-based steering techniques, additional forces can be added to the user to pull them toward a spatially consistent configuration, for example, by using a mass-spring and damper system that connects the user and the targeted destination. As a result, the user retains some control during the recovery phase, increasing their involvement and avoiding colliding with virtual obstacles that appear in the path.

Automatic Technique Enhancements

Chapter 3 presents an automatic method that allows the system to use algorithms to compute possible spatially consistent areas for the users based on the layout of virtual objects in the virtual environment. However, this method might induce a higher cognitive load for crowded scenes. Therefore, one of the future research directions is to enhance the automation technique by adjusting the clustering algorithm to obtain a good balance between the proposed number of virtual workspaces depending on the virtual scenario and the real workspace configuration. Moreover, depending on user expectations, skills and experiences, the virtual workspace's visual feedback could be automatically adjusted based on the amount of information contained in the scene [43] to avoid overloading the user's field of view and to fit virtual scenario needs.

Further Assessments for Tangible Interaction

Further investigations are required to evaluate the consistency recovery techniques presented in Chapter 4 for tangible interactions. It would be interesting to evaluate these techniques in various virtual scenarios using objects of different shapes, sizes, and characteristics. For instance, the teleportation of the user can be more appropriate than teleportation of the object or hybrid teleportation to allow the user to touch virtual objects in the scene that are considered immovable. In addition, it remains unclear how the techniques would perform in other VR scenarios or more cognitively challenging situations, for example, in an exploration task where the main goal is not purely to interact with objects.

Generic Model for Remote and Heterogeneous Systems

The last part of the thesis proposes several recovery techniques for co-located collaboration. Still, as mentioned in Chapter 5, it would be interesting to propose a generic model adapted to other collaborative contexts. For example, users usually possess different real workspaces in a distributed collaborative system constrained by the motion tracking area, physical obstacles, and the range of devices (e.g., haptic). By partially superposing user real workspace with the shared virtual workspace, spatial consistency can be recovered for remote users inside the overlapping area. Therefore, a generic superposing mechanism that can generate appropriate overlapping areas to meet different task demands is necessary. Users may use different navigation metaphors, in particular when heterogeneous devices are involved. Therefore, a generic switch model should also be able to process such asymmetric situations in a collaborative context.

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