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# Traceable Teleportation: Improving Spatial Learning in Virtual Locomotion

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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.

## Keywords:

Locomotion, virtual reality, point-and-teleport, undo-redo, spatial learning, spatial knowledge

## 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,

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12 point-and-teleport (P&T) is one of the most studied VR locomotion techniques by  
 13 the VR research community [1]. Widely used in various VR applications, the P&T  
 14 technique can have different variants, but typically, all these implementations fol-  
 15 low a "classical" instant transition P&T scheme: users can point to a position in  
 16 virtual spaces, trigger the teleportation, and then their viewpoints will be *instan-*  
 17 *taneously* translated to that position [2, 3].

18 Compared to other VR locomotion techniques, the P&T can emerge as a par-  
 19 ticularly advantageous technique in some areas. Notably, Bozgeyikli et al. have  
 20 highlighted its efficacy in facilitating travel across extended distances within vir-  
 21 tual environments (VEs). This is a finding that underscores its potential for en-  
 22 hancing navigation in VR [2]. Additionally, the consensus that appears to be  
 23 forming in the research community is that P&T tends to yield lower instances of  
 24 cybersickness in comparison to steering-based methods, such as those that employ  
 25 a joystick for movement control [3, 4].

26 However, P&T is not without its drawbacks. While efficient, the instanta-  
 27 neous point-and-teleport method can lead to increased disorientation; it may also  
 28 diminish the sense of presence within the VE [5, 6, 7] (but not all studies agree).  
 29 Alternatively, animated teleportation can be used. It seeks to offer a smoother  
 30 transition by simulating continuous motion during teleportation, but it has the  
 31 drawback of potentially elevating the risk of cybersickness [8]. Thus, it seems to  
 32 be relatively less used. These drawbacks pose a significant conundrum for VR  
 33 developers, who must weigh the trade-offs between preserving a user's spatial  
 34 orientation and inducing cybersickness. Therefore, it is imperative to enhance the  
 35 P&T technique by finding a middle ground that mitigates these challenges. This  
 36 would make VR more appealing to a wider audience. In order to understand why  
 37 we need to explore the spatial features of our environment. To understand why  
 38 the classical instant P&T causes disorientation, we need to explore how we under-  
 39 stand the surrounding environment spatially. Spatial learning is the pivotal internal  
 40 process in which we model our environment into spatial knowledge [9, 10]. In vir-  
 41 tual environments, the ability to understand and memorize spatial knowledge (e.g.  
 42 spatial layout, environment features) is crucial for effective navigation and inter-  
 43 action [11, 12]. Without robust spatial learning, users may not only experience  
 44 disorientation but also reduced efficiency in task completion [13], a diminished  
 45 sense of presence [14], and a frustrating user experience [15]. Thus, addressing  
 46 these cognitive issues is one of the keys in improving P&T.

47 With this in mind, we can examine the P&T technique to understand why it  
 48 may impair spatial knowledge. All P&T techniques can be dissected into three  
 49 key phases. The first phase is the *selection phase*, during which users can first

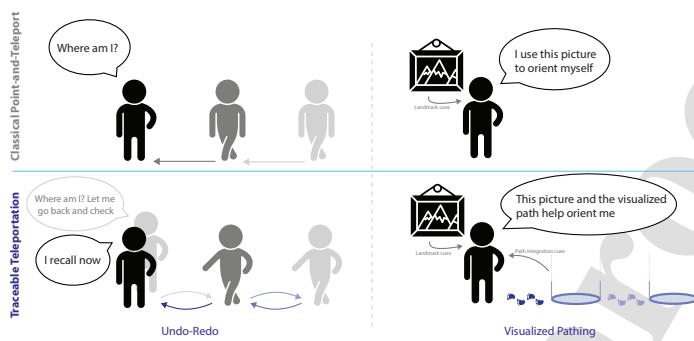


Figure 1: The classical P&T of VR locomotion technique (top) may hinder users' spatial learning in virtual spaces. The proposed *Traceable Teleportation (TTP)* (bottom) boosts users' orientation by incorporating two novel features: an *Undo-Redo* mechanism (left) and a *Visualized Path* (right).

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

<sup>74</sup> learning (Figure 1). Specifically, we first add an *Undo-Redo* mechanism to the  
<sup>75</sup> selection phase, so that users can instantly teleport to their previously visited lo-  
<sup>76</sup> cations without the need to turn around and re-select their desired destinations.  
<sup>77</sup> This feature helps the user to memorize the walk path by repetitive practice and  
<sup>78</sup> repetitive optical flow. Second, we introduce *Visualized Path*, which enables users  
<sup>79</sup> to review where they have visited locations by providing them with visual cues,  
<sup>80</sup> including halos that highlight the teleportation start and end points, and virtual  
<sup>81</sup> footprints connecting the halos. Both features facilitate the reorienting phase by  
<sup>82</sup> improving the users' spatial learning, and ultimately facilitating navigation and  
<sup>83</sup> orientation within virtual spaces.

