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Traceable teleportation: Improving spatial learning in virtual locomotion

Ye Jia [a,*], Zackary P.T. Sin [a], Chen Li [a,b], Peter H.F. Ng [a,c], Xiao Huang [a], George Baciu [a], Jiannong Cao [a], Qing Li [a]

[a] Department of Computing, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region of China
[b] Department of Applied Social Sciences, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region of China
[c] Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region of China

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ABSTRACT

In virtual reality, point-and-teleport (P&T) is a locomotion technique that is popular for its user-friendliness, lowering workload and mitigating cybersickness. However, most P&T schemes use instantaneous transitions, which has been known to hinder spatial learning. While replacing instantaneous transitions with animated interpolations can address this issue, they may inadvertently induce cybersickness. To counter these deficiencies, we propose ***Traceable Teleportation (TTP)***, an enhanced locomotion technique grounded in a theoretical framework that was designed to improve spatial learning. *TTP* incorporates two novel features: an *Undo-Redo* mechanism that facilitates rapid back-and-forth movements, and a *Visualized Path* that offers additional visual cues. We have conducted a user study via a set of spatial learning tests within a virtual labyrinth to assess the effect of these enhancements on the P&T technique. Our findings indicate that the *TTP Undo-Redo* design generally facilitates the learning of orientational spatial knowledge without incurring additional cybersickness or diminishing sense of presence.

1. Introduction

Although users feel immersed in boundless virtual spaces in virtual reality (VR), they are also usually confined within limited physical spaces. Among these, point-and-teleport (P&T) is one of the most studied VR locomotion techniques by the VR research community (Martinez et al., 2022). Widely used in various VR applications, the P&T technique can have different variants, but typically, all these implementations follow a "classical" instant transition P&T scheme: users can point to a position in virtual spaces, trigger the teleportation, and then their viewpoints will be *instantaneously* translated to that position (Bozgeyikli et al., 2019, 2016).

Compared to other VR locomotion techniques, the P&T can emerge as a particularly advantageous technique in some areas. Notably, Bozgeyikli et al. have highlighted its efficacy in facilitating travel across extended distances within virtual environments (VEs). This is a finding that underscores its potential for enhancing navigation in VR (Bozgeyikli et al., 2019). Additionally, the consensus that appears to be forming in the research community is that P&T tends to yield lower instances of cybersickness in comparison to steering-based methods, such as those that employ a joystick for movement control (Bozgeyikli et al., 2016; Habgood et al., 2018).

However, P&T is not without its drawbacks. While efficient, the instantaneous point-and-teleport method can lead to increased disorientation; it may also diminish the sense of presence within the VE (Bowman et al., 1997; Ruddle and Lessels, 2009; Clifton and Palmisano, 2020) (but not all studies agree). Alternatively, animated teleportation can be used. It seeks to offer a smoother transition by simulating continuous motion during teleportation, but it has the drawback of potentially elevating the risk of cybersickness (Rahimi et al., 2018). Thus, it seems to be relatively less used. These drawbacks pose a significant conundrum for VR developers, who must weigh the trade-offs between preserving a user's spatial orientation and inducing cybersickness. Therefore, it is imperative to enhance the P&T technique by finding a middle ground that mitigates these challenges. This would make VR more appealing to a wider audience. To understand why the classical instant P&T causes disorientation, we need to understand our surrounding environment spatially. Spatial learning is the pivotal internal process in which we model our environment into spatial knowledge (Chrastil and Warren, 2012; Miola et al., 2021). In virtual environments, the ability to understand and memorize spatial knowledge (e.g. spatial layout, environment features) is crucial for effective navigation and interaction (Singer et al., 1997; Lokka and Çöltekin, 2020). Without robust spatial learning, users may not only experience disorientation

* Corresponding author.
E-mail address: ye-aimmeng.jia@connect.polyu.hk (Y. Jia).

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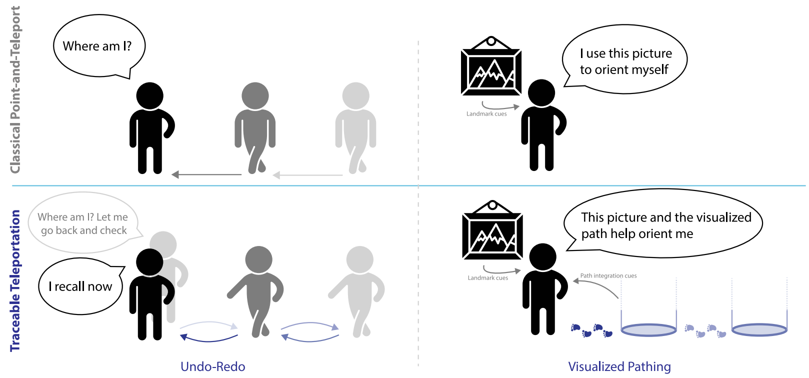

Fig. 1. The classical P&T of VR locomotion technique (top) may hinder users' spatial learning in virtual spaces. The proposed *Traceable Teleportation (TTP)* (bottom) boosts users' orientation by incorporating two novel features: an *Undo-Redo* mechanism (left) and a *Visualized Path* (right).

but also reduced efficiency in task completion (Müller et al., 2023), a diminished sense of presence (Buttussi and Chittaro, 2023), and a frustrating user experience (Langbehn et al., 2018). Thus, addressing these cognitive issues is one of the keys in improving P&T.

With this in mind, we can examine the P&T technique to understand why it may impair spatial knowledge. All P&T techniques can be dissected into three key phases. The first phase is the *selection phase*, during which users can first select a position in virtual spaces, usually by pointing and then confirming the selection. This leads to the second phase - the *transition phase*, which varies based on the type of teleportation. In the instant teleportation approach, the user's viewpoint is rapidly transferred to the selected destination with a minimal visual transition – such as a quick-shifting frame or a brief blank interlude – resulting in an immediate and stark transition in the visual scene. This process is noticeably less gradual than animated teleportation, which conveys the user's perspective through the virtual environment with a more protracted, fluid animation that mimics the sensation of "flying", "gliding", or "walking", providing a movement experience that unfolds more slowly and mimics natural motion. The third phase is the *reorienting phase*; it is the phase where the users move to and acclimatize in their new virtual location. Upon completion of the teleportation process, whether instantaneous or animated, users will familiarize themselves with their surroundings.

This paper's main contribution is to investigate how to enhance spatial knowledge for the classical P&T technique. Particularly, we choose to focus on the instant variant of P&T as animated teleportation will result in significant cybersickness. Thus, by starting with instant P&T, we develop a teleportation technique that can enable better spatial learning without exacerbating cybersickness.

To pinpoint the bottlenecks of P&T, we first enter a theoretical discussion that highlights possible improvements on spatial learning that could be made regarding a user's egocentric and allocentric spatial updating. Via observing the classical P&T, we find that improvements can be specifically made at the selection phase. Based on this finding, we propose ***Traceable Teleportation (TTP)***, which contains two enhancements to P&T for addressing its enduring problem with spatial learning (Fig. 1). Specifically, we first add an *Undo-Redo* mechanism to the selection phase, so that users can instantly teleport to their previously visited locations without the need to turn around and re-select their desired destinations. This feature helps the user to memorize the walk path by repetitive practice and repetitive optical flow. Second, we introduce *Visualized Path*, which enables users to review where they have visited locations by providing them with visual cues, including halos that highlight the teleportation start and end points, and virtual footprints connecting the halos. Both features facilitate the reorienting phase by improving the users' spatial learning, and ultimately facilitating navigation and orientation within virtual spaces.

To summarize, this paper aims to improve spatial learning for the classical P&T technique. We first start by exploring and pinpointing the deficiency of P&T in learning spatial knowledge via a theoretical discussion. Based on this discussion, we propose *TTP*, which includes two enhancements, *Undo-Redo* and *Visualized Path*, that can theoretically improve users' spatial knowledge (Section 3). To evaluate the proposed enhancements, we conducted a user study with a virtual labyrinth (Section 5). Experiments show that *TTP*'s *Undo-Redo* feature has significantly improved users' spatial knowledge of the labyrinth regarding orientation. The contributions are as follows:

- ***Traceable Teleportation (TTP)***, which enhances the classical P&T technique with *Undo-Redo* mechanism and *Visualized Path*. These enhancements aim at improving spatial learning.
- A theoretical discussion on P&T which pinpoints its bottleneck in spatial learning.
- A user study shows that *TTP*, specifically its *Undo-Redo* component, can enhance spatial knowledge for orientation without exacerbating cybersickness.

2. Related work

Locomotion is a broad topic in VR (Martinez et al., 2022). In this section, we will first provide a brief overview on different locomotion techniques, followed by a discussion on recent locomotion works on spatial learning, presence and cybersickness. Lastly, we will discuss other VR locomotion works that are based on P&T. Generally, there is a lack of discussion on how to improve spatial knowledge learning for the classical instantaneous P&T technique.

2.1. Types of VR locomotion

A classification system put forth by Di Luca et al. (2021) identifies four predominant methods by which users can traverse VEs: Walking in VR, Steering, Selection and Manipulation. Walking in VR mimics the natural movement of walking, enabling users to either physically walk within their actual space or simulate walking in place. This method is designed to mirror the intuitive experience of moving in the physical world and foster a strong sense of presence (Steinicke et al., 2009). Steering allows users to control their movement through the virtual space using devices like joysticks or controllers, offering a flexible approach to navigating without physical space requirements, akin to driving or flying (Raees et al., 2019; Usoh et al., 1999; Bozgeyikli et al., 2018; Zhang et al., 2019). Selection, or P&T, is a method that lets users move instantly to a chosen location within the virtual space, bypassing the need for walking or other physical locomotion, which can be ideal for limited physical environments (Medeiros et al., 2019; Matviienko et al., 2022). Manipulation involves direct interaction with the virtual environment, such as pushing virtual buttons or sliding the scenery, to initiate movement, leveraging hand controllers or gestures for navigation (Simeone et al., 2020). Generally, the previous research papers on locomotion interfaces propose a novel way to navigate in an environment. Ours, on the other hand, focuses on improving spatial learning for P&T.