<sup>84</sup> To summarize, this paper aims to improve spatial learning for the classical  
<sup>85</sup> P&T technique. We first start by exploring and pinpointing the deficiency of P&T  
<sup>86</sup> in learning spatial knowledge via a theoretical discussion. Based on this discus-  
<sup>87</sup> sion, we propose *TTP*, which includes two enhancements, *Undo-Redo* and *Visu-*  
<sup>88</sup> *alized Path*, that can theoretically improve users' spatial knowledge (Section 3).  
<sup>89</sup> To evaluate the proposed enhancements, we conducted a user study with a virtual  
<sup>90</sup> labyrinth (Section 5). Experiments show that *TTP*'s *Undo-Redo* feature has signif-  
<sup>91</sup> icantly improved users' spatial knowledge of the labyrinth regarding orientation.  
<sup>92</sup> The contributions are as follows:

- <sup>93</sup> • **Traceable Teleportation (TTP)**, which enhances the classical P&T tech-  
<sup>94</sup> nique with *Undo-Redo* mechanism and *Visualized Path*. These enhance-  
<sup>95</sup> ments aim at improving spatial learning.
- <sup>96</sup> • A theoretical discussion on P&T which pinpoints its bottleneck in spatial  
<sup>97</sup> learning.
- <sup>98</sup> • A user study shows that *TTP*, specifically its *Undo-Redo* component, can  
<sup>99</sup> enhance spatial knowledge for orientation without exacerbating cybersick-  
<sup>100</sup> ness.

## <sup>101</sup> 2. Related Work

<sup>102</sup> Locomotion is a broad topic in VR [1]. In this section, we will first provide  
<sup>103</sup> a brief overview on different locomotion techniques, followed by a discussion on  
<sup>104</sup> recent locomotion works on spatial learning, presence and cybersickness. Lastly,  
<sup>105</sup> we will discuss other VR locomotion works that are based on P&T. Generally,  
<sup>106</sup> there is a lack of discussion on how to improve spatial knowledge learning for the  
<sup>107</sup> classical instantaneous P&T technique.

2.1. Types of VR Locomotion	108
A classification system put forth by [16] 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 [17]. 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 [18, 19, 20, 21]. 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 [22, 23]. 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 [24]. 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.	109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125
2.2. Locomotion Works on Spatial Learning	126
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 [14]. 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 [15]. 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 [25]. 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	127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143

<sup>144</sup> walking-in-place techniques [26]. In another study focusing on distance estimation  
<sup>145</sup> within VR, Keil et al. found that participants using P&T outperformed those  
<sup>146</sup> using steering-based methods, suggesting an advantage for the teleportation tech-  
<sup>147</sup> nique in judging spatial distances [27]. Although these studies have investigated  
<sup>148</sup> virtual locomotion techniques regarding spatial learning, discussion on how to im-  
<sup>149</sup> prove their spatial learning is sparse. However poor spatial learning is a noticeable  
<sup>150</sup> issue as it will result in a worse user experience due to disorientation. This gap  
<sup>151</sup> has motivated us to propose novel enhancements to the P&T technique to improve  
<sup>152</sup> its efficacy in spatial knowledge acquisition and retention.

### <sup>153</sup> 2.3. Locomotion Works on Presence and Cybersickness

<sup>154</sup> The exploration of VR locomotion techniques' effects on presence (i.e., the  
<sup>155</sup> sense of being there in the virtual spaces), workload (i.e., the cognitive, perceptual,  
<sup>156</sup> and/or physical demands placed on a user while interacting with a VR system)  
<sup>157</sup> and cybersickness have produced insightful findings. Buttussi et al. examined the  
<sup>158</sup> influence of joystick-based, P&T, and leaning-based methods, discovering that  
<sup>159</sup> teleportation was associated with reduced nausea without affecting the sense of  
<sup>160</sup> presence when compared to the other techniques [28]. Likewise, in a study by  
<sup>161</sup> Langbehn et al., P&T was found to result in the lowest levels of cybersickness rel-  
<sup>162</sup> ative to joystick-based navigation, though it did not significantly affect presence  
<sup>163</sup> or workload [15]. Kim et al. and Christou and Aristidou also show similar results  
<sup>164</sup> in that steering generates more cybersickness than teleportation [29, 30]. In con-  
<sup>165</sup> trast, the study by Clifton et al. found the presence is worse for P&T compared to  
<sup>166</sup> the steering locomotion [7], which also aligns with Habgood et. al.'s work [4].  
<sup>167</sup> Bozgeyikli et al. expanded on these comparisons by evaluating walking-in-place,  
<sup>168</sup> P&T, joystick-based, flying, and hand-flapping techniques. Their study indicated  
<sup>169</sup> no significant differences in cybersickness between the methods, yet significant  
<sup>170</sup> variations in presence were observed, underscoring the nuanced effects of loco-  
<sup>171</sup> motion type on user experience [2]. Usoh et al. focused on subjective presence  
<sup>172</sup> and compared real walking with virtual walking-in-place and a flying technique,  
<sup>173</sup> noting a pronounced disparity in presence, with flyers feeling less present than  
<sup>174</sup> participants who engaged in either form of walking [19]. Overall, it seems that  
<sup>175</sup> generally, P&T method has been considered as a locomotion technique that miti-  
<sup>176</sup> gates perceived cybersickness. Its impact on presence, however, remains unclear.  
<sup>177</sup> Nonetheless, there is evidence suggesting that in some instances, P&T can achieve  
<sup>178</sup> a level of presence nearly equivalent to that of steering-based locomotion tech-  
<sup>179</sup> niques. Thus, due to its lower cybersickness and possibly comparable presence,  
<sup>180</sup> we choose the commonly used P&T as the interface to improve spatial learning.

2.4. P&T-based Works	181
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 [22]. 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 [23]. Of particular note, Müller et al. introduced an Undo feature in their work [13], 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 <i>Undo-Redo</i> 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 backwards. 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.	182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217
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 [13]. This finding contrasts with Bhandari et al., who integrated a swift, continuous transition process that preserves optical flow without exacerbating VR sickness [31].	
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 <i>Undo-Redo</i> scheme, which	

218 facilitates swift navigation among previously visited teleportation points without  
 219 reinitiation of the selection phase for the purpose of spatial learning.