2.2. Locomotion works on spatial learning

Recent studies have explored the impact of different VR locomotion techniques on spatial learning. Specifically, previous works showed mixed results in terms of spatial understanding (i.e., the ability to comprehend, analyze, and reason about spatial information) and spatial memory (i.e., the cognitive process of storing and retrieving information about the spatial environment). Buttussi's study demonstrates that the fidelity of VR setups and the choice of locomotion technique, such as teleport and steering, significantly impact the acquisition and retention of spatial knowledge in virtual environments (Buttussi and Chittaro, 2023). Langbehn et al. conducted an orientation performance assessment comparing joystick-based steering, P&T selection, and redirected walking techniques, and found no significant differences in spatial orientation across these methods (Langbehn et al., 2018). In a similar vein, Xu et al. utilized a placement error task to measure the precision of spatial memory and understanding, revealing that walking-in-place, P&T, and joystick-based steering locomotion techniques had comparable effects (Xu et al., 2017). Contrastingly, Harris et al. reported that users exhibited greater errors in a spatial orientation task when using a joystick-based steering technique as opposed to a leaning-based method. However, no notable discrepancies were observed between the leaning and the walking-in-place techniques (Harris et al., 2014). In another study focusing on distance estimation within VR, Keil et al. found that participants using P&T outperformed those using steering-based methods, suggesting an advantage for the teleportation technique in judging spatial distances (Keil et al., 2021). Although these studies have investigated virtual locomotion techniques regarding spatial learning, discussion on how to improve their spatial learning is sparse. However poor spatial learning is a noticeable issue as it will result in a worse user experience due to disorientation. This gap has motivated us to propose novel enhancements to the P&T technique to improve its efficacy in spatial knowledge acquisition and retention.

2.3. Locomotion works on presence and cybersickness

The exploration of VR locomotion techniques' effects on presence (i.e., the sense of being there in the virtual spaces), workload (i.e., the cognitive, perceptual, and/or physical demands placed on a user while interacting with a VR system) and cybersickness have produced insightful findings. Buttussi et al. examined the influence of joystick-based, P&T, and leaning-based methods, discovering that teleportation was associated with reduced nausea without affecting the sense of presence when compared to the other techniques (Buttussi and Chittaro, 2019). Likewise, in a study by Langbehn et al. P&T was found to result in the lowest levels of cybersickness relative to joystick-based navigation, though it did not significantly affect presence or workload (Langbehn et al., 2018). Kim et al. and Christou and Aristidou also show similar results in that steering generates more cybersickness than teleportation (Kim et al., 2023; Christou and Aristidou, 2017). In contrast, the study by Clifton et al. found the presence is worse for P&T compared to the steering locomotion (Clifton and Palmisano, 2020), which also aligns with Habgood et al.'s work (Habgood et al., 2018). Bozgeyikli et al. expanded on these comparisons by evaluating walking-in-place, P&T, joystick-based, flying, and hand-flapping techniques. Their study indicated no significant differences in cybersickness between the methods, yet significant variations in presence were observed, underscoring the nuanced effects of locomotion type on user experience (Bozgeyikli et al., 2019). Usoh et al. focused on subjective presence and compared real walking with virtual walking-in-place and a flying technique, noting a pronounced disparity in presence, with flyers feeling less present than participants who engaged in either form of walking (Usoh et al., 1999). Overall, it seems that generally, P&T method has been considered as a locomotion technique that mitigates perceived cybersickness. Its impact on presence, however, remains unclear. Nonetheless, there is evidence suggesting that in some instances, P&T can achieve a level of presence nearly equivalent to that of steering-based locomotion techniques. Thus, due to its lower cybersickness and possibly comparable presence, we choose the commonly used P&T as the interface to improve spatial learning.

2.4. P&T-based works

As mentioned, teleportation has three phases, transition, selection and re-orientation; these phases have been investigated by scholars. For the selection phase, a significant contribution has been made by Medeiros et al.; they advocate for parabolic casting, demonstrating its superiority in terms of speed and precision when compared to linear casting and active play area steering (Medeiros et al., 2019). In another work, Matviienko et al. complement these findings by showing how the amalgamation of linear aiming with immediate transitions can further boost the efficiency of target acquisition (Matviienko et al., 2022). Of particular note, Müller et al. introduced an Undo feature in their work (Müller et al., 2023), which shares similarities with our approach, yet differs significantly in three main aspects. First, while Müller et al. focused on exploration efficiency, our study is concerned with spatial learning. Second, our proposed *Undo-Redo* mechanism includes an additional Redo action, differentiating it from Müller's work. While the Undo function allows users to move backwards, it does not facilitate navigation back to pre-Undo locations. The addition of the Redo function to the selection phase, on the other hand, enables users to navigate through their teleportation history, both forward and backward. This design difference will subsequently result in different effects in terms of spatial learning. Undo will only assist in the efficiency of going backwards, while with Undo-Redo, users will be efficient with visiting the same area by moving backwards and forward. We will later show that repeated movement encourages spatial learning in Section 3. This important design difference also leads to the third difference; Müller et al. reported that the Undo action alone would impair spatial orientation, whereas our findings indicate that additionally incorporating a Redo function enhances spatial orientation.

Regarding the transition phase, Müller et al. have focused on optimizing movement visualization. Their research indicates a user preference for discrete visualization techniques, which are promising in reducing the incidence of cybersickness (Müller et al., 2023). This finding contrasts with Bhandari et al. who integrated a swift, continuous transition process that preserves optical flow without exacerbating VR sickness (Bhandari et al., 2018).

From the above, we can see that there is a lack of investigation in how to improve spatial learning for locomotion. At the same time, there is also a lack of locomotion work regarding how to quickly travel back-and-forth. Combined with our theoretical discussion later, we believe that the current P&T paradigm necessitates repeated selection processes for revisiting prior destinations. Thus, in pursuit of a more efficient mechanism, we propose the *Undo-Redo* scheme, which facilitates swift navigation among previously visited teleportation points without reinitiation of the selection phase for the purpose of spatial learning.

3. The traceable teleportation

The design of the proposed *TTP* technique is based on our theoretical analysis of how we, as humans, handle our surrounding spatial environment in VR. Our spatial knowledge learning process is mainly driven by two cognitive processes: egocentric and allocentric spatial updating. Due to its instant transition, the classical P&T hinders them. To address this issue, the proposed *TTP* theoretically bolsters these spatial updating processes, via *Undo-Redo* and *Visualized Path*, to amplify spatial learning. We show an overview of our theoretical discussion and how it connects to *TTP* with Fig. 2.

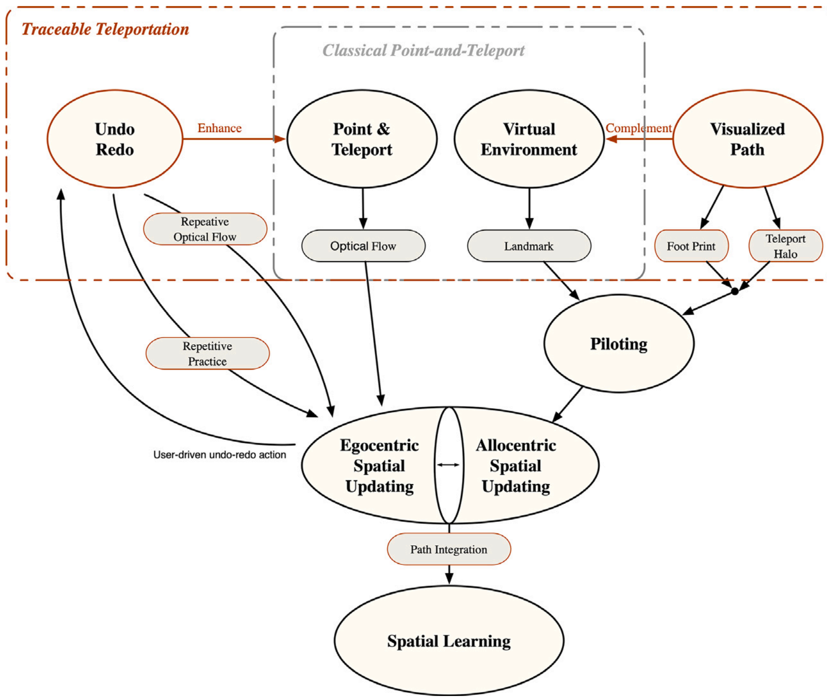

Fig. 2. The conceptual framework for spatial learning in P&T technique. Enhancements of *Traceable Teleportation (TTP)* are *Undo-Redo* and *Visualized Path* (red).

3.1. The theoretical framework

In this section, we lay out the theoretical framework concerning how virtual locomotion interacts with human perception of space. This discussion will enable us to highlight the issues of the classical P&T regarding disorientation. Particularly, we will discuss spatial learning and some key related concepts; they are egocentric spatial updating, allocentric spatial updating, piloting and optical flow. Their relationships are depicted in Fig. 2 as well.

Spatial Learning: When a human needs to navigate within an environment, they will need to first form a mental representation of their surrounding environment; the cognitive process is referred to as *spatial learning* (Chrastil and Warren, 2012; Miola et al., 2021; Tolman, 1948). More formally, it is the process for spatial understanding and constructing spatial memory, that is to acquire and memorize *spatial knowledge* (Buttussi and Chittaro, 2023; Shi et al., 2021), which is the knowledge about (virtual) environments' spatial properties (Kuipers, 1978) demonstrates that better spatial learning leads to improved spatial learning (Siegel and White, 1975; Werner et al., 1997). Naturally, the ability to comprehend the spatial layout of our environment is integral to routine activities—ranging from commuting and running errands to locating restaurants or finding our way home (Chrastil and Warren, 2012). This is driven by the acquisition of spatial knowledge, or spatial understanding, which lays the groundwork for memory by sensing the environment, identifying features, recognizing objects and categories, and constructing internal representations (Fuster, 2002). This internal framework manages spatial information, which subsequently forms the basis for spatial memory. On the other hand, the memorization of spatial knowledge, or spatial memory, is a facet of our memory system, which encodes, retains, and retrieves spatial details about our environment and our location within it—information crucial for goal-oriented navigation and indispensable for any embodied agent (Madl et al., 2015). The closely linked cognitive processes of spatial learning enable us to perceive, represent, and manipulate spatial information. Additionally, research also demonstrates that the learning process usually transitions from using simple symbolic memory anchors, such as landmarks, to more advanced cognitive mapping, like survey knowledge, and this process generally requires significant time (Shi et al., 2021).

It should be noted that our work treats spatial understanding and spatial memory as integral components of spatial learning. To learn about our spatial environment, we need to first keep track of ourselves with respect to the surrounding objects and environment.

Egocentric and Allocentric Spatial Updating: To keep track of their surroundings, humans typically employ an internal navigation model, termed *spatial updating*, for processing spatial information (Wang and Brockmole, 2003; Klatzky, 1998; J. Farrell and Thomson, 1998; Klatzky et al., 1998). It further relies on two types of spatial representation frameworks, one egocentric and the other allocentric. An egocentric representation references our current bodily position, such as the relationship between our location and the target's position (Klatzky, 1998). In contrast, an allocentric representation references outside of one's current body position, typically to multiple external landmarks. This is done by people developing the ability to imagine transformations or to use visual information without coupled vestibular and proprioceptive information to specify movement (Allen, 2003). This is often the case when drawing a cartographic map of an environment, as it necessitates detailed knowledge of the relative directions and distances of stationary landmarks (Klatzky, 1998; Meilinger and Vosgerau, 2010).

During egocentric spatial updating, a navigator utilizes both internal (idiothetic) signals (e.g., proprioception and vestibular feedback) and external (allothetic) signals (e.g., acoustic and optic flow) to continuously compute estimates of self-position and orientation within external space (Loomis, 1999). However, when there is a mismatch or conflict between the visual and vestibular inputs in VR, it can result in a perceptual illusion or distortion of spatial understanding. In such cases, the brain may prioritize one sensory input over the other, leading to a distorted perception of space, distance, and self-motion (Morat et al., 2021), and affecting the user's spatial understanding. On the other hand, in the context of allocentric spatial updating, this type of spatial updating relies on an allocentric reference frame (akin to the third-person perspective) (Klatzky, 1998) or an environmental representation system (Mou et al., 2004) to visualize the coordinates of objects, landmarks, and places and their interrelationships. Ultimately, both of

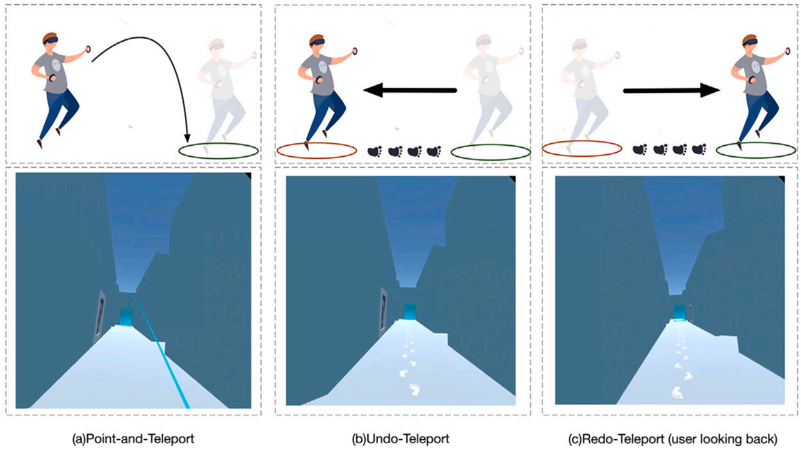

Fig. 3. Overview of the proposed *Traceable Teleportation (TTP)* VR locomotion technique. *(a)* The classical P&T. *(b)* Users can swiftly return to the starting point by utilizing the undo feature of the *Undo-Redo* mechanism and the *Visualized Path* contains the teleport halos and footprints. *(c)* Users can employ the redo feature of the *Undo-Redo* mechanism to revisit previous teleportation records in their history and the *Visualized Path* contains the teleport halos and footprints.

these representations are integrated through a cognitive process known as *path integration*, which is essential for spatial learning. This spatial learning then forms spatial understanding and memory and finally becomes an individual's spatial knowledge. Note that egocentric and allocentric spatial updating can rely on different methods to operate. Here, we focus on the fact that egocentric and allocentric spatial updating rely on optical flow and piloting to effect, respectively.

Optical Flow, or optic flow, is the perception of self-movement within a structured environment, leading to retinal image motion (Niemann et al., 1999). This phenomenon is crucial in adapting the visuo-locomotor mapping system (Bruggeman et al., 2007) and enhances spatial integration (Ayaz et al., 2013). It also influences both additive and multiplicative tuning gains for visual features such as orientation, direction, and spatial frequency (Dadarlat and Stryker, 2017; Mineault et al., 2016). Due to tracking space constraints in most VR applications, providing sufficient vestibular information in VEs is often impractical. Therefore, optical flow is seen as a reliable method for humans to execute egocentric spatial updating in VEs. The feasibility of integrating optical flow into VEs to enhance egocentric spatial updating has been validated in VR research (Kearns et al., 2002; Mollon, 1997) . Especially for teleportation, the locomotor direction is determined by the point in the flow field from which motion vectors radiate (Mollon, 1997), underlining the significance of optical flow in facilitating spatial awareness. However, as the classical instant P&T quickly transfers the user from one point to another, it is believed that the user will have difficulty processing the optic flow for spatial updating. Our experiments later will highlight this issue by comparing the classical implementation with our *Undo-Redo* enhancement that aims at improving egocentric spatial updating.

Piloting is integral to the human allocentric spatial updating cognitive process, an essential mental subroutine that facilitates understanding and memorization of space by referring to the process of memorizing locations as spatial anchors. Ordinarily, piloting involves observing known landmarks and determining the spatial relationships between the observer and these landmarks (Grant and Magee, 1998).

Proximal landmarks located close to the observer, predominantly provide positional information, while distal landmarks, situated farther away, convey directional information (Padilla et al., 2017). Besides landmarks, the environmental shape – such as that determined by room walls – can also serve as a significant cue for piloting (Kelly et al., 2008). By utilizing these visual cues to guide movement and navigation, individuals can navigate through their environment more effectively and efficiently, especially in situations where egocentric spatial updating may be unreliable or unavailable, such as in long-distance navigation (Ekstrom and Isham, 2017). Thus, ensuring features such as landmarks and environmental shapes are in sufficient numbers in VEs is an important consideration when facilitating efficacious piloting and navigation. In the subsequent section, we will introduce our proposed *Visualized Path*, which theoretically enhances the integration of navigational cues, thereby improving allocentric spatial updating.

3.2. Enhancements for the classical P&T

Humans use allocentric and egocentric spatial updating to gain spatial knowledge, which includes information about directions, angles, and distances (Cherep et al., 2020; Vasilyeva and Lourenco, 2012; Waller and Hodgson, 2013). The classic P&T method, as illustrated in Fig. 2, supports both egocentric and allocentric spatial updating by leveraging optical flow and environmental cues. However, compared to other virtual locomotion techniques, such as redirected walking, the P&T method lacks vestibular information. This absence hinders users' egocentric spatial updating, leading to inefficiencies in spatial knowledge acquisition (Kearns et al., 2002). To mitigate this limitation, the classic P&T technique can be enhanced by reinforcing the two spatial updating processes separately. This approach ensures that both allocentric and egocentric types of spatial updating are adequately covered, thereby improving the overall efficacy of the P&T method in facilitating spatial knowledge acquisition in VEs.

Enhancing Egocentric Spatial Updating: We propose the use of an *Undo-Redo* functionality to strengthen egocentric spatial updating, assisting users in reducing their efforts on spatial navigation and retaining orientation information. As depicted in Fig. 3(c) and (d), users can swiftly move to previous teleport points, and subsequently, easily return without the need to look back. This method allows users to retain more directional spatial information compared to the classical P&T method, where users need to re-select their destinations to achieve the same actions.

The *Undo-Redo* functionality theoretically contains two potential improvements. The first is Repetitive Practice, which has been identified as a critical factor in establishing durable memory due to its role in reinforcing neural connections (Oe et al., 2013). Research conducted on mice supports this, demonstrating that repeated training can stimulate brain functions, leading to a more pronounced use of hippocampus-dependent strategies (Lonnemann et al., 2023). Moreover, consistent practice has been shown to greatly enhance the levels of the Brain-Derived Neurotrophic Factor, which is crucial for regulating synaptic plasticity, including long-term potentiation. This has been demonstrated in studies involving rats (Mizuno et al., 2000). These findings underscore the potential of leveraging repetitive practice in VR locomotion techniques to enhance spatial memory. The second improvement is Repetitive Optical Flow. This can be attributed to the high-frequency teleport between the current location and the target position, as the user can directly teleport within the history points without needing to select points and then teleport. This repetitive optical flow provides users with more spatial information, potentially enhancing spatial memory formation while reducing cognitive load associated with repeated point selection.

Enhance allocentric spatial updating: We propose the *visualized path* strategy to provide more landmarks to users, thereby enhancing allocentric spatial updating. *Visualized Path* incorporates two elements: Teleport Halo and Foot Print. Specifically, *Visualized Path* includes the Teleport Halos of the most recent teleport positions, calculated using teleport history coordinates, and the connection of these halos by displaying the virtual footprints (See Fig. 3(a) and (b)). The halos and virtual footprints serve as virtual cues, potentially enhancing users' spatial learning within VEs. The size of the virtual footprint is calculated based on the user's height, matching their actual foot size , with the following formulas,

$$
\begin{aligned}
L_{height} &= L_{eye2foot}/\gamma \\
L_{footprint} &= L_{height}/\rho,
\end{aligned}
\tag{1}
$$

where the L_{height} denotes human height, L_{eye2foot} represents the distance from the eye to the foot that can be captured by the HMD when the user stands straight, and γ signifies the ratio of L_{eye2foot} to L_{height}. Additionally, ρ represents the height-to-foot ratio, and $L_{footprint}$ corresponds to the estimated footprint length as described in previous research. The value of γ is calculated to be approximately .911, as determined by the human body ratio parameters proposed in the previous study (Sheppard, 2013). Meanwhile, a value of ρ is set to 6, following the precedent established by prior work (Barreira et al., 2010). These parameters allow visual cues to translate distance information from the real world to VEs, thereby improving users' navigation and orientation within the virtual space. The *Visualized Path* serves as a guide for users to better navigate in VR, assisting them in understanding their location using proximal cues and their direction via distal cues (Padilla et al., 2017), and teleportation distance with the aid of footprints. Consequently, navigation and orientation within VEs may benefit from *Visualized Path*.