### 220 3. The Traceable Teleportation

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

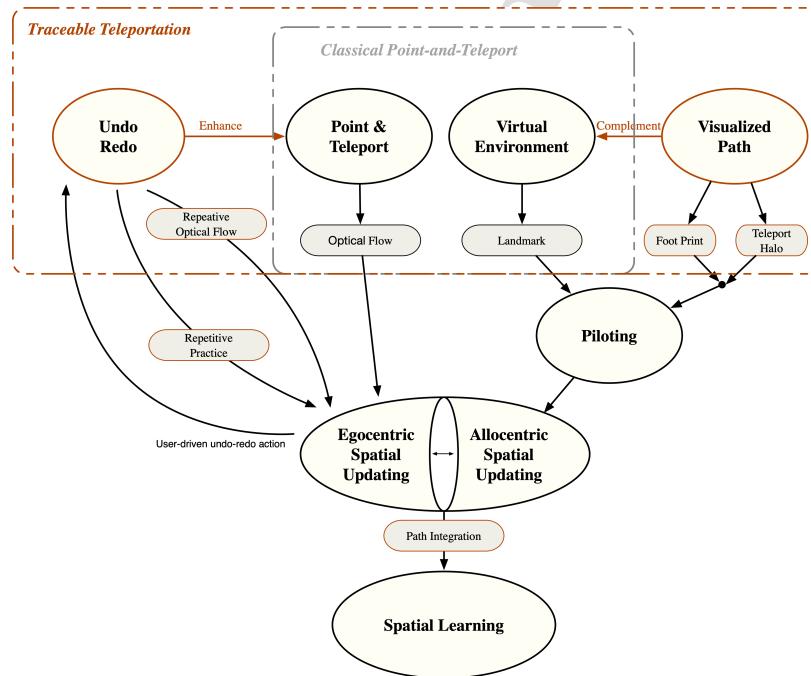


Figure 2: The conceptual framework for spatial learning in P&T technique. Enhancements of *Traceable Teleportation* (*TTP*) are *Undo-Redo* and *Visualized Path* (red)

#### 229 3.1. The theoretical framework

230 In this section, we lay out the theoretical framework concerning how virtual  
 231 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 Figure 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* [9, 10, 32]. More formally, it is the process for spatial understanding and constructing spatial memory, that is to acquire and memorize *spatial knowledge* [14, 33], which is the knowledge about (virtual) environments' spatial properties [34]. 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 [9]. 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 [35]. 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 [36]. 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 [33].

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 [37, 38, 39, 40]. 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 [38]. In contrast, an allocentric representation references outside of one's current body position, typically to multiple external landmarks. This is done by people devel-

270      oping the ability to imagine transformations or to use visual information without  
 271      coupled vestibular and proprioceptive information to specify movement [41]. This  
 272      is often the case when drawing a cartographic map of an environment, as it ne-  
 273      cessitates detailed knowledge of the relative directions and distances of stationary  
 274      landmarks [38, 42].

275      During egocentric spatial updating, a navigator utilizes both internal (idio-  
 276      thetic) signals (e.g., proprioception and vestibular feedback) and external (allo-  
 277      thetic) signals (e.g., acoustic and optic flow) to continuously compute estimates  
 278      of self-position and orientation within external space [43]. However, when there is  
 279      a mismatch or conflict between the visual and vestibular inputs in VR, it can result  
 280      in a perceptual illusion or distortion of spatial understanding. In such cases, the  
 281      brain may prioritize one sensory input over the other, leading to a distorted per-  
 282      ception of space, distance, and self-motion [44], and affecting the user's spatial  
 283      understanding. On the other hand, in the context of allocentric spatial updating,  
 284      this type of spatial updating relies on an allocentric reference frame (akin to the  
 285      third-person perspective) [38] or an environmental representation system [45] to  
 286      visualize the coordinates of objects, landmarks, and places and their interrelation-  
 287      ships. Ultimately, both of these representations are integrated through a cognitive  
 288      process known as *path integration*, which is essential for spatial learning. This  
 289      spatial learning then forms spatial understanding and memory and finally becomes  
 290      an individual's spatial knowledge. Note that egocentric and allocentric spatial up-  
 291      dating can rely on different methods to operate. Here, we focus on the fact that  
 292      egocentric and allocentric spatial updating rely on optical flow and piloting to  
 293      effect, respectively.

294      **Optical Flow**, or optic flow, is the perception of self-movement within a struc-  
 295      tured environment, leading to retinal image motion [46]. This phenomenon is cru-  
 296      cial in adapting the visuo-locomotor mapping system [47] and enhances spatial  
 297      integration [48]. It also influences both additive and multiplicative tuning gains  
 298      for visual features such as orientation, direction, and spatial frequency [49, 50].  
 299      Due to tracking space constraints in most VR applications, providing sufficient  
 300      vestibular information in VEs is often impractical. Therefore, optical flow is seen  
 301      as a reliable method for humans to execute egocentric spatial updating in VEs.  
 302      The feasibility of integrating optical flow into VEs to enhance egocentric spatial  
 303      updating has been validated in VR research [51, 52]. Especially for teleportation,  
 304      the locomotor direction is determined by the point in the flow field from which  
 305      motion vectors radiate [52], underlining the significance of optical flow in facili-  
 306      tating spatial awareness. However, as the classical instant P&T quickly transfers  
 307      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 [53].

Proximal landmarks located close to the observer, predominantly provide positional information, while distal landmarks, situated farther away, convey directional information [54]. Besides landmarks, the environmental shape—such as that determined by room walls—can also serve as a significant cue for piloting [55]. 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 [56]. 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 [57, 58, 59]. The classic P&T method, as illustrated in Figure 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 [51]. 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.