In summary, by combining *Undo-Redo* and *Visualized Path*, we propose *TTP* to enhance both egocentric and allocentric spatial updating, which can be used together to improve spatial learning (Cherep et al., 2020). This combination serves as a powerful tool for improving the teleportation experience, allowing users to easily retrace their steps for better spatial learning. By providing clear and intuitive guidance, our technique should enable users to teleport more efficiently and effectively, ultimately enhancing their overall experience.

4. Research question and hypothesis

Our study explores the effects of *TTP* on spatial learning. To this end, we used a unique labyrinth setting to quantitatively compare distance and angular offsets, which serve as objective measures of these impacts. Concurrently, we aim to ensure that the implementation of *TTP* does not compromise user experience while enhancing spatial learning. To assess the users' experience in VR, we adopted subjective measures, including the Simulation Sickness Questionnaire (SSQ), NASA Task Load Index (NASA-TLX), and the Igroup Presence Questionnaire (IPQ). All the measures are described in detail in Section 5.4. Our research questions and hypotheses were:

RQ1 Does *TTP* enhance users' spatial learning?
RQ2 What impact does *TTP* have on users' VR experience?

The introduction of the *Undo-Redo* and *Visualized Path* functionalities is hypothesized to independently augment both egocentric and allocentric spatial updates (Section 3). Accordingly, our research framework posits a discrete evaluation of the impacts attributable to each enhancement on spatial learning. Moreover, potential synergistic effects arising from the concurrent application of these enhancements will be subjected to analysis. As outlined in our conceptual framework depicted in Fig. 2, we have formulated hypothesis on spatial learning:

H1a The *Undo-Redo* mechanism significantly influences the human directional awareness.
H1b The *Undo-Redo* mechanism significantly influences the human distance estimation.
H1c The *Visualized Path* significantly affects the human directional awareness.
H1d The *Visualized Path* significantly affects the distance estimation.
H1e There exists an interaction effect between the *Undo-Redo* mechanism and the *Visualized Path* on the human directional awareness.

H1f There exists an interaction effect between the *Undo-Redo* mechanism and the *Visualized Path* on the human distance estimation.

Based on insights from prior research (see Section 2), several studies have suggested that P&T maintains a comparable sense of presence to other locomotion techniques (Bozgeyikli et al., 2019; Habgood et al., 2018; Langbehn et al., 2018; Buttussi and Chittaro, 2019). Furthermore, evaluations by Langbehn et al. indicate no significant difference in workload between teleportation and other locomotion methods (Langbehn et al., 2018). Additionally, teleportation generally results in lower cybersickness compared to other techniques (Bozgeyikli et al., 2019; Buttussi and Chittaro, 2019; Kim et al., 2023). Based on these presented discussions, we have formulated hypotheses on Cybersickness, Sense of presence, and Workload:

H2a Neither significant main effects nor interaction effects exist in the sense of presence (represented by IPQ sub-scores and overall scores) for both *UndoRedo* mechanism and *Visualized Path*.
H2b Neither significant main effects nor interaction effects exist in workload (represented by NASA-TLX sub-scores and overall scores) for both *UndoRedo* mechanism and *Visualized Path*.
H2c Neither significant main effects nor interaction effects exist in cybersickness (represented by SSQ sub-scores and overall scores) for both *UndoRedo* mechanism and *Visualized Path*.

5. Method

5.1. Experimental design and task

In this study, we examined the effects of *TTP* on users' spatial learning, workload, cybersickness, and sense of presence, employing a 2×2 factorial experimental design. Fig. 4 illustrates the experimental flow. We established three groups featuring different aspects of *TTP*: *TTP-UV*, which utilized the full functionality of *TTP*; *TTP-U*, which incorporated *TTP* without *Visualized Path*; and *TTP-V*, which used *TTP* without the *Undo-Redo* mechanism. The fourth group, *P&T*, operated with the classical P&T technique.

All four groups were administered the same set of target finding and memory tasks. The experiment was divided into three phases: training, exploration, and testing. For more detailed information about these phases, please refer to Section 5.5.

5.1.1. Participants

This study received ethical approval from the Institutional Review Board of The Hong Kong Polytechnic University. A total of 82 participants were recruited via on-campus posters and social networks. All participants were either studying or working at The Hong Kong Polytechnic University. Due to feelings of nausea, two participants chose to withdraw from the experiment. As a result, 80 participants were randomly assigned to one of four groups, with each group composed of 20 individuals. After the experiment, participants who were unable to locate all three targets were identified as non-completers (see

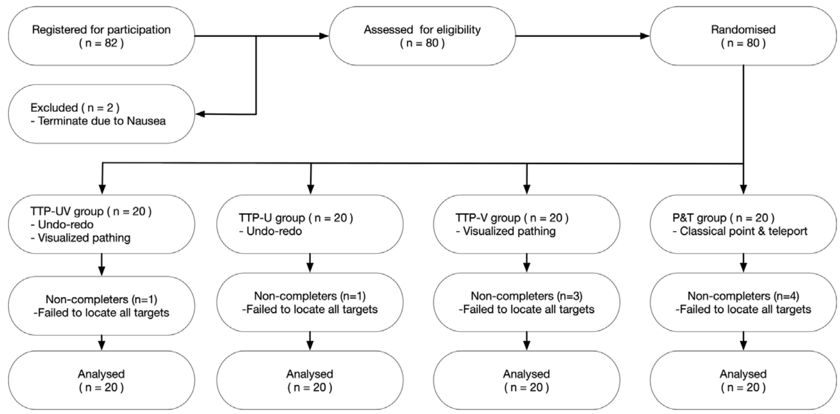

Fig. 4. The flow diagram of the experiment.

Table 1
Demographics of the participants.

	No. of participants	Gender, male(%)	Age, mean(SD)
TTP-UV	20	10 (50.00)	23.50 (4.39)
TTP-U	20	6 (30.00)	25.55 (7.92)
TTP-V	20	6 (30.00)	26.55 (7.80)
P&T	20	9 (45.00)	27.35 (7.10)
Total	80	31 (39.75)	25.74 (7.02)

Fig. 4). We have detail described how we handle the non-completers in Section 5.6.

The majority of participants had prior VR experience (61.25%) and regularly played video games (81.25%). To ensure the reliability of the study results and minimize the impact of confounding variables, only participants with normal or corrected-to-normal vision were included in the study, and those with color vision deficiency were excluded. Detailed demographics of the participants are provided in Table 1. Informed consent was obtained from all participants, who received a financial compensation of HK$50 for their time and involvement in the study.

5.2. Virtual labyrinth

There were prior works that applied a virtual labyrinth to test spatial knowledge learning (Ericson and Warren, 2020; Guo et al., 2019; Chrastil and Warren, 2013), but the design of the labyrinth lacks a clear standard, which may influence the test performance and make it difficult to do follow-up research. Therefore, our research proposed a labyrinth design procedure that can guide the generation of the labyrinths. When using a labyrinth in a virtual spatial knowledge test, there were two classic tasks namely Path Finding and Target Finding. Each task requires participants to move in the virtual labyrinth and remember specific objects (Chrastil and Warren, 2013). Consequently, to ensure fairness in the challenge of locating all objects within a labyrinth, the positions of these objects must be evenly distributed throughout the maze. As explained below, we achieve this by setting the angular offset between objects to an identical value and ensuring that the distances from the starting point to each object follow an arithmetic progression.

Two main steps are taken to assign objects in the virtual labyrinth. Firstly, the offset angular $\alpha(i)$ of each object is determined based on the total number of objects in the labyrinth, which is represented by n.

$$\alpha(i) = \frac{2\pi}{n} \cdot i \tag{2}$$

Secondly, the distance from the start point to the ith object in a labyrinth with a half-length of L and n objects, where each object is placed at equal intervals, is given by:

$$d(i) = \frac{L}{n} \cdot (i-1) \tag{3}$$

We use polar coordinates to describe the positions of the objects, resulting in coordinates of the form $(d(i), \alpha(i))$. These coordinates are then randomly assigned to each object in the labyrinth.

To promote user engagement and stimulate exploration within the virtual labyrinth, the design incorporates a central square-shaped corridor with numerous branches extending from it. As illustrated in Fig. 5, each target is situated at the end of these sub-branches. To heighten the challenge, some sub-branches are purposeful empty, requiring users to explore multiple paths before discovering the correct one. Every sub-branch features a corner that obscures the user's view of the main corridor and connects to it randomly, either from the inside or outside. The virtual labyrinth's starting point is positioned at the heart of the central square corridor. Accessible via an X-shaped entrance emanating from the starting point, this corridor connects to the main corridor. To assist users in identifying their location, four virtual paintings are strategically arranged along the walls of the central corridor. The paintings also serve as landmarks that users can reference when devising strategies for navigation and target acquisition. Additionally, the virtual labyrinth incorporates auditory cues to enrich the user's experience and offer supplementary information about the surrounding environment. For instance, when users first discover an object, a hint sound is played, providing auditory feedback and confirmation of their successful interaction with the environment. This labyrinth, with its intricate design elements that foster a sense of complexity and ambiguity, serves as a test of the user's spatial learning.

We developed our experimental environment using Unity, wherein one unit corresponds to one meter. This means that the virtual environment is designed to have a 1 : 1 ratio with the real world. In our experimental setup, we place three objects at the ends of three branches to challenge participants' spatial memory and comprehension. Three objects are included in our experiments, and the half-length of the virtual labyrinth is set to 36 m. Based on the aforementioned formulas, the angular offsets are calculated to be 120°, 240°, and 360°, respectively. Furthermore, their linear distances from the starting point were determined at 12 m, 18 m, and 24 m. The width of the labyrinth hallway is set to approximately 2.5 m. This configuration aimed to create a more complex environment, requiring participants to effectively navigate and orient themselves within the virtual space.

5.3. Apparatus

The four groups experienced the virtual labyrinth using an Oculus Quest 2 head-mounted display (HMD), which connected wirelessly to a laptop via the Oculus Air Link. The HMD's built-in speakers provided the audio for the virtual labyrinth. The laptop was equipped with an Intel Core i7-12700H processor, 16 GB of RAM, and an NVIDIA RTX 3060 graphics card. Utilizing the Oculus Integration SDK for Unity's software

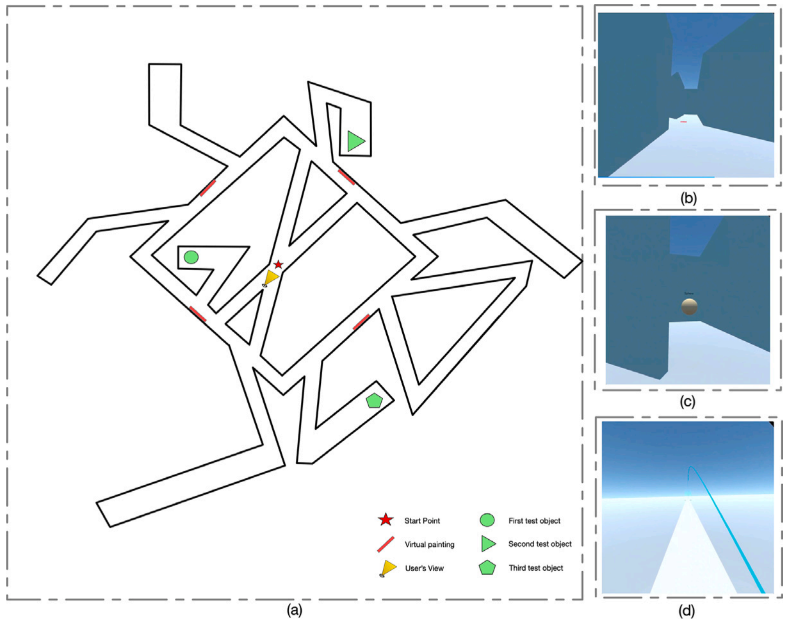

Fig. 5. The environment of the virtual labyrinth. *(a)* The overview of the virtual labyrinth *(b)* The user's first-person view in the virtual labyrinth *(c)* One of the test objects in the virtual labyrinth *(d)*The test scene of the experiment.

development and debugging tools,[1] it was confirmed that the Oculus Quest 2 maintained its maximum refresh rate of 90 Hz throughout the entire exposure. The right-hand Oculus Touch controller facilitated the classic P&T method, while the left-hand controller implemented our proposed *Undo-Redo* function. As a result, both the *TTP-UV* and *TTP-U* interacted with the environment using two Oculus Touch controllers, whereas the *TTP-V* and *P&T* relied solely on the right-hand Oculus Touch controller for interactions. We assign the teleport function to the right controller because most commercial VR applications default to using the right hand to control VR locomotion. It is important to note that, functional or not, all users will hold two controllers during the experiment. This consistent setup ensures that every participant has the same physical experience while immersed in the VR environment.

5.4. Measures

5.4.1. Spatial learning

To evaluate participants' performance in spatial learning, we employed two measures for spatial knowledge: angular offset error (AOE) and distance offset error (DOE). The two factors were calculated based on three points' coordinates: the start point, the target's point, and a user-selected point (refer to Section 5.5). The AOE is calculated by

$$\theta = \cos^{-1}\left(\frac{(\mathbf{r_A} - \mathbf{r}) \cdot (\mathbf{r_B} - \mathbf{r})}{\|\mathbf{r_A} - \mathbf{r}\|\|\mathbf{r_B} - \mathbf{r}\|}\right) \quad (4)$$

and the DOE is calculated by

$$d = \left\| \mathbf{r_A} - \mathbf{r} \,|-|\, \mathbf{r_B} - \mathbf{r} \right\|, \quad (5)$$

where $\mathbf{r} = (x, y)$ represents the starting point's coordinates, $\mathbf{r_A} = (x_a, y_a)$ represents the target point's coordinates, $\mathbf{r_B} = (x_b, y_b)$ represents the coordinates of the participant's selected point.

Utilizing both AOE and DOE, we were able to conduct a comprehensive and objective assessment of the participant's spatial learning. Primary spatial knowledge can be conceptualized as a labeled place graph, which effectively organizes learned locations by connecting them through nodes that represent estimated distances and angular offsets, as described by Ericson and Warren (2020). Accordingly, we adopted the angular offset to quantify the accuracy of participants' spatial directional awareness, and the distance offset to measure the precision of their distance estimations. Collectively, these metrics offered a precise evaluation of the participants' performance in the spatial task. It should be noted that our work treats spatial understanding and memory as integral parts of spatial learning. Here, our evaluation did not separately measure the users' acquisition and retention of spatial knowledge. As such, a good measure may indicate strong spatial understanding, while the exact performance for spatial memory may be less clear as our evaluation starts soon after the users learn about their environment.

5.4.2. Presence

The Igroup Presence Questionnaire (IPQ) (Schubert et al., 2001) was used to evaluate the sense of presence among the participants of all four groups. IPQ has been widely used to measure the sense of presence in prior studies on locomotion (e.g., Clifton and Palmisano (2020), Buttussi and Chittaro (2019)). The instrument has 14 items measured on a seven-point scale, with higher scores indicating higher presence. Because some items were adapted from previously published scales, the original response anchors were kept. For example, one item states, "In the computer-generated world I had a sense of 'being there'" which is adopted from Slater and Usoh (1993), and the corresponding response anchors are between "not at all" (1) and "very much" (7). Another item states, "How much did your experience in the VE seem consistent with your real-world experience?" which is adapted from Witmer and Singer (1994), and the corresponding response anchors are between "not consistent" (1) and "very consistent" (7). These items are separated into four dimensions namely Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL), and Sense of being there (General).

5.4.3. Task load

The NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988) was used to evaluate the mental, physical, and temporal demands, performance, frustration, and effort of the participants when completing the spatial learning task in VR. NASA-TLX is the most commonly used instrument for evaluating task load when studying usability. We used the predefined weights of six subscales of the NASA-TLX as our indices for measuring task load. The instrument derives an overall task load score based on respondents' ratings on six items with a range of "very low" (0) to "very high" (10).

[1] https://developer.oculus.com/downloads/package/unity-integration

5.4.4. Cybersickness

The Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) was used to evaluate the cybersickness among the participants before and after the experiment. SSQ has been widely used to measure cybersickness in prior studies on locomotion (e.g., Rahimi et al. (2018), Clifton and Palmisano (2020)). The questionnaire asks respondents to rate 16 symptoms between "none" (0) to "severe" (3). The 16 symptoms are categorized into three sub-categories, including nausea, oculomotor, and disorientation. We used the change in SSQ scores of each participant before and after the experiment for data analysis, which is a common technique to reduce the effects of individual differences in the sample (Jung et al., 2021).

5.5. Procedure

Each individual who responded to the participant recruitment advertisement completed a pre-questionnaire to ensure they met the experiment requirements. Upon arrival at the experiment location, participants were asked to fill out a consent form and complete Questionnaire A, which included a SSQ test, a simple spatial ability test, demography data, and their prior experience with VR and video games. Following this, we played a tutorial video that explained the experiment procedure, the task in the virtual labyrinth, and the three experiment phases. After the introduction, participants confirmed their understanding of the tasks, and we addressed any confusion that they encountered. Additionally, we informed participants that they could terminate the experiment at any time if they felt discomfort or distress. The following are the phases of the experiment.

Training Phase: During the training phase, participants were provided with the VR device and instructed to use the assigned teleportation technique. The locomotion technique available to users depends on their assigned group. For instance, a user in the TTP-UV group will have access to the *Undo-Redo* action and will be able to see the *Visualized Path*. Conversely, a user in the P&T group will experience only the classical P&T technique without any enhancements. It is worth noting that for the *Visualized Path*, we intentionally did not inform participants that the footprint's length matches their actual footprint observe whether it naturally influenced their spatial perception without any preconceived biases. Participants were placed in a square-shaped plane and shown three target objects which they were required to find during the exploration phase. Upon declaring their familiarity with the locomotion technique, the experiment environment changed to the exploring phase.

Exploring Phase: In this phase, participants were instructed to start from the designated start point and informed that the exploration would last for 10 min. At the beginning of the exploration, we emphasized that their task was to find all the targets they had seen in the training phase and to remember the spatial relationship between the targets and the start point. Participants were notified of the remaining two minutes during the exploration phase but were not given any other time updates to prevent time pressure from affecting their exploration strategy. At the end of the allocated time, we instructed participants to stop their movement and begin the next phase of the experiment.

Test Phase: In the test phase, participants were teleported back to the start point and asked to reorient themselves to ensure they had a correct spatial direction awareness. Subsequently, we removed all the labyrinth components, including the hallway, branches, and targets, leaving only the start point label. Participants were then informed which target object they needed to find and asked to select the direction of the target by pressing a button to lock their visual direction index line. Subsequently, participants were told to teleport along the index line until they believed that they had arrived at the object's location. At this moment, we recorded their position as the 'user-selected point.' This point, together with the starting point and the target point, will be utilized to calculate both the angular offset error and the distance offset error, as detailed in Section 5.4.1. The procedure was then repeated: participants were transported back to the starting point and asked to reorient themselves to ensure accurate spatial direction awareness before attempting to locate the next target. This cycle was conducted sequentially until all three targets were found, always following a specific order.

After the test phase, we asked participants to complete questionnaire B (including the SSQ test, NASA-TLX test, and IPQ test details described in Section 5.4). At the end of the experiment, participants signed the receipt of the compensation.

5.6. Data preprocessing

In spatial learning assessments, unequal completion rates of the labyrinth exploration task among the four participant groups pose a potential issue. Analyzing only data from participants who completed the task risks bias, especially with highly varying completion rates across groups. This imbalance could improperly influence the comparative analysis. To address this, the approach to non-completers must be considered thoughtfully. Excluding these individuals may distort the data by omitting potentially high-error values critical for comprehensive assessment. Therefore, rather than disregarding them, we assigned the largest offset error values within each group to non-completers. This inclusion ensures their data is represented, reflecting worst-case performance. Strategically assigning high error values to unsuccessful participants maintains balance in the comparative analysis for accurate group performance reflection. As for Presence, Task Load, and Cybersickness measures, we cannot assume that non-completers represent the worst case for these measures. Thus, we only removed their values (one from TTP-UV, one from TTP-U, three from TTP-V, and four from T&P) from the data used for analysis. Furthermore, to eliminate extreme anomalies, we excluded any data exceeding three standard deviations from its group mean, which is crucial for reliable findings.

5.7. Statistical analysis

The statistical analysis serves two primary aims: investigating the main effects of the *Visualized Path* and *Undo-Redo* mechanisms, and exploring their interaction effects. Preparing for two-way ANOVA, Levene's test checked homogeneity of variances (Glaser, 2004), and Shapiro–Wilk tested normality (Mudholkar et al., 1995), both required ANOVA assumptions. If satisfied, a standard two-way ANOVA examined the main and interaction effects. Otherwise, the non-parametric Aligned Rank Transform (ART) approach was taken using the ARTool package,[2] followed by the standard two-way ANOVA (Wobbrock et al., 2011). The threshold for statistical significance was established at a p-value of .05 for all analyses.