345 As depicted in Figure 3 (c) and (d), users can swiftly move to previous teleport  
 346 points, and subsequently, easily return without the need to look back. This method  
 347 allows users to retain more directional spatial information compared to the clas-  
 348 sical P&T method, where users need to re-select their destinations to achieve the  
 same actions.

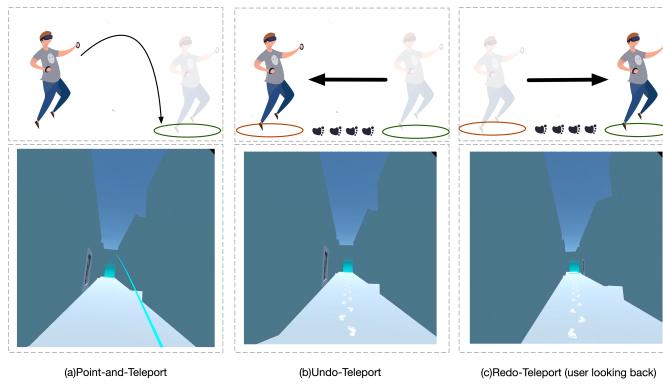


Figure 3: Overview of the proposed *Traceable Teleportation (TTP)* VR locomotion technique. (a) The classical P&T. (b) Users can swiftly return to the starting point by utilizing the undo feature of the *Undo-Redo* mechanism and the *Visualized Path* contains the teleport halos and footprints. (c) Users 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.

349  
 350 The *Undo-Redo* functionality theoretically contains two potential improve-  
 351 ments. The first is Repetitive Practice, which has been identified as a critical  
 352 factor in establishing durable memory due to its role in reinforcing neural con-  
 353 nections [60]. Research conducted on mice supports this, demonstrating that re-  
 354 peated training can stimulate brain functions, leading to a more pronounced use of  
 355 hippocampus-dependent strategies [61]. Moreover, consistent practice has been  
 356 shown to greatly enhance the levels of the Brain-Derived Neurotrophic Factor,  
 357 which is crucial for regulating synaptic plasticity, including long-term potentiation.  
 358 This has been demonstrated in studies involving rats [62]. These findings  
 359 underscore the potential of leveraging repetitive practice in VR locomotion tech-  
 360 niques to enhance spatial memory. The second improvement is Repetitive Optical  
 361 Flow. This can be attributed to the high-frequency teleport between the current  
 362 location and the target position, as the user can directly teleport within the history  
 363 points without needing to select points and then teleport. This repetitive optical  
 364 flow provides users with more spatial information, potentially enhancing spatial  
 365 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 Figure 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,

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

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  $\gamma$  signifies the ratio of  $L_{eye2foot}$  to  $L_{height}$ . Additionally,  $\rho$  represents the height-to-foot ratio, and  $L_{footprint}$  corresponds to the estimated footprint length as described in previous research. The value of  $\gamma$  is calculated to be approximately .911, as determined by the human body ratio parameters proposed in the previous study [63]. Meanwhile, a value of  $\rho$  is set to 6, following the precedent established by prior work [64]. 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 [54], 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 [57]. 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.

#### 397 4. Research Question and Hypothesis

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

407 **RQ1** Does *TTP* enhance users' spatial learning?

408 **RQ2** What impact does *TTP* have on users' VR experience?

409 The introduction of the *Undo-Redo* and *Visualized Path* functionalities is hy-  
 410 pothesized to independently augment both egocentric and allocentric spatial up-  
 411 dates (Section 3). Accordingly, our research framework posits a discrete evalua-  
 412 tion of the impacts attributable to each enhancement on spatial learning. More-  
 413 over, potential synergistic effects arising from the concurrent application of these  
 414 enhancements will be subjected to analysis. As outlined in our conceptual frame-  
 415 work depicted in Figure 2, we have formulated hypothesis on spatial learning:

416 **H1a** The *Undo-Redo* mechanism significantly influences the human directional  
 417 awareness.

418 **H1b** The *Undo-Redo* mechanism significantly influences the human distance es-  
 419 timation.

420 **H1c** The *Visualized Path* significantly affects the human directional awareness.

421 **H1d** The *Visualized Path* significantly affects the distance estimation.

422 **H1e** There exists an interaction effect between the *Undo-Redo* mechanism and  
 423 the *Visualized Path* on the human directional awareness.

424 **H1f** There exists an interaction effect between the *Undo-Redo* mechanism and  
 425 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 [2, 4, 15, 28]. Furthermore, evaluations by Langbehn et al. indicate no significant difference in workload between teleportation and other locomotion methods [15]. Additionally, teleportation generally results in lower cybersickness compared to other techniques [2, 28, 29]. Based on these presented discussions, we have formulated hypotheses on Cybersickness, Sense of presence, and Workload: 426  
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- 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*. 434  
435  
436
- 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*. 437  
438  
439
- 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*. 440  
441  
442

## 5. Method 443

5.1. *Experimental design and task* 444

In this study, we examined the effects of *TTP* on users' spatial learning, workload, cybersickness, and sense of presence, employing a  $2 \times 2$  factorial experimental design. Figure 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. 445  
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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. 452  
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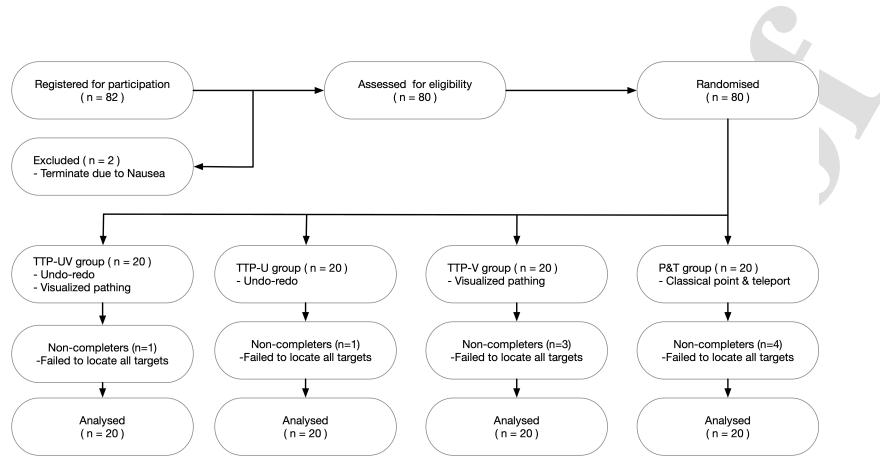


Figure 4: The flow diagram of the experiment.

### 456 5.1.1. Participants

457 This study received ethical approval from the Institutional Review Board of  
 458 The Hong Kong Polytechnic University. A total of 82 participants were recruited  
 459 via on-campus posters and social networks. All participants were either studying  
 460 or working at The Hong Kong Polytechnic University. Due to feelings of nausea,  
 461 two participants chose to withdraw from the experiment. As a result, 80 partici-  
 462 pants were randomly assigned to one of four groups, with each group composed  
 463 of 20 individuals. After the experiment, participants who were unable to locate  
 464 all three targets were identified as non-completers (see Figure 4). We have detail  
 465 described how we handle the non-completers in section 5.6 .

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

### 473 5.2. Virtual labyrinth

474 There were prior works that applied a virtual labyrinth to test spatial knowl-  
 475 edge learning [65, 66, 67], but the design of the labyrinth lacks a clear standard,  
 476 which may influence the test performance and make it difficult to do follow-up  
 477 research. Therefore, our research proposed a labyrinth design procedure that can  
 478 guide the generation of the labyrinths. When using a labyrinth in a virtual spatial

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)

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 [67]. 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  $n$ .

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

Secondly, the distance from the start point to the  $i^{\text{th}}$  object in a labyrinth with a half-length of  $L$  and  $n$  objects, where each object is placed at equal intervals, is given by:

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

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 Figure 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

502 labyrinth's starting point is positioned at the heart of the central square corridor.  
 503 Accessible via an X-shaped entrance emanating from the starting point, this cor-  
 504 ridor connects to the main corridor. To assist users in identifying their location,  
 505 four virtual paintings are strategically arranged along the walls of the central corri-  
 506 dor. The paintings also serve as landmarks that users can reference when devising  
 507 strategies for navigation and target acquisition. Additionally, the virtual labyrinth  
 508 incorporates auditory cues to enrich the user's experience and offer supplemen-  
 509 tary information about the surrounding environment. For instance, when users  
 510 first discover an object, a hint sound is played, providing auditory feedback and  
 511 confirmation of their successful interaction with the environment. This labyrinth,  
 512 with its intricate design elements that foster a sense of complexity and ambiguity,  
 513 serves as a test of the user's spatial learning.

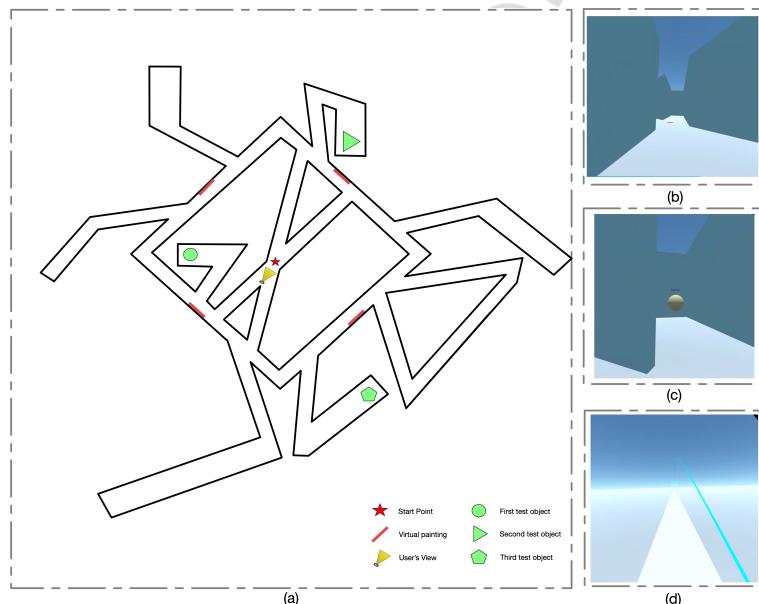


Figure 5: The environment of the virtual labyrinth. (a) The overview of the virtual labyrinth (b) The user's first-person view in the virtual labyrinth (c) One of the test objects in the virtual labyrinth (d)The test scene of the experiment

514 We developed our experimental environment using Unity, wherein one unit  
 515 corresponds to one meter. This means that the virtual environment is designed to  
 516 have a 1 : 1 ratio with the real world. In our experimental setup, we place three  
 517 objects at the ends of three branches to challenge participants' spatial memory  
 518 and comprehension. Three objects are included in our experiments, and the half-

length of the virtual labyrinth is set to 36 meters. 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 meters, 18 meters, and 24 meters. The width of the labyrinth hallway is set to approximately 2.5 meters. 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, 16GB of RAM, and an NVIDIA RTX 3060 graphics card. Utilizing the Oculus Integration SDK for Unity's software development and debugging tools<sup>1</sup>, it was confirmed that the Oculus Quest 2 maintained its maximum refresh rate of 90Hz throughout the entire exposure. The right-hand Oculus Touch controller facilitated the classic P&Tation 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

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

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<sup>1</sup><https://developer.oculus.com/downloads/package/unity-integration>