6. Result

6.1. Spatial learning

The overall descriptive statistic results for the AOE and DOE, across all four experimental conditions, are displayed in Table 2.

Results for the **First Test Object**: A two-way ANOVA was conducted in accordance with the ART. For the AOE, we removed two outliers in TTP-UV, two outliers in TTP-U, and four outliers in TTP-V. The result showed that *Undo-Redo* mechanism had a significant main effect ($F(1,68) = 7.761$, $p = .007$, $\eta_p^2 = .102$), whereas the *Visualized Path* did not ($F(1,68) = .704$, $p = .404$, $\eta_p^2 = .010$). No interaction effect was observed ($F(1,68) = .074$, $p = .786$, $\eta_p^2 = .001$). Regarding the DOE, we removed two outliers in TTP-U. The result indicated that neither

[2] https://depts.washington.edu/acelab/proj/art/

Table 2
Descriptive statistics for Angular Offset Error (AOE) and Distance Offset Error (DOE) among three test targets.

Experiment target	Variable	TTP-UV	TTP-U	TTP-V	P&T
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
First Target	AOE	48.99 (7.27)	62.60 (9.08)	85.78 (11.53)	91.94 (13.05)
	DOE	78.23 (26.75)	24.17 (4.91)	74.79 (16.80)	81.59 (32.52)
Second Target	AOE	45.58 (7.77)	49.18 (10.85)	90.09 (14.47)	81.44 (14.63)
	DOE	33.05 (11.64)	16.65 (4.88)	29.79 (9.80)	8.38 (7.23)
Third Target	AOE	53.21 (10.09)	79.97 (11.96)	82.22 (14.44)	84.37 (14.29)
	DOE	21.10 (10.45)	17.88 (7.33)	68.76 (25.13)	15.01 (7.80)

the *Undo-Redo* mechanism ($F(1,74) = 2.324$, $p = .132$, $\eta_p^2 = .030$) nor the *Visualized Path* ($F(1,74) = .173$, $p = .679$, $\eta_p^2 = .002$) demonstrated significant main effects. Likewise, no interaction effect was observed ($F(1,74) = 1.098$, $p = .298$, $\eta_p^2 = .015$).

Results for the **Second Test Object**: Following the ART, a two-way ANOVA was executed. For the AOE, we removed two outliers in TTP-UV and two outliers in TTP-U. The result showed that the *Undo-Redo* mechanism displayed a significant main effect ($F(1,72) = 10.042$, $p = .002$, $\eta_p^2 = .122$), while the *Visualized Path* did not ($F(1,72) = .302$, $p = .585$, $\eta_p^2 = .004$). No interaction effect was detected ($F(1,72) = .139$, $p = .710$, $\eta_p^2 = .002$). Concerning the DOE, neither the *Undo-Redo* mechanism ($F(1,76) = .067$, $p = .797$, $\eta_p^2 = .001$) nor the *Visualized Path* ($F(1,76) = .026$, $p = .872$, $\eta_p^2 = .000$) showed significant main effects. Also, no interaction effect was observed ($F(1,76) = .061$, $p = .805$, $\eta_p^2 = .001$).

Results for the **Third Test Object**: A two-way ANOVA was conducted. In terms of the AOE, we removed two outliers in TTP-UV and two outliers in TTP-U. The result indicated that the *Undo-Redo* mechanism had a significant main effect ($F(1,72) = 3.983$, $p = .050$, $\eta_p^2 = .052$), while the *Visualized Path* did not ($F(1,72) = 3.284$, $p = .073$, $\eta_p^2 = .044$). No interaction effect was detected ($F(1,72) = .009$, $p = .927$, $\eta_p^2 = .001$). For the DOE, we removed two outliers in TTP-UV and two outliers in TTP-U. The result showed that neither the *Undo-Redo* mechanism ($F(1,72) = 3.951$, $p = .051$, $\eta_p^2 = .052$) nor the *Visualized Path* ($F(1,72) = 1.69$, $p = .198$, $\eta_p^2 = .023$) exhibited significant main effects. Additionally, there was no interaction effect ($F(1,72) = 1.193$, $p = .278$, $\eta_p^2 = .016$).

In summary, our findings indicate that the *Undo-Redo* mechanism generally exerts a significant impact on the AOE, thereby corroborating H1a, while it does not have main effects on the DOE, thus refuting hypothesis H1b. The *Visualized Path* did not exhibit significant main effects on either the AOE or the DOE, leading to the rejection of hypotheses H1c and H1d. Moreover, we found no interaction effects between the *Undo-Redo* mechanism and the *Visualized Path*, resulting in the non-support of hypotheses H1e and H1f.

6.2. Presence

The descriptive results for the IPQ are shown in Table 3. For all sub-scales and the Total IPQ score, the two-way ANOVA analysis was conducted. The result shows that there are no significant main effects found for *Undo-Redo* mechanism in terms of SP ($F(1,67) = .001$, $p = .973$, $\eta_p^2 = .000$), INV ($F(1,67) = .059$, $p = .809$, $\eta_p^2 = .001$), REAL ($F(1,67) = .819$, $p = .369$, $\eta_p^2 = .012$), General presence ($F(1,67) = 1.715$, $p = .195$, $\eta_p^2 = .025$), and the Total IPQ score ($F(1,67) = .132$, $p = .718$, $\eta_p^2 = .002$). In a parallel manner, the *Visualized Path* also manifested no significant main effects on SP ($F(1,67) = .144$, $p = .705$, $\eta_p^2 = .002$), INV ($F(1,67) = .029$, $p = .864$, $\eta_p^2 = .000$), REAL ($F(1,67) = .429$, $p = .515$, $\eta_p^2 = .006$), General presence ($F(1,67) = .509$, $p = .478$, $\eta_p^2 = .025$), and the Total IPQ score ($F(1,67) = .010$, $p = .922$, $\eta_p^2 = .000$). Additionally, there are no interaction effects found regarding SP ($F(1,67) = .0358$, $p = .705$, $\eta_p^2 = .002$), INV ($F(1,67) = .0358$, $p = .705$, $\eta_p^2 = .002$), REAL ($F(1,67) = .068$, $p = .796$, $\eta_p^2 = .001$), General presence ($F(1,67) = 2.923$, $p = .092$, $\eta_p^2 = .042$), and the Total IPQ score ($F(1,67) = .687$, $p = .410$, $\eta_p^2 = .010$).

To summarize, neither the *Undo-Redo* nor the *Visualized Path* mechanisms exert a significant effect on the sense of presence. Consequently, H2a, which hypothesizes that these mechanisms will not affect the sense of presence, was accepted by the results.

6.3. Task load

The descriptive results for the NASA-TLX are displayed in Table 3. We conducted the two-way ANOVA analysis were revealed that there is no significant main effect were found for *Undo-Redo* mechanism on Mental Demand ($F(1,67) = 1.168$, $p = .284$, $\eta_p^2 = .017$), Physical Demand ($F(1,67) = 1.074$, $p = .304$, $\eta_p^2 = .016$), Temporal Demand ($F(1,67) = 1.241$, $p = .269$, $\eta_p^2 = .018$), Performance ($F(1,67) = 1.044$, $p = .311$, $\eta_p^2 = .015$), Effort ($F(1,67) = 2.232$, $p = .140$, $\eta_p^2 = .032$), Frustration ($F(1,67) = 1.060$, $p = .307$, $\eta_p^2 = .016$), Overall Score ($F(1,67) = 1.659$, $p = .202$, $\eta_p^2 = .024$). Also, the *Visualized Path* does not have the main effects on Mental Demand ($F(1,67) = 1.061$, $p = .307$, $\eta_p^2 = .016$), Physical Demand ($F(1,67) = 1.828$, $p = .181$, $\eta_p^2 = .027$), Temporal Demand ($F(1,67) = .270$, $p = .605$, $\eta_p^2 = .004$), Performance ($F(1,67) = .185$, $p = .669$, $\eta_p^2 = .003$), Effort ($F(1,67) = .295$, $p = .589$, $\eta_p^2 = .004$), Frustration ($F(1,67) = .393$, $p = .533$, $\eta_p^2 = .006$), Overall Score ($F(1,67) = .957$, $p = .331$, $\eta_p^2 = .014$). Lastly, there are also no interaction effect between *Undo-Redo* mechanism and *Visualized Path* for Mental Demand ($F(1,67) = .578$, $p = .450$, $\eta_p^2 = .009$), Physical Demand ($F(1,67) = .331$, $p = .567$, $\eta_p^2 = .005$), Temporal Demand ($F(1,67) = 1.737$, $p = .192$, $\eta_p^2 = .025$), Performance ($F(1,67) = .933$, $p = .338$, $\eta_p^2 = .014$), Effort ($F(1,67) = .295$, $p = .589$, $\eta_p^2 = .004$), Frustration ($F(1,67) = .032$, $p = .860$, $\eta_p^2 = .000$), Overall Score ($F(1,67) = .073$, $p = .788$, $\eta_p^2 = .001$).

In summary, neither the *Undo-Redo* mechanism and *Visualized Path* mechanism have the significant main effects or interaction effects regarding task load. Therefore, H2b, which hypothesizes that these mechanisms will not affect the task load, was accepted by the results.

6.4. Cybersickness

The impact of the *Undo-Redo* and *Visualized Path* mechanisms on cybersickness was meticulously scrutinized through a series of two-way ANOVA analyses. SSQ general results are shown in Table 3. The results suggest a minimal influence of these mechanisms on all evaluated aspects of cybersickness. There are no main effects found for *Undo-Redo* on Nausea ($F(1,67) = 1.048$, $p = .310$, $\eta_p^2 = .015$), Oculomotor ($F(1,67) = .137$, $p = .713$, $\eta_p^2 = .002$), Disorientation ($F(1,68) = .637$, $p = .428$, $\eta_p^2 = .009$), and the overall SSQ score ($F(1,67) = .332$, $p = .566$, $\eta_p^2 = .005$). Additionally, *Visualized Path* does have the main effect on the Nausea ($F(1,67) = .456$, $p = .502$, $\eta_p^2 = .007$), Oculomotor ($F(1,67) = .041$, $p = .839$, $\eta_p^2 = .001$), Disorientation ($F(1,67) = .633$, $p = .429$, $\eta_p^2 = .009$), and the Overall SSQ score ($F(1,67) = .122$, $p = .728$, $\eta_p^2 = .002$). Apropos interaction effects, no significant interactions were discerned for Nausea ($F(1,67) = .789$, $p = .378$, $\eta_p^2 = .012$), Oculomotor ($F(1,67) = 1.146$, $p = .288$, $\eta_p^2 = .017$), Disorientation ($F(1,67) = .067$,

Table 3
Descriptive statistics results of IPQ, NASA-TLX, and SSQ.