551 and the DOE is calculated by

$$d = ||\mathbf{r}_A - \mathbf{r}| - |\mathbf{r}_B - \mathbf{r}||, \quad (5)$$

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

555 Utilizing both AOE and DOE, we were able to conduct a comprehensive and  
556 objective assessment of the participant's spatial learning. Primary spatial knowl-  
557 edge can be conceptualized as a labeled place graph, which effectively organizes  
558 learned locations by connecting them through nodes that represent estimated dis-  
559 tances and angular offsets, as described by Ericson et al. [65]. Accordingly, we  
560 adopted the angular offset to quantify the accuracy of participants' spatial direc-  
561 tional awareness, and the distance offset to measure the precision of their distance  
562 estimations. Collectively, these metrics offered a precise evaluation of the partic-  
563 ipants' performance in the spatial task. It should be noted that our work treats  
564 spatial understanding and memory as integral parts of spatial learning. Here, our  
565 evaluation did not separately measure the users' acquisition and retention of spa-  
566 tial knowledge. As such, a good measure may indicate strong spatial understand-  
567 ing, while the exact performance for spatial memory may be less clear as our  
568 evaluation starts soon after the users learn about their environment.

#### 569 5.4.2. Presence

570 The Igroup Presence Questionnaire (IPQ) [68] was used to evaluate the sense  
571 of presence among the participants of all four groups. IPQ has been widely used  
572 to measure the sense of presence in prior studies on locomotion (e.g., [7, 28]).  
573 The instrument has 14 items measured on a seven-point scale, with higher scores  
574 indicating higher presence. Because some items were adapted from previously  
575 published scales, the original response anchors were kept. For example, one item  
576 states, "In the computer-generated world I had a sense of 'being there'" which is  
577 adopted from [69], and the corresponding response anchors are between "not at  
578 all" (1) and "very much" (7). Another item states, "How much did your experience  
579 in the VE seem consistent with your real-world experience?" which is adapted  
580 from [70], and the corresponding response anchors are between "not consistent"  
581 (1) and "very consistent" (7). These items are separated into four dimensions  
582 namely Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL),  
583 and Sense of being there (General).

5.4.3. Task load	584
The NASA Task Load Index (NASA-TLX) [71] 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.	585
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).	586
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5.4.4. Cybersickness	593
The Simulator Sickness Questionnaire (SSQ) [72] 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., [8, 7]).	594
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 [73].	595
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5.5. Procedure	602
Each individual who responded to the participant recruitment advertisement completed a pre-questionnaire to ensure they met the experiment requirements.	603
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.	604
Following this, we played a tutorial video that explained the experiment procedure, the task in the virtual labyrinth, and the three experiment phases.	605
After the introduction, participants confirmed their understanding of the tasks, and we addressed any confusion that they encountered.	606
Additionally, we informed participants that they could terminate the experiment at any time if they felt discomfort or distress.	607
The following are the phases of the experiment.	608
<b>Training Phase:</b> During the training phase, participants were provided with the VR device and instructed to use the assigned teleportation technique.	609
The locomotion technique available to users depends on their assigned group.	610
For instance, a user in the TTP-UV group will have access to the <i>Undo-Redo</i> action	611
and will be able to see the <i>Visualized Path</i> .	612
Conversely, a user in the P&T group will experience only the classical P&T technique without any enhancements.	613
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620 is worth noting that for the *Visualized Path*, we intentionally did not inform par-  
 621 ticipants that the footprint's length matches their actual footprint observe whether  
 622 it naturally influenced their spatial perception without any preconceived biases.  
 623 Participants were placed in a square-shaped plane and shown three target objects  
 624 which they were required to find during the exploration phase. Upon declar-  
 625 ing their familiarity with the locomotion technique, the experiment environment  
 626 changed to the exploring phase.

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

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

651 After the test phase, we asked participants to complete questionnaire B (in-  
 652 cluding the SSQ test, NASA-TLX test, and IPQ test details described in sec-  
 653 tion 5.4). At the end of the experiment, participants signed the receipt of the  
 654 compensation.

<b>5.6. Data preprocessing</b>	655
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.	656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673
<b>5.7. Statistical analysis</b>	674
The statistical analysis serves two primary aims: investigating the main effects of the <i>Visualized Path</i> and <i>Undo-Redo</i> mechanisms, and exploring their interaction effects. Preparing for two-way ANOVA, Levene's test checked homogeneity of variances [74], and Shapiro-Wilk tested normality [75], 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 <sup>2</sup> , followed by the standard two-way ANOVA [76]. The threshold for statistical significance was established at a <i>p</i> – value of .05 for all analyses.	675 676 677 678 679 680 681 682 683
<b>6. Result</b>	684
<b>6.1. Spatial learning</b>	685
The overall descriptive statistic results for the AOE and DOE, across all four experimental conditions, are displayed in Table 2.	686 687

<sup>2</sup><https://depts.washington.edu/acelab/proj/art/>

688      Results for the **First Test Object**: A two-way ANOVA was conducted in ac-  
 689 cordance with the ART. For the AOE, we removed two outliers in TTP-UV, two  
 690 outliers in TTP-U, and four outliers in TTP-V. The result showed that *Undo-Redo*  
 691 mechanism had a significant main effect ( $F(1, 68) = 7.761, p = .007, \eta_p^2 = .102$ ),  
 692 whereas the *Visualized Path* did not ( $F(1, 68) = .704, p = .404, \eta_p^2 = .010$ ). No  
 693 interaction effect was observed ( $F(1, 68) = .074, p = .786, \eta_p^2 = .001$ ). Regard-  
 694 ing the DOE, we removed two outliers in TTP-U. The result indicated that neither  
 695 the *Undo-Redo* mechanism ( $F(1, 74) = 2.324, p = .132, \eta_p^2 = .030$ ) nor the *Visu-*  
 696 *alized Path* ( $F(1, 74) = .173, p = .679, \eta_p^2 = .002$ ) demonstrated significant main  
 697 effects. Likewise, no interaction effect was observed ( $F(1, 74) = 1.098, p = .298,$   
 698  $\eta_p^2 = .015$ ).

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

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

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

the non-support of hypotheses H1e and H1f.

724

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)

## 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.

745 **6.3. Task load**

746 The descriptive results for the NASA-TLX are displayed in Table 3. We con-  
 747 ducted the two-way ANOVA analysis were revealed that there is no significant  
 748 main effect were found for *Undo-Redo* mechanism on Mental Demand ( $F(1,67) =$   
 749  $1.168, p = .284, \eta_p^2 = .017$ ), Physical Demand ( $F(1,67) = 1.074, p = .304,$   
 750  $\eta_p^2 = .016$ ), Temporal Demand ( $F(1,67) = 1.241, p = .269, \eta_p^2 = .018$ ), Per-  
 751 formance ( $F(1,67) = 1.044, p = .311, \eta_p^2 = .015$ ), Effort ( $F(1,67) = 2.232,$   
 752  $p = .140, \eta_p^2 = .032$ ), Frustration ( $F(1,67) = 1.060, p = .307, \eta_p^2 = .016$ ), Over-  
 753 all Score ( $F(1,67) = 1.659, p = .202, \eta_p^2 = .024$ ). Also, the *Visualized Path*  
 754 does not have the main effects on Mental Demand ( $F(1,67) = 1.061, p = .307,$   
 755  $\eta_p^2 = .016$ ), Physical Demand ( $F(1,67) = 1.828, p = .181, \eta_p^2 = .027$ ), Temporal  
 756 Demand ( $F(1,67) = .270, p = .605, \eta_p^2 = .004$ ), Performance ( $F(1,67) = .185,$   
 757  $p = .669, \eta_p^2 = .003$ ), Effort ( $F(1,67) = .295, p = .589, \eta_p^2 = .004$ ), Frustra-  
 758 tion ( $F(1,67) = .393, p = .533, \eta_p^2 = .006$ ), Overall Score ( $F(1,67) = .957, p =$   
 759  $.331, \eta_p^2 = .014$ ). Lastly, there are also no interaction effect between *Undo-Redo*  
 760 mechanism and *Visualized Path* for Mental Demand ( $F(1,67) = .578, p = .450,$   
 761  $\eta_p^2 = .009$ ), Physical Demand ( $F(1,67) = .331, p = .567, \eta_p^2 = .005$ ), Temporal  
 762 Demand ( $F(1,67) = 1.737, p = .192, \eta_p^2 = .025$ ), Performance ( $F(1,67) = .933,$   
 763  $p = .338, \eta_p^2 = .014$ ), Effort ( $F(1,67) = .295, p = .589, \eta_p^2 = .004$ ), Frustration  
 764 ( $F(1,67) = .032, p = .860, \eta_p^2 = .000$ ), Overall Score ( $F(1,67) = .073, p = .788,$   
 765  $\eta_p^2 = .001$ ).

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

770 **6.4. Cybersickness**

771 The impact of the *Undo-Redo* and *Visualized Path* mechanisms on cybersick-  
 772 ness was meticulously scrutinized through a series of two-way ANOVA analy-  
 773 ses. SSQ general results are shown in Table 3. The results suggest a mini-  
 774 mal influence of these mechanisms on all evaluated aspects of cybersickness.  
 775 There are no main effects found for *Undo-Redo* on Nausea ( $F(1,67) = 1.048,$   
 776  $p = .310, \eta_p^2 = .015$ ), Oculomotor ( $F(1,67) = .137, p = .713, \eta_p^2 = .002$ ), Dis-  
 777 orientation ( $F(1,68) = .637, p = .428, \eta_p^2 = .009$ ), and the overall SSQ score  
 778 ( $F(1,67) = .332, p = .566, \eta_p^2 = .005$ ). Additionally, *Visualized Path* does have  
 779 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 ( $F(1,67) = .067, p = .797, \eta_p^2 = .001$ ), 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.

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

item	IPQ <sup>1</sup>					NASA-TLX <sup>2</sup>							SSQ <sup>3</sup>			
	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)

<sup>1</sup> IPQ1 refers SP, IPQ2 refers INV, IPQ3 refers REAL, IPQ4 refers General, and IPQ5 refers Total IPQ score.

<sup>2</sup> 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.

<sup>3</sup> SSQ1 refers Nausea, SSQ2 refers Oculomotor, SSQ3 refers Disorientation and SSQ4 refers overall SSQ score.

## 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

796 a blend of objective and subjective measures to investigate the effects of these im-  
 797 provements by implementing a  $2 \times 2$  factorial experimental design. Spatial learn-  
 798 ing was quantified by analyzing two primary metrics: AOE and DOE. Concur-  
 799 rently, to subjectively assess the impact of the *TTP* method on users' experiences,  
 800 surveys focusing on three main areas were conducted: the sense of presence, per-  
 801 ceived workload, and cybersickness.

### 802 7.1. Exploring the effect of *TTP* on human spatial learning

803 To address **RQ1**, we employed a labyrinth with three memory tasks to identify  
 804 the effects and compared AOE and DOE. These two metrics imply the partici-  
 805 pant's understanding and memory of the spatial relationship between their posi-  
 806 tion to the target's position. Therefore, the influence of the *TTP* on spatial learning  
 807 can be separately discussed in the level of direction and distance (AOE corre-  
 808 sponds to the spatial direction awareness, and DOE corresponds to the distance  
 809 estimation).