	IPQ[a]					NASA-TLX[b]							SSQ[c]			
	IPQ1	IPQ2	IPQ3	IPQ4	IPQ5	TLX1	TLX2	TLX3	TLX4	TLX5	TLX6	TLX7	SSQ1	SSQ2	SSQ3	SSQ4
item	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
TTP-UV	3.32 (.80)	3.11 (.80)	2.68 (.80)	3.42 (1.35)	3.14 (.65)	7.89 (1.24)	4.58 (2.22)	6.84 (1.68)	5.42 (2.78)	7.37 (1.34)	5.74 (2.42)	6.31 (.86)	16.07 (26.43)	16.36 (25.43)	19.19 (30.37)	22.44 (35.26)
TTP-U	3.10 (1.23)	3.30 (.75)	2.54 (.58)	3.11 (1.56)	3.01 (.89)	8.00 (1.29)	5.00 (2.67)	5.89 (2.31)	6.16 (2.09)	7.79 (1.44)	6.21 (2.53)	6.51 (1.29)	26.61 (37.16)	25.53 (40.99)	28.17 (40.95)	35.63 (53.16)
TTP-V	3.19 (.59)	3.24 (.70)	2.50 (.62)	3.29 (1.05)	3.05 (.41)	7.18 (2.38)	3.71 (1.99)	5.59 (2.06)	6.47 (2.10)	7.00 (1.94)	5.24 (2.63)	5.86 (1.28)	15.15 (20.25)	21.40 (26.15)	14.58 (40.13)	27.06 (29.64)
P&T	3.24 (1.03)	3.19 (.69)	2.44 (.63)	4.06 (1.19)	4.06 (1.29)	7.88 (1.46)	4.75 (2.11)	6.00 (2.58)	6.19 (1.68)	7.00 (1.79)	5.50 (2.28)	6.22 (1.34)	13.71 (25.59)	15.16 (23.81)	19.17 (29.81)	20.34 (30.72)

[a] IPQ1 refers SP, IPQ2 refers INV, IPQ3 refers REAL, IPQ4 refers General, and IPQ5 refers Total IPQ score.

[b] TLX1 refers Mental Demand, TLX2 refers Physical Demand, TLX3 refers Temporal Demand, TLX4 refers performance, TLX5 refers Effort, TLX6 refers Frustration and TLX refers Overall score.

[c] SSQ1 refers Nausea, SSQ2 refers Oculomotor, SSQ3 refers Disorientation and SSQ4 refers overall SSQ score.

$p = .797$, $\eta_p^2 = .001$), or the total SSQ score ($F(1,67) = 1.156$, $p = .286$, $\eta_p^2 = .017$).

In summary, neither the *Undo-Redo* nor the *Visualized Path* mechanisms have the main effect or interaction effect for the cybersickness. Thus, H2c, which hypothesizes these mechanisms will not increase the cybersickness, was accepted by the results.

7. Discussion

The aim of this study is twofold. The first objective is to present a novel approach, referred to as *TTP*, which incorporates two advancements – *Undo-Redo* and *Visualized Path* – to enhance conventional teleport-based locomotion techniques. These advancements are designed to augment spatial comprehension and memory within virtual settings. The second objective of this research is to utilize a blend of objective and subjective measures to investigate the effects of these improvements by implementing a 2 × 2 factorial experimental design. Spatial learning was quantified by analyzing two primary metrics: AOE and DOE. Concurrently, to subjectively assess the impact of the *TTP* method on users' experiences, surveys focusing on three main areas were conducted: the sense of presence, perceived workload, and cybersickness.

7.1. Exploring the effect of TTP on human spatial learning

To address **RQ1**, we employed a labyrinth with three memory tasks to identify the effects and compared AOE and DOE. These two metrics imply the participant's understanding and memory of the spatial relationship between their position to the target's position. Therefore, the influence of the *TTP* on spatial learning can be separately discussed in the level of direction and distance (AOE corresponds to the spatial direction awareness, and DOE corresponds to the distance estimation).

7.1.1. TTP strengthen human direction awareness

Our analysis revealed a significant main effect of the *Undo-Redo* mechanism on the AOE, with lower values indicating better spatial direction awareness across all memorization tasks, which supported hypothesis H1a. We attribute the efficacy of the *Undo-Redo* mechanism to two main factors: its ability to improve exploration efficiency and its capacity to reduce orientation effort. Participants using the *Undo-Redo* feature could simplify the selection phase by quickly navigating between previously visited points, thereby facilitating a more convenient familiarization with VEs. This was substantiated by those who can use the *Undo-Redo* mechanism which makes it only have one non-completer for each group compared to those without that have three and four non-completers for TTP-V group and T&P group respectively. It seems that *Undo-Redo* mechanism can enhance the efficiency of memorization for the spatial learning task. Additionally, *Undo-Redo* mechanism allows participants to maintain their gaze in the target's direction while returning to the start point, providing consistent directional cues and reducing the need for reorientation. Without this feature, participants may need to rely on external reference points, increasing memory load. Our experimental design minimized additional orientation cues. We removed wall shadows and used consistent textures to focus on the effects of the internal mechanisms. These measures strengthen the evidence that the *Undo-Redo* mechanism can enhance the users' directional sense. This conclusion is consistent with earlier studies suggesting that the egocentric experience plays a crucial role in the selection and encoding of reference directions (Rump and McNamara, 2013; McNamara et al., 2003). These findings support our theoretical framework that the *Undo-Redo* mechanism significantly enhances direction sense by reinforcing egocentric spatial updating, as detailed in Section 3.

Contrarily, the *Visualized Path* did not significantly affect the AOE, and no interaction effect was noted, which rejected hypothesis H1c and H1e. The lack of a significant impact from the *Visualized Path* was surprising, given our initial expectation that it would function as a cognitive landmark system to enhance spatial direction awareness. Nevertheless, it appears that the *Undo-Redo* mechanism alone was adequate in providing directional guidance within the context of our experiments. A possible explanation might be that our implementation of the *Visualized Path* was limited to only the five most recent teleportation points, making these landmarks less stable than fixed ones, such as the paintings within the labyrinth. Another possible explanation is that users may unconsciously rely on other landmarks instead of the Visualized Path, as we did not inform them that the length of the footprint matches their real footprint during the experiment.

Overall, the *Undo-Redo* mechanism significantly enhances spatial orientation, whereas the *Visualized Path* does not exhibit significant improvements.

7.1.2. Differential effects on distance of spatial learning

Unexpectedly, our study revealed that the *Undo-Redo* and *Visualized Path* features did not significantly impact how participants perceived distance in VEs, which rejected our initial hypothesis on H1b, H1d, and H1f. This intriguing result hints at a complex interaction between different types of sensory information when physical feedback, such as proprioceptive and vestibular cues, is absent.

To understand this, imagine driving a car. Your estimation of distance comes from two main sources—the optic flow, or how the scenery changes visually as you move, and landmarks, which serve as reference points. These normally work together seamlessly. However, in VEs, prior research by Mason et al. (2023) suggests that people handle these sources of information differently, potentially leading to confusion.

During our experiment, we observed the participants in *TTP-UV* group seemed more hesitant when doing the distance test compared to those with single enhancement groups. This may suggest that there is a conflict between the optic flow and the *Visualized Path* depicted through footprints. Despite accurately translating real-world footprints into the virtual space as a measure of distance, they seemed to compete with the virtual environment's optic flow cues. This conflict might be why participants struggled to reconcile the two types of distance information, possibly resulting in the larger mean, though not statistically significant, differences in DOEs we observed in the *TTP-UV* group.

Moreover, Kearns et al. (2002) have shown a tendency for individuals to depend more on optic flow rather than landmarks when estimating distance. This could explain the smaller mean, though not statistically significant, differences in DOEs in the *TTP-U* group, which had access to the *Undo-Redo* feature, suggesting that repeated exposure to optic flow may improve distance perception in VEs. Another angle is that distances in VEs, especially when viewed through an HMD, are often underperceived, as noted by Kelly et al. (2022). Our visualized footprints may not have provided sufficient landmarks to overcome this underperception.

To quickly summarize, while the idea of importing real-world distance cues like footprints into VEs is appealing, it is clear that they can clash with innate virtual cues like optic flow, leading to inaccuracies in how distance is perceived. Future research should therefore focus on finding effective ways to combine these cues in VEs. Our results indicate that the *Undo-Redo* mechanism shows promise in enhancing distance perception within VEs. This is evidenced by the consistently lower DOEs observed in the *TTP-U* group, although these differences did not reach statistical significance when compared to other groups.

7.2. Exploring the effect of TTP on user experience

Understanding the impact of *TTP* on user experience is crucial, especially when it is used to enhance people's spatial comprehension and memory. To address **RQ2**, we employed a series of surveys to determine the effect of *TTP* on user experience.

With regard to the IPQ, the results reveal that neither the *Undo-Redo* nor the *Visualized Path* mechanisms exerted prominent main or interaction effects, which support our hypothesis H2a. This finding suggests that the *TTP* mechanism does not adversely impact the users' sense of presence within the virtual environment. Interestingly, the *Undo-Redo* action, a feature not typically available in the past popular VR user experience, was successfully integrated into the VEs in this study. Despite its novelty, the *Undo-Redo* mechanism did not compromise the users' sense of presence. This observation is of considerable significance, as maintaining a robust sense of presence is integral to fostering effective user engagement and immersion in VEs. The ability to introduce novel interactions, such as *Undo-Redo*, while preserving this sense of presence, opens new avenues for enhancing user experiences in VR.

Regarding the NASA-TLX and in line with hypothesis H2b, the *Undo-Redo* and *Visualized Path* mechanisms do not influence user workload. This finding aligns with Müller et al. who reported that the *Undo* action does not significantly impact workload (Müller et al., 2023). Our results further reveal that even when additional actions are required with *Undo-Redo*, there is no increase in overall demand for users.

For the SSQ, despite that Wu et al. reported that increased optical flow correlates with higher perceived cybersickness (Wu and Suma Rosenberg, 2022), our *TTP* implementation does not seem to exacerbate cybersickness. Our results indicate that the *Undo-Redo* feature, which incorporates repetitive optical flow, does not significantly affect the SSQ scores. This suggests that our proposed *TTP* method may effectively counter the issue that more optical flow could cause more perceived cybersickness. We attribute our success in not significantly increasing cybersickness primarily to the P&T technique itself, which is a key advantage of this locomotion technique (Buttussi and Chittaro, 2019). Our findings further confirm that the use of *Undo-Redo*, which introduces more optical flow by enhancing user interaction opportunities, does not statistically significantly increase cybersickness.

8. Limitation and future work

Several limitations of this study must be considered when interpreting our results. First, due to the COVID-19 pandemic, our experiment was limited to on-campus participants, which may have affected the quality of our sample. Furthermore, our participants predominantly had at least an undergraduate level of education, which may limit the generalizability of our findings to a broader population.

It is important to note that the gender distribution is not consistent across the groups, which is a limitation of this study. This imbalance could potentially influence spatial learning outcomes. Previous studies have indicated that there are inherent differences in spatial abilities between genders (Schug et al., 2022; Naurzalina et al., 2015; Gavazzi et al., 2022), which could affect the results of our research. Addressing this imbalance in future studies could help clarify the impact of gender on spatial learning in virtual environments.

Another limitation arises from cultural differences. Cognitive processing strategies in East Asian societies tend to be more context-dependent compared to those in Western societies (Saulton et al., 2017). Given that our participants were predominantly from East Asian societies, this cultural difference may have implications for the interpretation of our experimental results.

Our experiment was limited by the use of only one labyrinth layout to test the effectiveness of our proposed labyrinth design principles for spatial learning. Although our results suggest that these principles are beneficial for the specific labyrinth used in the experiment, further research is needed to determine whether they are equally effective across different labyrinth layouts. Future studies could address this limitation by testing our principles on a variety of labyrinths, providing a more comprehensive understanding of their potential applications.

The HMD we used in the study is a limitation as well. The limited field of view of the Oculus Quest 2, which provides only a 104° field of view compared to the human normal of approximately 200° (Klymenko and Rash, 1995), may have negatively affected our results. Previous research has suggested that a wider field of view can have a positive effect on memory and presence in VR (Lin et al., 2002). Future studies could address this limitation by using an HMD device with a better field of view, which may improve task performance in the VR environment.

The *Undo-Redo* function has demonstrated its potential to enhance human spatial learning. However, its internal mechanisms still require further exploration. For instance, how does the *Undo-Redo* action differ from simply looking back? While Müller et al. have compared orientation Undo with standard undo techniques (Müller et al., 2023), additional research is necessary to expand our understanding. One interesting observation from our user study is that participants employed the *Undo-Redo* function in distinct ways. Some users primarily used *Undo-Redo* to recall the target direction, while others utilized it to swiftly navigate through the labyrinth. Consequently, due to the varied approaches to using the *Undo-Redo* function, it is challenging to model the relationship between the frequency of *Undo-Redo* actions and the metrics of AOE and DOE linearly. However, this could be a potential direction for future research, employing a simpler environment to evaluate the relationship between the frequency of *Undo-Redo* actions and spatial learning performance.

9. Conclusion

This study presents *TTP*, a novel VR locomotion technique that introduces two key enhancements to the classical P&T technique: the *Undo-Redo* mechanism and the *Visualized Path* feature. Their addition is theoretically motivated and aims to address P&T's deficiency in spatial learning according to the theoretical discussion. We have conducted a thorough analysis of the impact of these enhancements through a 2×2 factorial experimental design, comparing their performance against the standard P&T method.

The *TTP* method shows considerable promise in improving some dimensions of spatial learning within VEs. The *Undo-Redo* mechanism, in particular, has been shown to augment orientational spatial knowledge by leveraging the benefits of repeated optical flow and practice. While the *Undo-Redo* mechanism plays a significant role in this improvement, the contribution of the *Visualized Path* warrants additional research. This feature has the potential to enhance the effectiveness of the *Undo-Redo* mechanism could be further understood by exploring various *Visualized Path* configurations in conjunction with the *Undo-Redo* feature in future studies. Regarding distance estimation capabilities, our results indicate that while the enhancements tested, particularly the *Undo-Redo* mechanism, did not significantly improve distance perception, there is potential for future application. Although the increase in distance estimation accuracy from the *Undo-Redo* mechanism was not statistically significant, further research could illuminate ways to optimize these features and potentially improve accuracy in VR navigation.

In conclusion, evidence suggests that *TTP* can generally improve spatial learning regarding orientation without exacerbating cybersickness or reducing their sense of presence in the virtual space.

CRediT authorship contribution statement

Ye Jia: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zackary P.T. Sin:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Conceptualization. **Chen Li:** Writing – rerevisedview & editing, Supervision, Conceptualization. **Peter H.F. Ng:** Validation, Supervision. **Xiao Huang:** Investigation, Funding acquisition. **George Baciu:** Writing – review & editing, Project administration. **Jiannong Cao:** Writing – rerevisedview & editing, Funding acquisition. **Qing Li:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Ethical approval

The study was approved by the Institutional Review Board of The Hong Kong Polytechnic University under the approval number HSEARS20221121002.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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Ye Jia is working toward his MPhil degree at the Department of Computing, The Hong Kong Polytechnic University. He received his B.Eng from Chongqing University Of Arts and Science. He has authored and co-authored papers in IEEE TLT, IEEE VR, and IEEE MetaCom. His research interests include human–computer interaction, virtual reality, and augmented reality.

Zackary P.T. Sin is a research assistant professor at the Department of Computing, The Hong Kong Polytechnic University, where he received his Ph.D. and B.Sc. degrees. He is an experienced multimedia researcher and developer with publications in IEEE

VR, SIGGRAPH i3D, CHI PLAY and IEEE TLT. His main research areas are metaverse, computer graphics and human–computer interaction.

Chen Li is an assistant professor affiliated with the Department of Applied Social Sciences and the Department of Computing at The Hong Kong Polytechnic University. He received B.Sc. in Computer Science and Technology from Nanjing University, and M.Sc. in Computer Science, and Ph.D. from the City University of Hong Kong. His research interests include virtual reality, augmented reality, serious games, and spatial user interface.

Peter H. F. Ng is currently an Assistant Professor in the Department of Computing (COMP) and Rehabilitation Sciences (RS) at PolyU, and he is in charge of the Game Lab and deputy programmer leader of FT Broad Discipline of Computing (EIS Steam) in COMP. His interests are AI, health applications, APP, games, and XR development. He received his B.Sc.,M.Sc., and Ph.D. at PolyU in 2004, 2007 and 2013. He received one of the best ACG+ Capital teams from the Hong Kong Home Affairs Department in 2017, Merit Awards of Teaching by PolyU FENG in 2017 and 2021, Team awards of Teaching by PolyU FENG in 2021, Merit Awards of Service by PolyU FENG in 2019, Gold winner for the Community Outreach Award (eLFA2021) in 2021, Best ten teachers in the Greater Bay Area STEM Excellence Award 2022 (HKSAR).

Xiao Huang is an assistant professor in the Department of Computing at The Hong Kong Polytechnic University. He received Ph.D. in Computer Engineering from Texas A&M University in 2020, M.S. in Electrical Engineering from Illinois Institute of Technology in 2015, and B.S. in Engineering from Shanghai Jiao Tong University in 2012. His research interests include large language models, graph neural networks, knowledge graphs, question answering, and recommender systems. He won the Best Paper Award Honorable Mention at SIGIR 2023.

George Baciu has been a Professor in the Department of Computing (COMP) at the Hong Kong Polytechnic University (PolyU). He holds degrees in Applied Mathematics and Computer Science, and a Ph.D. in Systems Engineering from University of Waterloo. He has been member of the Waterloo Computer Graphics Lab and the Pattern Analysis and Machine Intelligence (PAMI) Lab. Dr. Baciu is the founding director of the GAME Lab at HKUST in 1993, and the Graphics and Multimedia Applications (GAMA) Lab in 2000 in COMP, PolyU. His research interests include Information Visualization, Cognitive Computing, Cloud Computing and Distributed Machine Learning, VR and Computer Graphics, with applications to cognitive digital agents, digital twins, motion synthesis, animation, collision detection, geometric modeling, and image analysis. He has published extensively in computer graphics, image processing, and VR journals and conferences and has served as chair of intl. conferences such as Game Technology Conference (GTEC), Pacific Graphics, VRST (and VRCIA), Eurographics, CGI, CAD/Graphics, and Computer Animation and Social Agents (CASA), IEEE Intl. Conf. on Cognitive Informatics and Cognitive Computing (ICCI*CC). He is a Senior Member of IEEE and a Member of ACM.

Jiannong Cao received the M.Sc. and Ph.D. degrees in computer science from Washington State University. He is currently a Chair Professor with the Department of Computing, The Hong Kong Polytechnic University (PolyU). He is also the Dean of Graduate School, the Director of Research Institute of Artificial Intelligent of Things and the Internet and Mobile Computing Lab, and the Vice Director of the University's Research Facility in Big Data Analytics with PolyU. He has coauthored five books, co-edited nine books, and published over 500 papers in major intl. journals and conf. proceedings. His research interests include distributed systems and blockchain, wireless sensing and networking, big data and machine learning, and mobile cloud and edge computing. He is a member of Academia Europaea, a Fellow of IEEE and an ACM Distinguished Member.

Qing Li received the BEng degree in computer science from Hunan University (Changsha, China), and the M.Sc. and Ph.D. degrees in computer science, from the University of Southern California (Los Angeles, USA). He is currently a Chair Professor with the Department of Computing, The Hong Kong Polytechnic University. His research interests include multi-modal data management, conceptual data modeling, social media, Web services, and e-learning systems. He has authored or co-authored more than 500 publications in these areas. He is actively involved in the research community. He is a Fellow of IEEE, AAIA, IET(UK), and a Distinguished Member of CCF (China).