#### 810 7.1.1. *TTP* strengthen human direction awareness

811 Our analysis revealed a significant main effect of the *Undo-Redo* mechanism  
 812 on the AOE, with lower values indicating better spatial direction awareness across  
 813 all memorization tasks, which supported hypothesis H1a. We attribute the efficacy  
 814 of the *Undo-Redo* mechanism to two main factors: its ability to improve explo-  
 815 ration efficiency and its capacity to reduce orientation effort. Participants using  
 816 the *Undo-Redo* feature could simplify the selection phase by quickly navigating  
 817 between previously visited points, thereby facilitating a more convenient famili-  
 818 arization with VEs. This was substantiated by those who can use the *Undo-Redo*  
 819 mechanism which makes it only have one non-completer for each group com-  
 820 pared to those without that have three and four non-completers for TTP-V group  
 821 and T&P group respectively. It seems that *Undo-Redo* mechanism can enhance  
 822 the efficiency of memorization for the spatial learning task. Additionally, *Undo-*  
 823 *Redo* mechanism allows participants to maintain their gaze in the target's direction  
 824 while returning to the start point, providing consistent directional cues and reduc-  
 825 ing the need for reorientation. Without this feature, participants may need to rely  
 826 on external reference points, increasing memory load. Our experimental design  
 827 minimized additional orientation cues. We removed wall shadows and used con-  
 828 sistent textures to focus on the effects of the internal mechanisms. These measures  
 829 strengthen the evidence that the *Undo-Redo* mechanism can enhance the users' di-  
 830 rectional 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 [77, 78]. 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. [79] 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, pos-

868 sibly resulting in the larger mean, though not statistically significant, differences  
 869 in DOEs we observed in the *TTP-UV* group.

870 Moreover, Kearns et al.[51] have shown a tendency for individuals to depend  
 871 more on optic flow rather than landmarks when estimating distance. This could  
 872 explain the smaller mean, though not statistically significant, differences in DOEs  
 873 in the *TTP-U* group, which had access to the *Undo-Redo* feature, suggesting that  
 874 repeated exposure to optic flow may improve distance perception in VEs. Another  
 875 angle is that distances in VEs, especially when viewed through an HMD, are often  
 876 underperceived, as noted by Kelly et al. [80]. Our visualized footprints may not  
 877 have provided sufficient landmarks to overcome this underperception.

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

### 886 7.2. Exploring the effect of TTP on user experience

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

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

903 Regarding the NASA-TLX and in line with hypothesis H2b, the *Undo-Redo*  
 904 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 [13]. 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 [81], 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 [28]. 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 [82, 83, 84], 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 [85]. 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

941 they are equally effective across different labyrinth layouts. Future studies could  
 942 address this limitation by testing our principles on a variety of labyrinths, providing  
 943 a more comprehensive understanding of their potential applications.

944 The HMD we used in the study is a limitation as well. The limited field of  
 945 view of the Oculus Quest 2, which provides only a 104° field of view compared  
 946 to the human normal of approximately 200° [86], may have negatively affected  
 947 our results. Previous research has suggested that a wider field of view can have a  
 948 positive effect on memory and presence in VR [87]. Future studies could address  
 949 this limitation by using an HMD device with a better field of view, which may  
 950 improve task performance in the VR environment.

951 The *Undo-Redo* function has demonstrated its potential to enhance human  
 952 spatial learning. However, its internal mechanisms still require further explo-  
 953 ration. For instance, how does the *Undo-Redo* action differ from simply look-  
 954 ing back? While Müller et al. have compared orientation Undo with standard  
 955 undo techniques [13], additional research is necessary to expand our understand-  
 956 ing. One interesting observation from our user study is that participants employed  
 957 the *Undo-Redo* function in distinct ways. Some users primarily used *Undo-Redo*  
 958 to recall the target direction, while others utilized it to swiftly navigate through  
 959 the labyrinth. Consequently, due to the varied approaches to using the *Undo-*  
 960 *Redo* function, it is challenging to model the relationship between the frequency  
 961 of *Undo-Redo* actions and the metrics of AOE and DOE linearly. However, this  
 962 could be a potential direction for future research, employing a simpler environ-  
 963 ment to evaluate the relationship between the frequency of *Undo-Redo* actions  
 964 and spatial learning performance.

## 965 9. Conclusion

966 This study presents *TTP*, a novel VR locomotion technique that introduces  
 967 two key enhancements to the classical P&T technique: the *Undo-Redo* mecha-  
 968 nism and the *Visualized Path* feature. Their addition is theoretically motivated  
 969 and aims to address P&T's deficiency in spatial learning according to the theo-  
 970 retical discussion. We have conducted a thorough analysis of the impact of these  
 971 enhancements through a  $2 \times 2$  factorial experimental design, comparing their per-  
 972 formance against the standard P&T method.

973 The *TTP* method shows considerable promise in improving some dimensions  
 974 of spatial learning within VEs. The *Undo-Redo* mechanism, in particular, has been  
 975 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.

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**11. Ethical approval**

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

**12. Disclosure statement**

No potential conflict of interest was reported by the author (s).

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## Highlights

Traceable Teleportation: Improving Spatial Learning in Virtual Locomotion

Ye Jia, Zackary P. T. Sin, Richard Chen Li, Peter H. F. Ng, Xiao Huang, George Baciu, Jiannong Cao, Qing Li

- Traceable Teleportation: A VR locomotion technique aimed at improving spatial learning.
- Theoretical discussion to pinpoint point-and-teleport's bottleneck in spatial learning
- User study suggests that TTP's Undo-Redo design can enhance spatial knowledge for orientation.

**Declaration of interests**

- 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.
- The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: