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A Comprehensive Review of Redirected Walking Techniques: Taxonomy, Methods, and Future Directions

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Abstract Virtual reality (VR) allows users to explore and experience a computer-simulated virtual environment so that VR users can be immersed in a totally artificial virtual world and interact with arbitrary virtual objects. However, the limited physical tracking space usually restricts the exploration of large virtual spaces, and VR users have to use special locomotion techniques to move from one location to another. Among these techniques, redirected walking (RDW) is one of the most natural locomotion techniques to solve the problem based on near-natural walking experiences. The core idea of the RDW technique is to imperceptibly guide users on virtual paths, which might vary from the paths they physically walk in the real world. In a similar way, some RDW algorithms imperceptibly change the structure and layout of the virtual environment such that the virtual environment fits into the tracking space. In this survey, we first present a taxonomy of existing RDW work. Based on this taxonomy, we compare and analyze both contributions and shortcomings of the existing methods in detail, and find view manipulation methods offer satisfactory visual effect but the experience can be interrupted when users reach the physical boundaries, while virtual environment manipulation methods can provide users with consistent movement but have limited application scenarios. Finally, we discuss possible future research directions, indicating combining artificial intelligence with this area will be effective and intriguing.

Keywords virtual reality, locomotion, redirected walking

1 Introduction

With the development of virtual reality (VR) technologies, VR devices such as head-mounted displays (HMDs) and trackers are becoming less expensive and more light-weight, which makes more consumers willing to experience those fancy and interesting VR applications in their daily life. When exploring a large virtual environment, special locomotion techniques are very necessary to allow VR users to move from one place to another place. Natural walking is the most common locomotion technique in our real world, which was proven to have the ability to improve the sense of presence [1, 2] and help users perform better in searching tasks [2, 3]. However, free traveling in the virtual world is mostly impossible due to the limited physical tracking space [4], especially for room-scale VR users. For instance, VR users can frequently reach the physical boundaries and obstacles during VR exploration, where the standing positions need to be corrected by the forced physical turn-backs. This method can effectively avoid physical collisions, but it could also break

Survey

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both the presence and the immersion [5, 6], and therefore degrades the overall user VR experience.

To solve this problem, some representative virtual locomotion techniques including teleportation [7–9], walking-in-place [10–12] and redirected walking (RDW) [13–17] were proposed to provide comfortable and efficient navigation in immersive virtual environments (IVEs). Among these techniques, RDW provides the highest natural feeling of walking because it is the most similar to natural walking, and users can perceive the correct proprioceptive, kinesthetic, and vestibular stimulation [18]. The core idea of RDW is to guide the user away from the physical boundaries by introducing imperceptible manipulations in the IVE. With the help of the RDW technique, users can make better use of their limited tracking space to explore a relatively larger virtual space.

Applying view manipulation for walking redirection is a practical idea. For example, when a user walks along a straight road in a large IVE, the system can slightly rotate the virtual camera and the user will unconsciously compensate the manipulation, which leads to the effect that the user is actually walking along an arc in the real world instead. Thus, various RDW methods were proposed based on different heuristics and can be generally classified into reactive and predictive methods. Reactive methods [19–21] redirect the user without considering the future walking path. For example, the steer-to-center (S2C) method always redirects the user to the center of the tracking space no matter how the user walks in the IVE. On the contrary, predictive methods [22–24] will predict the user's next movement first by analyzing both the physical and virtual environments for making more efficient redirection strategies. However, when the tracking space is small enough, the user can still reach the physical boundaries, which should be corrected overtly by resetting methods [25].

Besides, some RDW methods can adjust the virtual architecture properties in the virtual environment dynamically or compress the large virtual environment to the given physical space statically, without manipulating the user camera view or causing collisions to the physical boundaries [26–28]. For example, the Change Blindness algorithm [26] utilizes the blindness of the VR user to change the location of the doorways and corridors, which can manipulate the walking paths imperceptibly. Other methods can directly map the virtual environment into the given physical space [29–32]. But these methods are just suitable for special VEs and may introduce visual distortions.

To make the RDW technique applicable in various application scenarios, there have been more specific RDW tasks recently investigated, including multiple user co-location navigation [20, 33, 34], walking in physical tracking spaces with irregular shapes or obstacles [33, 35, 36], redirection for passive haptics to offer haptic feedback during virtual exploration [37–41], etc. Research on these RDW tasks can enhance the method performance, improve algorithm usability and make the user experience more diverse from different perspectives.

The emergence of novel RDW algorithms accelerates the development of common open-source libraries and benchmarks, which can make the deployment process of RDW methods more convenient and time-saving. Moreover, researchers can run adequate simulation with less effort and evaluate algorithm performance through intuitive visualization and detailed statistic results. For example, Azmandian *et al.* [42] released an open-source redirected walking toolkit (RDWT) as a Unity3D package①. Researchers can directly import this package to their projects and utilize the provided APIs to customize algorithms and assess their innovative ideas. Besides, the implementation of several classic methods such as S2C and S2O is integrated in this toolkit for comparison and reference. Li *et al.* [43] further proposed an open-source library and benchmark called OpenRDW, which has a redesigned framework based on RDWT and more functionalities including the implementation of state-of-the-art RDW methods, supporting multi-user real walking or simulation, containing various tracking spaces for evaluation, etc.

Besides RDW, other forms of redirected locomotion [44–47] such as redirected driving [44] and redirected jumping (RDJ) [45, 46] have also been proposed to extend the usability of redirection techniques. Fig. 1 briefly summarizes the key events of RDW development.

In comparison with other surveys and existing work which summarized redirected locomotion techniques, Suma *et al.* [48] presented a taxonomy of redirection techniques according to geometric flexibility and the possibility that the manipulation will be noticed by users, while ours focuses on more aspects including platforms and tasks. Nilsson *et al.* [18] provided a survey which gives an overview of the RDW technique from the original paper of Razzaque *et al.* [13] to 2018, and

①Unity 3d game engine. https://unity.com/, March 2022.

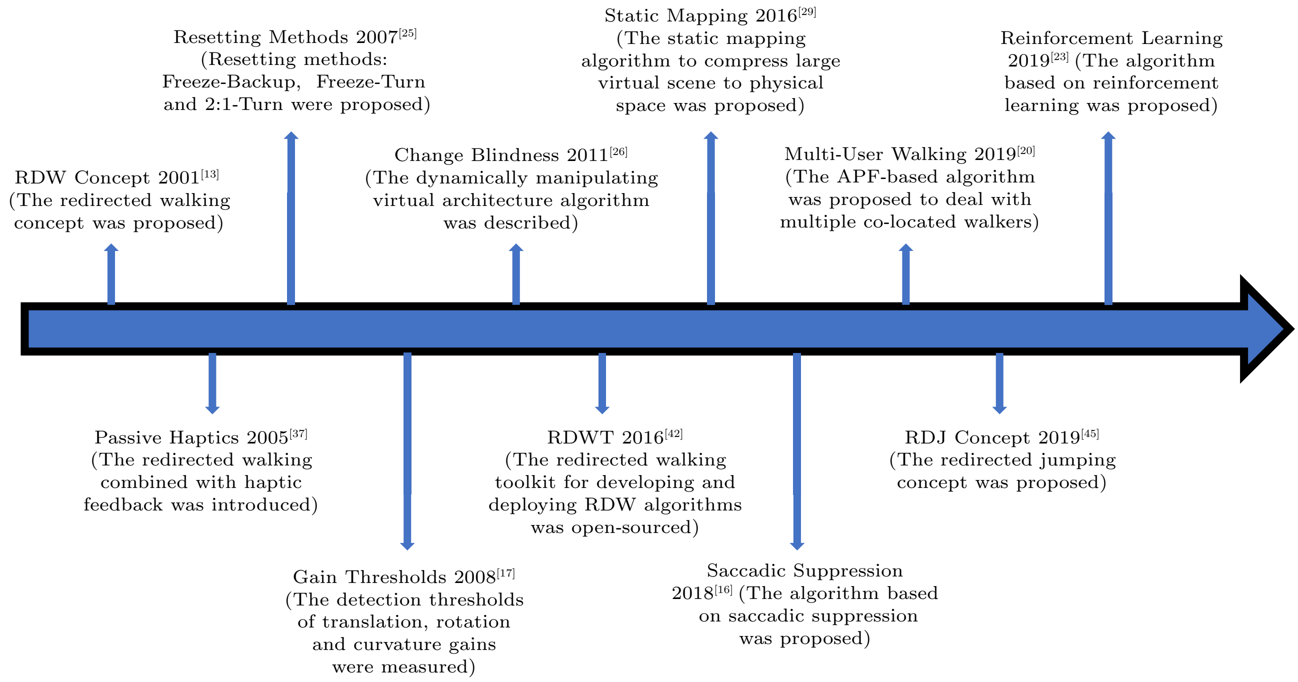


Fig.1. Brief summary of key developments in redirected walking.

Langbehn and Steinicke[49] also presented a short summary of the RDW technique, while ours adds more content about state-of-the-art techniques like reinforcement learning based methods and redirect jumping. Bishop and Abid[50] presented a survey which summarizes the existing types of virtual reality locomotion systems including RDW, active walking interface and controller-based locomotion, while ours mainly focuses on redirected locomotion techniques related to position changing.

In this survey, we first present a taxonomy of redirected walking, then summarize the existing work based on this taxonomy, and finally discuss the future directions.

The rest of this paper is organized as follows. We first reveal the taxonomy of redirected walking from our perspectives (Section 2). Based on the proposed taxonomy, the existing user study work for gain evaluation will be introduced first (Section 3), which can provide theoretical support for RDW algorithms. These algorithms are designed according to different principles and competent for diverse tasks, which will be introduced in Section 4. Besides, RDW algorithms also require reliable platforms or benchmarks for development, deployment and evaluation (Section 5). To save physical space, other forms of redirected locomotion techniques were also proposed and proven to be effective (Section 6). Finally, we will propose and discuss the possible future research directions (Section 7) and draw informative conclusions of this paper (Section 8).

2 Taxonomy of Redirected Walking

According to different research objectives and problems to be addressed, we present a taxonomy of redirected walking, which divides the existing work into three major parts: gain perception, algorithm, and platform. The gain perception part is mainly related to user experiments on detection threshold measurements, which can be further divided into the detection threshold for subtle manipulations and overt manipulations. For example, Steinicke *et al.* first classified subtle manipulations into three types: translation gain, rotation gain and curvature gain[41], and then they quantified these detection thresholds through user experiments[15]. Langbehn *et al.*[51] later supplemented the concept of bending gains, which can be used when the curvature of the virtual path is known. Cho *et al.*[52] also introduced and measured the detection thresholds of backward and sideward walking gains. Although most measurement work is for subtle manipulations, overt manipulations can get better results under some certain situations[53,54]. For example, Schmite *et al.*[53] measured the rotation detection threshold when the user's presence will break, and found that when rotation gains are greater than 1.0, immersion breaks quite late after the gain is detectable. Those detection thresholds can be used in view manipulation RDW algorithms relying on manipulating the user's virtual camera to steer the user to walk towards the open physical area, while the other type of RDW algorithms utilizes the manipulations of the virtual environment. For view manipulation algorithms, reactive methods steer the user without considering the future movement. For example, the steer-to-center (S2C) method [14] always steers the user to the center of the walking area. When the user's future walking path is predictable, predictive methods will make better redirection strategies by considering the layout of the virtual environment. But sometimes users can still reach the physical boundaries, which should be corrected overtly by using resetting methods [25]. Learning-based [23, 24, 34] and saccadic suppression based [16] algorithms have also been proposed, which are effective and intriguing. Some RDW open-source platforms [42, 43] also emerge to help develop and deploy RDW algorithms, which can save effort for re-implementing the existing work and make comparisons easier. Fig.2 reveals the taxonomy of our survey.

3 Gain Perception

In this section, we first introduce the general form for different types of gains in Subsection 3.1. Then we relevant related user studies for measuring detection thresholds in Subsection 3.2 and other common measurements in Subsection 3.3.

3.1 General Form

For viewpoint-manipulation based RDW methods, the manipulations of the movement of virtual camera

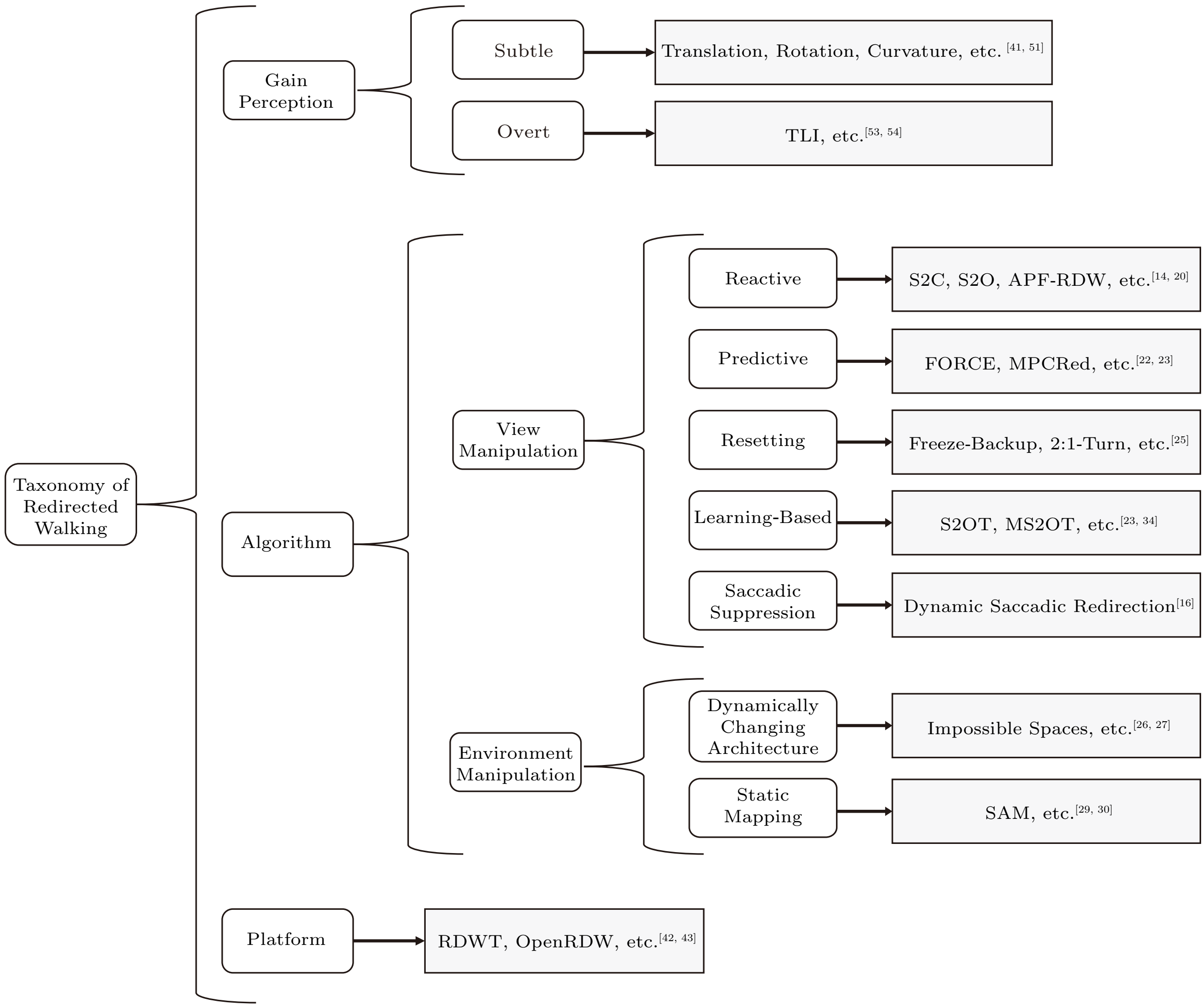


Fig.2. Taxonomy of redirected walking.

are usually called gains (see Fig.3). There are different types of gains which are used jointly to manipulate the virtual path in order to avoid physical collisions. From the taxonomy of Steinicke *et al.* [41,55], gains of redirection techniques include translation, rotation and curvature gains, where translation gains scale the user's moving speed, resulting in a faster or slower translation movement in the virtual space; rotation gains scale the speed of rotation, allowing the user to turn faster or slower; curvature gains steer the virtual orientation during the moving process. Besides, other types of gains like bending gains [51] and relative gains [56] have also been proposed recently to enrich the potential application scenarios. Gains can be formulated for quantified usages. For example, the translation gain g_T can be defined as $g_{\rm T} = d_{\rm virtual}/d_{\rm real}$, where $d_{\rm virtual}$ stands for the translation distance in the VE and $d_{\rm real}$ represents the translation distance in the real world. In order to make the VR experience comfortable and immersive, this manipulation should be limited to certain detection thresholds, which need to be measured by repeated real user studies. Subsection 3.2 and Subsection 3.3 introduce the relative work of detection thresholds and other measurement evaluations respectively.

3.2 Measurement of Detection Thresholds

While redirected walking can be useful for modifying the mapping of movements between the real world and the virtual environment, this technique needs to be studied from both qualitative and quantitative perspectives. If the manipulation of the virtual camera is too obvious, it will probably be noticed by the VR user and induce a feeling of unnaturalness. In this regard, researchers usually conduct psychophysical experiments to estimate detection thresholds, which can define the appropriate range of manipulations for users' comfortable walking experiences. Based on divergent purposes, types of manipulations can be classified into subtle manipulation and overt manipulation. The former category of manipulation abides by the imperceptible rule and is relatively preferable in most cases, while the latter is more suitable when the practical limitation should be taken into consideration while ensuring the safety of the VR user [18].

3.2.1 Subtle Manipulation

Subtle manipulations manipulate the camera view without being perceived by VR users, aiming to make the VR experience close to the experience in the real world. Most of the existing work used two-alternative forced-choice tasks (2AFC) to estimate the thresholds, where participants are required to choose one option from two possible answers, e.g., "Was the virtual movement smaller or greater than the physical movement?" [15]. Steinicke *et al.* [15,17] quantified detection thresholds of rotation, translation and curvature gains through a series of experiments in this way, and their experimental results demonstrated that the translation gains should be limited within 0.86 to 1.26, rotation gains should be limited within 0.67 to 1.24, and the radius for curvature gain should be no less than 22.03 m [15,55,57,58]. In addition, Langbehn *et al.* [51] introduced the concept of bending gains which can be used when the VR user is walking along a curved virtual path. According to their user studies, results found

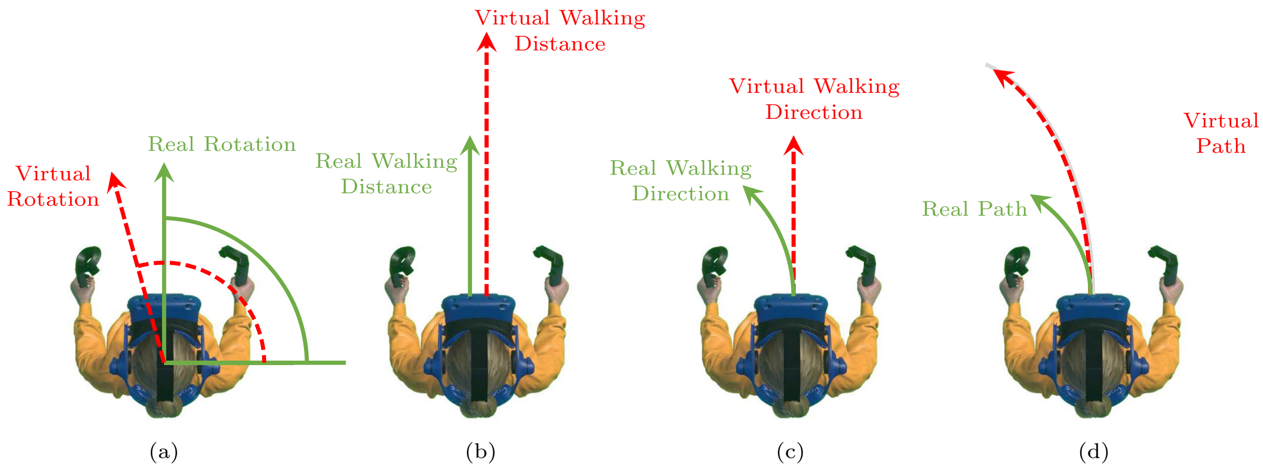


Fig.3. Four types of gains to manipulate the virtual viewpoint of the user. (a) Rotation gains (in standing pose). (b) Translation gains (moving forward). (c) Curvature gains (moving forward). (d) Bending gains (moving along a curve).

this method can bend the radius of a virtual curvature path up to 4.35 times than its corresponding physical path. Besides, Langbehn *et al.*[59] also evaluated the proper gain settings to redirect the user's view movement during eye blinking without being noticed. Cho *et al.*[52] latterly introduced non-forward steps including the backward step and the sideward step into redirected walking and identified a similar detectable range of translation gains and a wider detectable range of curvature gains than forward steps. Grechkin *et al.*[57] concluded that additional translation gain did not affect on the thresholds of curvature gain, indicating that in practice they could be applied together. Besides the thresholds in completely computer-rendered virtual scenes, Zhang *et al.*[60] found smaller detection thresholds of translation and rotation gains in 360° telepresence systems. Kim *et al.*[56] introduced the concept of relative translation gains which can be used in asymmetric mixed reality (MR) remote collaboration systems. Their method can create a mutual movable space between the reference space of the augmented reality (AR) host and that of the virtual reality (VR) client by adjusting the remote client's walking speed for each axis of a VR space.

Existing studies also investigated what factors may have an influence on detection thresholds. Williams and Peck[61] tested rotation gains in consideration of field-of-view (FoV), gender and distractors. Their results showed that the detection thresholds significantly differed between FoVs, while with 110° FoV, males had significantly higher detection thresholds than females. Distractors influenced differently between gender groups according to their findings. Besides, the human sensitivity to manipulations was also shown to be related to body movement velocity[62, 63]. Neth *et al.*[62] found that people were less likely to identify curvature gains with a lower walking speed, and there they designed a velocity-dependent curvature gain and validated its effectiveness. Paludan *et al.*[64] tested the effect of visual density for rotation gains, which revealed no significant difference between 4 and 16 object scenarios. Lately, Schmelter *et al.*[65] verified the usability of common interactions (Looking, Picking Up, Throwing, Shooting and Sword Fighting) to distract users and thus enable to apply additional rotations, and they also did a confirm study with proposed steer-to-action techniques.

Various sensual cues have been shown to be related to detection thresholds. Serafin *et al.*[66] conducted two experiments on blindfolded participants to determine the threshold of acoustic rotation and curvature gains. Later, Nilsson *et al.*[67] found similar thresholds for rotation gain with or without audio when visual cues were presented. Meyer *et al.*[68] further decoupled the influence visual and acoustic stimuli, revealing a slight trend for higher curvature gain thresholds with acoustical cues only. Kruse *et al.*[58] investigated the effects of visual cues on the translation detection threshold, and found visual cues in a virtual environment are more important for manipulation detection. A more recent study[69] showed that human would combine incongruent visual and auditory cues to determine the location of objects. Therefore, auditory cues can be utilized to change the visual location of objects, which in turn increased curvature gains. Sakono *et al.*[70] found users were less likely to notice continuous changes when dynamic bending and curvature gains were applied, and users perceived less discomfort compared with the constant gains.

The measured detection thresholds might have wide variability among people. To account for the discrepancy, Hutton *et al.*[71] proposed to use the method of parameter estimation through sequential testing (PEST) to calibrate rotation gains for each individual user. Rothacher *et al.*[72] had participants conducting perceptual-cognitive tasks and determined the detection thresholds simultaneously, showing that people with higher visual dependency have higher tolerance to redirection gains. Bölling *et al.*[73] then compared the detection threshold of curvature gain before and after exposure to a constant curvature gain, suggesting a proper way for individuals to adapt to larger gains in redirection techniques.

Most of RDW work researched on constant stimuli manipulations by counting the proportion of users' two-alternative forced choices from multiple repeated testing trials, while the time cost of user experiments can be quite high and may cause trouble to VR users when experiencing long-exposure VR locomotion. To address this problem, Chen *et al.*[74] proposed the adjustment-based method for detection threshold measurements. Compared with methods of constant stimuli, their method can provide similar ranges of manipulations and save about 33% experiment time. Grechkin *et al.*[57] also discussed the time constraint problem caused by constant stimuli methods and found the adaptive method can be a suitable alternative. Congdon and Steed[75] studied the effects of gain change rates by comparing three different methods: sudden gain change, slow gain change and constant gain, which found that it is harder to detect the variation by applying the slow gain change method.

3.2.2 Overt Manipulation

Compared with subtle manipulation, although overt manipulations do not consider whether they can be noticed by users, they have their own advantages on virtual interaction where smaller physical space is available. For example, detection thresholds of overt manipulations when users are immersed in IVEs are not the same as the detection thresholds of subtle manipulations. Schmite *et al.* [53] proposed the threshold of limited immersion (TLI) to find the amount of rotation gain that self-reported presence will break. They continuously altered the rotation gains and asked participants to report when the presence broke during a search and collection task. According to their findings, immersion breaks quite late after the gain is detectable when rotation gains are greater than 1.0, while the presence can even break before established detection thresholds are reached when gains are less than 1.0. Rietzler *et al.* [54] confirmed that users could accept much larger curvature gains than detectable manipulation, extending the capability of redirection techniques by greatly reducing the amount of the body movement. With similar intuition, Simeone *et al.* [76] designed another walking technique in the context of room-scale VR through overtly manipulating the virtual environment, which was faster and more preferred than compared techniques. Overt techniques have already been used in many other systems [77], especially for bridging the gap between large virtual environments and limited physical space. The major detection thresholds in existing literature are listed in Table 1.

3.3 Evaluation

Besides detection threshold measurements, other common measurements are also useful for evaluating both subjective feelings or objective performance. Several investigations aimed to analyze the relationship between virtual avatar and redirected walking. Kruse *et al.* [58] considered the translation gains with the presence of the virtual self-representation of the user's feet and the virtual environment, and their experimental results found more visual cues can lead to higher presence. Reimer *et al.* [78] explored whether full-body representation would have an effect on the detection thresholds of translation and curvature gains by user studies, which found the presence of virtual body does not have significant effect on the detectability but can cause the illusion of easier detection. Nguyen *et al.* [79] experimented to investigate the effect of sense of embodiment (SoE) during the curvature detection threshold measurement process. Their results showed the perspective and movement congruency has significant effects on the SoE.

Presence refers to the psychological sense of "being there" [80], used to describe the illusion that users leave their physical place and are transported to virtual environments. If users associate themselves with the virtual environment more, they will feel higher presence [81]. Usoh *et al.* [1] reaffirmed this finding and further suggested that real walking is a better presence-enhancing locomotion technique than virtual walking. By eliminating noisy sounds and enabling higher FoV [82, 83] and multi-sensory perception [55], the sense of presence in redirected walking should be improved.

Simulator sickness can degrade the users' VR experience. The cause of simulator sickness is related to the conflicting and inconsistent visual, proprioceptive, vestibular signals [84]. Simulator Sickness Questionnaire (SSQ) [85] is the most common approach to assessing simulator sickness, including 16 questions with four levels. Participants are usually instructed to fill in SSQs before and after an experiment, often with an increase of SSQ scores in varying degrees. Previous results confirmed that redirected walking with careful design can induce little increased simulator sickness [15, 62]. Moreover, researches have indicated that simulator sickness is related to FoV [82], threshold gains [61], etc.

The interconnection regarding redirected walking and cognitive load also received concerns since the amount of cognitive resources human beings have is limited. Bruder *et al.* [86] employed a dual-tasking method to study the mutual influence between redirected walking and working memory tasks. It was found that curvature gains were correlated with spatial and verbal working memory demands, and smaller curvature radius usually led to higher cognitive load. Similarly, Nguyen *et al.* [87] determined significant effects of cognitive load on curvature gains, which means subjects were less sensitive to redirection while performing a dual-task.

4 Algorithm

This section first introduces the existing redirected walking algorithms which allow VR users to walk in large virtual space within the limited physical place, and then classifies different tasks which these algo-

Table 1. Major Detection Thresholds in Existing Literature

Gain	Comment	Threshold	Source
Translation (horizontal)	Question bias	0.78 – 1.22	Steinicke *et al.*, 2008 [17]
	-	0.86 – 1.26	Steinicke *et al.*, 2009 [15]
	-	0.87 – 1.29	Bruder *et al.*, 2012 [44]
	Driving	0.94 – 1.36	Bruder *et al.*, 2012 [44]
	-	0.86 – 1.26	Kruse *et al.*, 2018 [58]
	Virtual feet	0.88 – 1.15	Kruse *et al.*, 2018 [58]
	Low-cue VE	0.73 – 1.25	Kruse *et al.*, 2018 [58]
	Jumping	0.68 – 1.44	Hayashi *et al.*, 2019 [45]
	Backward steps	0.84 – 1.33	Cho *et al.*, 2021 [52]
Translation (vertical)	Jumping	0.09 – 2.16	Hayashi *et al.*, 2019 [45]
	Stretching (VR)	0.84 – 2.55	Matsumoto *et al.*, 2020 [47]
	Stretching (telepresence)	2.58 – 34.10	Matsumoto *et al.*, 2020 [47]
	Crouching (VR)	0.83 – 1.94	Matsumoto *et al.*, 2020 [47]
	Crouching (telepresence)	1.12 – 3.41	Matsumoto *et al.*, 2020 [47]
Rotation	Question bias	0.59 – 1.10	Steinicke *et al.*, 2008 [17]
	-	0.67 – 1.24	Steinicke *et al.*, 2009 [15]
	-	0.68 – 1.26	Bruder *et al.*, 2012 [44]
	Driving	0.77 – 1.26	Bruder *et al.*, 2012 [44]
	-	0.93 – 1.27	Paludan *et al.*, 2016 [64]
	16 objects	0.82 – 1.20	Paludan *et al.*, 2016 [64]
	TLI	0.58 – 1.85	Schmitz *et al.*, 2018 [53]
	Jumping	0.50 – 1.39	Hayashi *et al.*, 2019 [45]
Curvature	Question bias	$r > 16$ m	Steinicke *et al.*, 2008 [17]
	Question bias & 2 m start-up	$r > 24$ m	Steinicke *et al.*, 2008 [17]
	-	$r > 22.03$ m	Steinicke *et al.*, 2009 [17]
	-	$r > 14.92$ m	Bruder *et al.*, 2012 [44]
	Driving	$r > 8.97$ m	Bruder *et al.*, 2012 [44]
	$v = 0.75$ m/s	$r > 10.57$ m	Neth *et al.*, 2012 [62]
	$v = 1.00$ m/s	$r > 23.75$ m	Neth *et al.*, 2012 [62]
	$v = 1.25$ m/s	$r > 26.99$ m	Neth *et al.*, 2012 [62]
	Audio	$r > 27.5$ m	Serafin *et al.*, 2013 [66]
	Audio & vision	$r > 6.0$ m	Meyer *et al.*, 2016 [68]
	Constant stimuli	$r > 6.41$ m	Grechkin *et al.*, 2016 [57]
	Maximum likelihood	$r > 11.61$ m	Grechkin *et al.*, 2016 [57]
	Jumping	$r > 7.64$ m	Jung *et al.*, 2019 [46]
	Backward steps	$r > 10.95$ m (right); $r > 10.30$ m (left)	Cho *et al.*, 2021 [52]
Bending	$r_{\text{real}} = 1.25$ m	3.25	Langbehn *et al.*, 2017 [51]
	$r_{\text{real}} = 2.5$ m	4.35	Langbehn *et al.*, 2017 [51]

rithms aim to complete. According to different implementations, these algorithms can be classified into two general classes: view manipulation and architecture manipulation. The first type of algorithms will not change the structure of the virtual environment, but will slightly induce the user to walk to the open area of the physical tracking space by manipulating the virtual camera's movement. But if the physical space is relatively small, VR users will still have the possibility to reach the physical boundaries or obstacles, which should be corrected overtly by resetting methods. In comparison, this problem will not happen to algorithms based on manipulating virtual architecture, because these algorithms directly map the virtual environment into the given physical tracking space dynamically or statically. Nevertheless, the architecture of the virtual environment has special requirements, which can bring applicability issues to these algorithms.

4.1 View Manipulation

This subsection introduces algorithms based on view manipulation. Generally, redirection algorithms can be classified into reactive methods and predictive methods, while resetting methods are adopted when VR users reach the boundaries. Besides, there are other types of methods utilizing reinforcement learning or based on saccadic suppression.

4.1.1 Reactive Methods

As a preliminary attempt, many RDW algorithms were proposed to manipulate the user's walking path to induce the user deviate from the boundaries, without considering the next movement the user possibly intends to take. These methods are usually categorized as reactive methods. Razzaque *et al.* first introduced the Redirected Walking in Place (RWP) method in a CAVE system [88], which imperceptibly rotates the VE when the user is walking in place. Results showed that this method can reduce the chance of seeing blank walls, thus increasing the sense of presence. Razzaque also described several redirected walking algorithms [14] including: steer-to-center (S2C) always guiding VR users to the center of the tracking space, steer-to-orbit (S2O) guiding VR users to walk along a circular orbit around the center and steer-to-multiple-targets (S2MT) guiding VR users to a given set of targets (see Fig.4). Field and Vamplew [89] proposed a variation method which extends the applicability of the original redirected walking algorithm by using nested orbits or figure-eight patterns. After that, Hodgson and Bachmann [19] compared S2C, S2O, S2MT and a mixed version of S2MT and S2C (named steer-to-multiple+center), which discovered that S2C outperforms the other three methods under most circumstances, while S2O surpasses S2C when a user performs a very long straight walking or makes orthogonal turns. However, previous algorithms were only designed to handle regular physical area. When the tracking space becomes irregular or contains obstacles, the performance of these algorithms will be severely affected, thus disturbing the user's walking experience. To improve the usability of RDW methods under different physical environments, Bachmann *et al.* [20] introduced a redirected walking algorithm based on artificial potential fields (APF-RDW) for the first time. This method can formulate the direction and intensity of force provided by other users and physical boundaries, which can be used for more effectively avoiding collision under complex walking environments. Thomas *et al.* [36] proposed a general reactive APF-RDW algorithm called Push/Pull Request (P2R) which can be used in the physical tracking space with obstacles. Unlike P2R, which treats obstacles as a whole (the square boundaries are composed of four rectangular obstacles), Messinger *et al.* [33] analyzed another APF-RDW, dividing the lines comprising the obstacles or physical boundaries into smaller segments, and the force is provided by the center of each segment. Dong *et al.* [21] also improved the APF-RDW method by using novel attraction target setting strategies and state predictions, reducing 20% resets than [33].

4.1.2 Predictive Methods

In some cases, the user's future walking path is predictable according to certain task rules or the given physical and virtual environments. This predicted virtual path can be utilized by predictive RDW methods to make better redirection manipulation strategies and improve the user's walking experience. For example, Zmuda *et al.* [22] proposed the Fully Optimized Redirected Walking for Constrained Environments (FORCE) method that can identify collision-free paths from a map describing tracking space's shape and obstacle distribution. These paths can offer additional

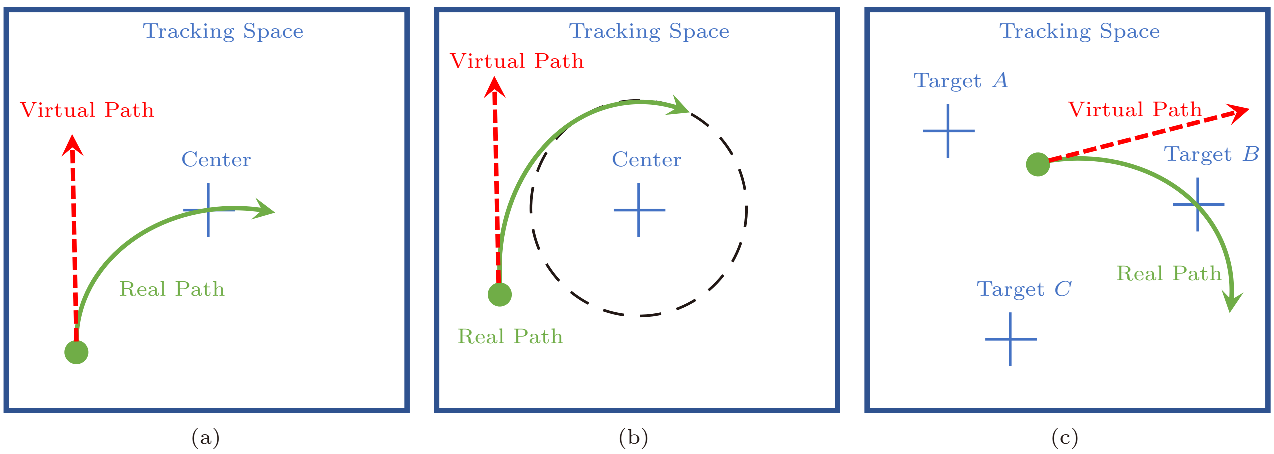


Fig.4. Three types of steering algorithms based on gain manipulations. (a) Steer-to-center. (b) Steer-to-orbit. (c) Steer-to-multiple-targets.

information to help their search-based algorithm find the optimal steering manipulations. Later, Nescher *et al.*[90] developed a more general algorithm called Model Predictive Control Redirection (MPCRed), which can make better strategies on different redirection manipulations. Azmandian *et al.*[91] presented a theoretical framework leveraging knowledge of both physical and virtual layout and adopted a tree search to find the optimal redirection parameters, which can help reduce potential presence breaks. To make the predicted future walking trajectory more flexible, they later proposed a method which leverages navigation meshes to automatically generate environment annotation graphs for prediction[92]. Starting with creating polygonal meshes of the irregular virtual geometric area, each mesh polygon is represented as a node. The predictor then chooses a polygon node containing the user's current position and employs a depth limited shortest path algorithm to find a set of branching nodes and terminal nodes, and finally uses these nodes to construct the predicted trajectory.

4.1.3 Resetting

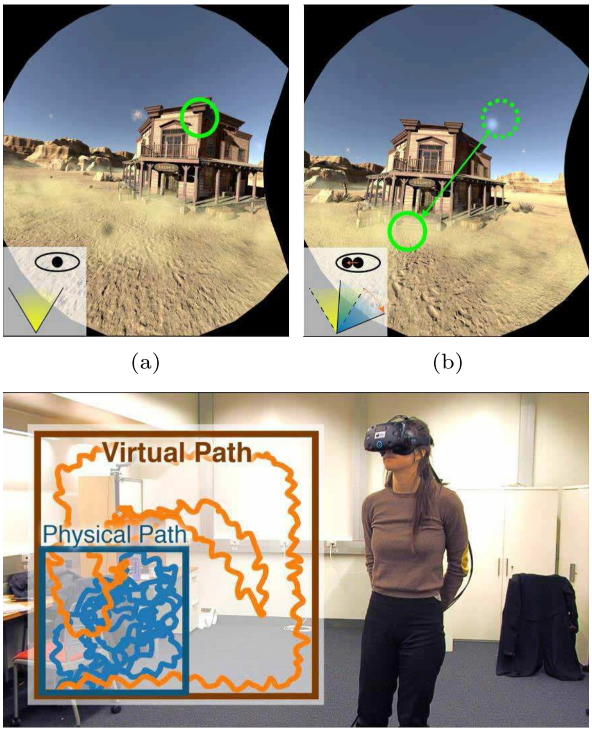
Compared with the extremely open virtual area, the physical space seems to be highly constrained in most scenarios, especially in room-scale venues. To support users' infinite virtual walking within the limited tracking area, Williams *et al.*[25] demonstrated three simple but effective resetting methods: Freeze-Backup, Freeze-Turn, and 2:1-Turn, where the virtual visual content will be frozen when freeze methods take effect. The Freeze-Backup requires the user to step back while Freeze-Turn and 2:1-Turn ask the user to turn around by 180 degree. After the resetting operation is performed, the user can continue the moving process. Xie *et al.*[93] proposed a system to explore large virtual environment by combining the translation gain and the resetting method, and their experimental results found the resetting method can remedy the limits of translation gain and preserve users' spatial awareness of the virtual space. Yu *et al.*[94] designed a system to offer participants redirected walking experiences for educational purposes and concluded that narrative-driven resets can make the walking experience seamless and enhanced. Zhang *et al.*[95] argued that most reset strategies were based on simple heuristics, which could be improved by the approach of finite element analysis. Based on this approach, they proposed a novel optimization-based reset algorithm which can significantly reduce the number of resets and adapt to various RDW algorithms. Besides, they proposed a novel out-of-place resetting algorithm[96], which can calculate the walking area heat map to guide users to the most suitable positions for further movement, thus increasing the average walking distance between resets.

4.1.4 Learning-Based Methods

Most learning-based RDW methods can be categorized as predictive methods, and they are suitable for handling higher-dimensional environmental information and achieve better results than traditional search-based methods. Learning-based methods make real-time decisions based on the current user state and the surrounding environment to avoid future collisions. For example, Lee *et al.*[23] proposed the steer-to-optimal-target (S2OT) algorithm, which employs a double deep Q-network (DDQN) based on reinforcement learning to dynamically calculate the optimal steering target of the physical space. Experimental results showed this method can be adaptive to various virtual environments. They later proposed the Multi-User Steer-to-Optimal-Target (MS2OT) algorithm[34], which extends the previous work into the multi-user scenario by using the Dueling Double Deep Network (D3QN) as a learning framework. Strauss *et al.*[24] regarded the redirection problem as a Markov decision process, and adopted the Proximal Policy Optimization (PPO), a reinforcement learning algorithm for deep neural network training. Their novel method can observe the user's position and orientation and suggest the optimal rotation, translation, and curvature gains for free exploration.

4.1.5 Saccadic Suppression

A saccade is the rapid eye movement when people quickly change their fixation points. Normally, there are several saccades occurring during a second period, where the saccadic duration is about 20 ms to 200 ms[97]. Saccadic suppression is a phenomenon that viewers are momentarily blind when their rapid eye movements happen, which can be exploited to redirect an VR user without their notice. Bolte and Lappe[98] applied the online saccade detection algorithm to investigate the amount of reorientation and reposition during saccades, showing it is possible to imperceptibly manipulate HMD users. Langbehn *et al.*[99] provided suggestions about the experiment design for measurements of reorientation and reposition during eye blinks in VE. To evaluate the amount of visual changes during the user's eye blink, they[59] also measured translation and rotation detection thresholds along tree main axes by user studies and a confirmatory user study where they combined measured gains with current RDW algorithms and proved the feasibility of their results. Nguyen and Kunz [100] argued that measurements of the former work were conservative because no real walking was performed during the evaluation process; therefore they measured the rotation detection thresholds during blinking when users were walking in VE. Sun *et al.* [16] proposed a novel RDW method tracking and utilizing saccadic suppression to redirect the user during the temporary blindness, together with a subtle gaze direction method to induce more user saccades, able to map a 6.4 m × 6.4 m virtual space into a 3.5 m × 3.5 m real room (see Fig.5).



(a) (b)

(c)

Fig.5. Example of saccadic redirection [16]. (a) Rendered content from the viewer's HMD left eye, and the overlaid green circle indicates the visualizations of tracked eye gaze and the lower left corner shows the view frustum. (b) The system redirects the user by rotating the virtual environment when it detects the events of saccades and head rotations. (c) Recorded movements of the virtual path in a much larger 6.4 m × 6.4 m synthetic space can be mapped into a 3.5 m × 3.5 m real physical room.

4.2 Virtual Environment Manipulation

Although viewpoint-manipulation based RDW algorithms can greatly reduce the required physical tracking space, it is inevitable that the users will collide with the physical borders when they are experiencing the room-scale VR. Therefore, reset techniques are often adopted to overtly adjust the user's direction, which may break the immersive VR and increase the cybersickness. In this subsection, we will introduce algorithms based on manipulating the virtual environment to enable VR users to explore larger virtual space within smaller physical space. Typically, these algorithms can be divided into two types: dynamically changing the virtual architecture and statically mapping the virtual space into the given physical space. The former needs to pre-determine the virtual architecture and the relative scripts to control the logic, which is hard to be reused in other virtual environments. The latter can be applied into most maze type virtual spaces, but distortions of the virtual environment can be caused due to the static compression.

4.2.1 Dynamically Changing Architecture

This subsection introduces RDW algorithms which compress the large virtual environment to the limited small physical tracking space by dynamically manipulating the virtual architecture (see Fig.6). First of all, Suma *et al.* [26] proposed the algorithm by taking advantage of "Change Blindness", which was described as utilizing the VR user's inability to detect changes of the virtual architecture. In their experiment, the location of the doorways and corridors behind the user's back would be changed when the user entered a virtual room; thus the virtual walking paths were manipulated without being noticed by the user. According to this algorithm, a room of about 219 square meters can be compressed into a 4.3 m × 4.3 m physical space. After that, they further proposed another algorithm called Impossible Spaces [27], which can compress self-overlapping architectures into a smaller physical space. According to this algorithm, a small virtual room can overlap by up to 56% while larger virtual rooms can overlap by up to 31%. Vasylevska *et al.* proposed the Flexible Spaces strategy which enables VR users to infinitely walk within a dynamically generated virtual room layout [28] without noticing the manipulations.

4.2.2 Static Mapping

Methods based on dynamically changing the architecture are intriguing and encouraging, but they are limited to the virtual environments with special interior architectures and manually predefined logics. To make this technique adaptive to more virtual scenes with less human labor, the static mapping method was proposed

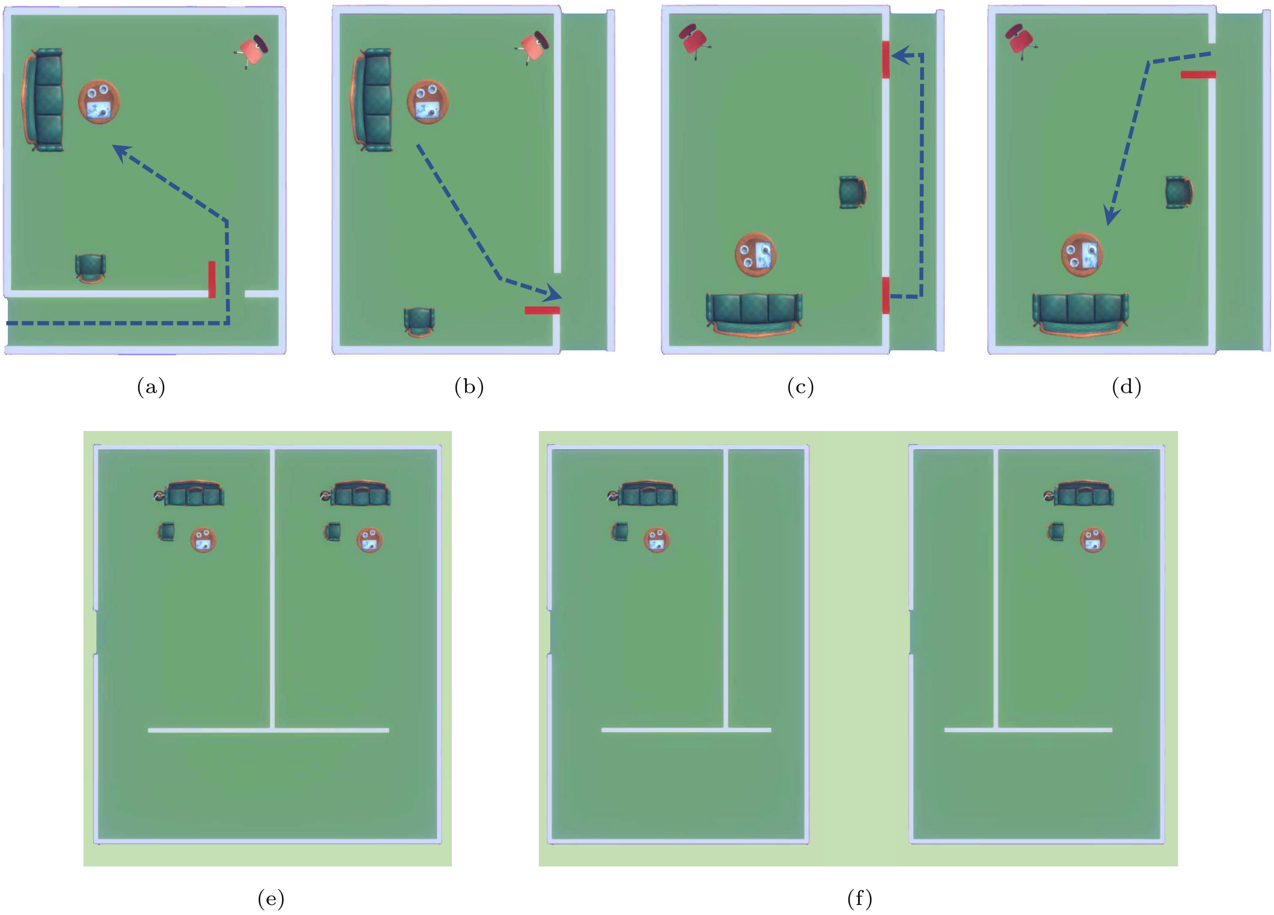


Fig. 6. Two examples showing the dynamically changing architecture redirection process. (a)–(d) describe the Change Blindness algorithm[26] which can compress two virtual rooms into the same tracking space. (a) The user enters the room and walks to the sofa. (b) The corridor is rotated 90°, and the user walks towards the door. (c) A new door appears, and the user walks along the corridor. (d) The user enters another generated overlapping room. (e) and (f) represent the Impossible Spaces algorithm[27] which can be used to overlap two virtual rooms about 50%, where (e) shows the original room with 0% overlap and (f) shows the dynamically changing room with 50% overlap.

to directly map the large virtual scene into the user's physical room and retain visual fidelity of the VE at the same time. Sun *et al.*[29] first proposed the 2D floor plan mapping based redirected walking method which is able to warp the VE appearance into a given physical tracking space. However, their method still causes noticeable distortions. Dong *et al.*[30] presented Smooth Assembly Mapping (SAM), a divide-and-conquer algorithm, able to map large-scale virtual scenes with low isometric distortions. Their algorithm first divides the virtual scene into smaller patches, which are later mapped into the physical space individually, and finally a global optimization is applied to assemble patches and minimize the entire distortion (see Fig. 7). Two years later, Dong *et al.*[31] extended their method to support multiple user free walking and introduced bending gains to acquire better space compression capability. Users can physically interact with each other in both VE and physical space at the same time. Cao *et al.*[32] argued that static mapping redirection was required to deform the virtual scene more reasonable, and proposed a feature-guided path redirection method aiming to reduce scene distortions, especially the distortions at regions with abundant visual detail. Besides the advantages and benefits, some drawbacks of static mapping methods are also worth noticing. The distortions of virtual scenes may degrade the navigation comfort and the preprocessing for mapping large complicated virtual scene is time-consuming and not suitable for large open spaces and dynamic geometry changes such as moving obstacles in the physical world. Furthermore, solving the mapping problem of highly-occluded scenes can also be a future challenge for static mapping methods.

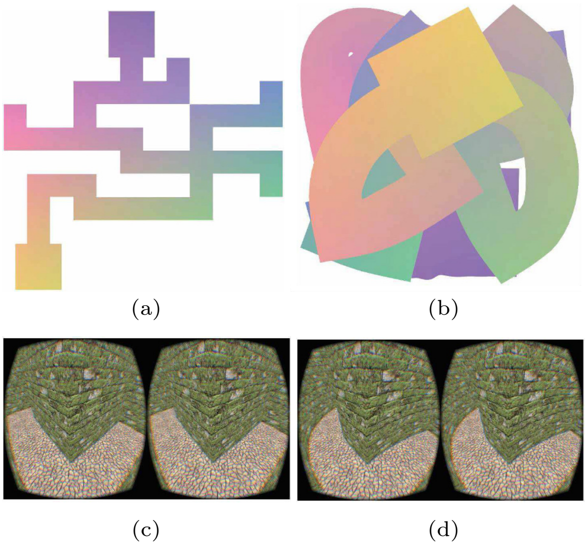


Fig.7. Example of the static mapping algorithm [30]. (a) Original virtual environment structure. (b) Mapped virtual environment structure in the given physical space. (c) The first person view of the non-distorted virtual environment. (d) The first person view of the distorted virtual environment at similar viewpoints.

4.3 Distractors

Some algorithms use distractors to attract the VR user's attention and take the opportunity to manipulate the view of the virtual camera. These methods are considered as manipulating the viewpoint and the virtual environment at the same time. Peck *et al.* [101] introduced the method which uses visual and audial distractors to attract the VR user's attention. When the user is focusing on the distractors, the method slightly rotates the direction of the virtual head, and thus redirects the user towards a more open space. This method was preferred and regarded more natural by attendees because the presence can remain at a high level compared with other overt reorientation techniques. Their experimental results also suggested that adding the environment sound should increase the user's feeling of presence and improve visual realism. Peck *et al.* [102] also built a locomotion interface called Improved Redirection with Distractors (IRD), which allows users to really walk through larger VEs with a small physical space by using distractors to keep the user's safety and redirect the user's path towards the center of the tracking space. Using events can also be beneficial for imperceptibly manipulating the walking path. For example, Neth *et al.* [62] conducted studies using virtual agents to slow down or intersect the user's walking, which can be utilized for creating more opportunities for redirection. Rewkowski *et al.* [103] evaluated the effectiveness of RDW with auditory distractors, and found auditory RDW can be suitable for complex navigation tasks including crossing streets and avoiding obstacles.

4.4 Tasks

This subsection introduces the potential tasks. The RDW methods are aiming to complete, which can reflect the performance, usability and robustness of these algorithms from different perspectives.

4.4.1 Multiple Users Co-Walking

Most of previous RDW work only considered collision avoidance of a single user. Therefore, multi-user redirection in the same tracking space needs further exploration. There are some special issues emerging in multi-user redirection. For example, because the VR users' behaviors are usually unpredictable and the locomotion of one user always interrupts another user's experience, how to effectively avoid collisions from these dynamically walking users becomes a huge challenge. Moreover, RDW manipulations cause the discrepancy of positions between the virtual and the real environment, which means when users meet at the same location of VE, they may be far apart from each other in the real world, which will degrade the reality of virtual experience. To reduce the collision possibility when RDW was applied to multiple VR users, Bachmann *et al.* [104] extended the S2C method to predict collisions and allow two users to share the same tracking space and Azmandian *et al.* [105] compared multiple strategies to prevent two-user collisions, but these methods do not scale well to a larger group of users. Bachmann *et al.* [20] proposed the artificial potential fields [106] based redirected walking technique (APF-RDW), which repels multiple users from physical walls and repels each other when they are walking in the same physical tracking space. Messinger *et al.* [33] further improved this APF-RDW and tested in tracking spaces of varied shapes by simulations. Lee *et al.* [34] introduced reinforcement learning to solve this problem by extending the original Steer-To-Optimal-Target (S2OT) RDW method [23], which outperforms the state-of-the-art APF-RDW [33] in multi-user simulation experiments. Dong *et al.* [21] proposed dynamic APF-RDW method for multi-user redirected walking, which is combined with novel attraction target setting strategies and state predictions, reducing resets by 20% in general compared with [33]. They later thought boundary conflicts in the multi-user redirected walking could be decreased by considering the density of users in the tracking space, so that they proposed the dynamic density-based redirected walking method which adjusts the user distribution through the density force, aiming to increase the center density and lower the boundary density [107]. Results show on average about 30% potential conflicts can be reduced in their method compared with existing reactive multi-user redirection algorithms. Gain-based RDW algorithms can diverge an VR user's virtual and real positions, which means when two VR users are close to each other in VR space, they may be far apart in the real tracking space, leading to the failure of collaboration activities such as shaking hands or carrying the same physical object. This problem can be alleviated by adding a recovery method [108] in gain-based RDW or naturally solved by using static mapping RDW [31].

4.4.2 Irregular Scene

Most RDW algorithms like S2C have high performance in standard rectangular physical tracking space. However, most of physical areas are irregular and there are even obstacles (see Fig.8), which will significantly increase the reset number, leading to frequent breaks of users' immersive experiences. Therefore, adapting RDW methods to handling this special case is significantly worth studying. Azmandian *et al.* [109] conducted simulated studies to investigate the effect of the rectangular physical space size and shape on S2C and S2O, suggesting square tracked spaces are the most suitable for redirection compared with those elongated rectangle spaces and the minimum physical area where redirection techniques can work effectively is 6 m × 6 m. Chen *et al.* [35] combined steering-based RDW with greedy and planning algorithms to cope with irregular and dynamic physical environments. Messinger *et al.* [33] tested RDW methods in irregular shapes (rectangle, trapezoid, cross, L-shape) and confirmed APF-RDW outperforms the traditional S2C method. Thomas and Rosenberg [36] also confirmed that APF-RDW achieves better performance than S2C when there is an obstacle in the square physical space. Lee *et al.* [34] employed reinforcement learning to predict users' future movements, reducing more resets than APF-RDW [33] in physical rooms with varied shapes. Williams *et al.* [110] proposed the alignment-based redirection controller (ARC) with the purpose of making the matches of the user's proximity to physical obstacles as close as possible to the virtual counterparts, which outperformed APF-RDW [36]. They also proposed a novel method by computing the visibility polygon for the user's physical and virtual locations and steering the user to walk towards the most likely polygon region, which can properly handle both static and dynamic irregular physical tracking spaces and significantly reduce more resets than prior algorithms [111]. Static mapping RDW algorithms [29–31] consider the static obstacles in physical spaces during the processing stage. The dynamic saccadic redirection method proposed by Sun *et al.* [16] also considers collision avoidance of both static and dynamic obstacles.

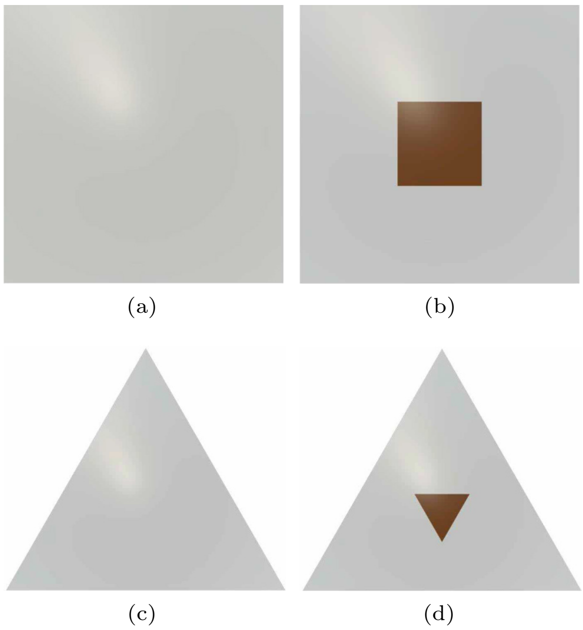


Fig. 8. Different types of tracking spaces [43]. (a) Traditional normal regular tracking space. (b) Regular tracking space with an obstacle. (c) Tracking space with an irregular shape. (d) Irregular tracking space with an obstacle.

4.4.3 Passive Haptics

The RDW technique can greatly reduce the required physical tracking space for natural walking in VR, but there are seldom RDW algorithms taking interactions with the physical environment such as passive haptic feedback into consideration. Nevertheless, mapping the virtual interactive objects into physical counterparts with similar haptic properties can provide users with a sense of touch and greatly enhance users' presence (see Fig.9). Kohli *et al.* [37] suggested that the strict one-to-one mapping between the VE and the real world is not actually required, which means the mapping only needs to be satisfied for special virtual objects, and one real proxy prop could be reused to offer the haptic feedback for many virtual objects. Steinicke *et al.* [41] proposed the taxonomy of redirection techniques to redirect the VR user to a real proxy prop imperceptibly when the

(a) (b) (c)

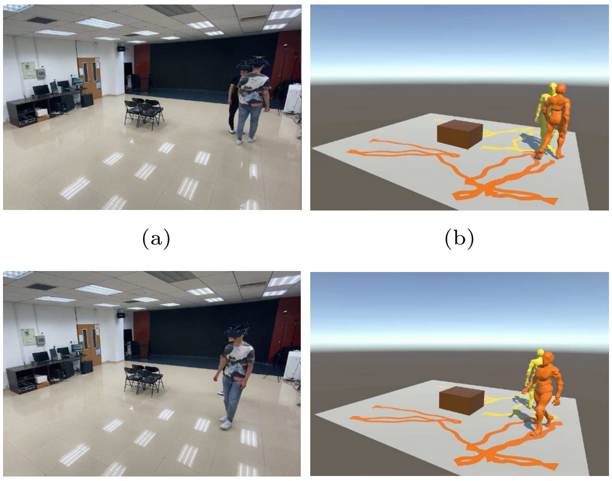
Fig.9. Example of passive haptics in redirected walking. (a) A user is walking and being steered by the RDW technique. (b) The user touches a stone block in the virtual world. (c) The user can acquire the physical haptic feedback from the real table at the same time [41].

user was close to a virtual object. To use the latest artificial potential function (APF) based RDW algorithms in passive haptic tasks, Thomas and Rosenberg [112] utilized the attractive force component in APF to align the given physical and virtual positions where the passive haptic feedback is expected to be acquired. Further improvement of this work was mentioned in [40]. Wang *et al.* proposed a constrained path redirection method to find the most suitable physical counterpart for the virtual target, which can provide correct physical feedback at the right time [39]. Recently, there has been a new trend to introduce learning-based methods to solve this problem. Chen *et al.* [38] proposed a novel reinforcement learning algorithm to handle passive haptics tasks at the first time. Their method utilizes a novel reward function which takes both the physical boundary avoidance and consistency of user-object positioning into consideration, and outperforms the previous methods from experimental results. Besides allowing users to interact with static virtual objects under the effect of RDW, making them acquire the haptic feedback when interacting with each other is also a problem worthy of study. Min *et al.* [108] designed a recovery algorithm using both subtle RDW algorithms and overt recovery to allow two VR users to shake hands in the physical space as well as the virtual space simultaneously, which is able to increase users' presence and satisfaction.

5 Platform

Although RDW is a powerful locomotion technique, most of RDW work is not open-sourced and hard to implement. Also there are seldom public toolkits and benchmarks in this field, which makes it challenging to compare different methods and hinders the progression of RDW research. Therefore, Peck *et al.* [113] designed a large-scale real-walking locomotion interface called RFED using redirection and distractors to enable users to walk in VE which is larger than the corresponding physical space, but it is not open-sourced and out of date.

To help researchers deploy and develop the RDW technique, Azmandian *et al.* [42] provided an open-source redirected walking toolkit (RDWT) as a Unity3D package to help users implement and deploy RDW methods easier. In their implementation, classical redirection controllers such as S2C and S2O are integrated to manage subtle manipulations and 2:1-Turn resetter [25] is offered to redirect the user when a collision with physical borders is about to happen. Users can experience the RDW technique by keyboard control or using HMD for real walking. Additionally, various procedurally generated paths for large-scale auto simulations are also available to evaluate performances between different RDW algorithms. Simulation data such as reset counts, the distance between resets and overall applied gains are recorded in the backstage and the data can be exported as Excel files for further analysis. With the continuous development of RDW research field, researchers have shown great interest in adapting the RDW technique to more complex and detailed conditions, like handling multiple co-located user redirection and irregular physical tracking spaces. Moreover, the emergence of new RDW algorithms requires the continuous updating of existing platform framework to offer more novel features like supporting reinforcement learning deployment. Therefore, Li *et al.* [43] presented OpenRDW, an open-source library and benchmark for developing, deploying and evaluating RDW methods under different testing conditions. In their library, researchers can easily access to the application program interfaces (APIs) of scenes and avatars, customize the RDW controllers, and simulate and visualize the walking process (see Fig.10). Compared with the redirected walking toolkit, OpenRDW contains more new features including supporting multi-user real walking or simulation, containing size-varied or shape-varied tracking spaces with obstacles for comprehensive testing, integrating both the classic and state-of-the-art RDW algorithms, and allowing the deployment of reinforcement learning algorithms. Table 2 summarizes the key related work of redirected walking.



(a) (b) (c) (d)

Fig.10. Demo of multi-user real walking process on the OpenRDW platform [43]. (a) A collision happened when two users encountered each other in the tracking space. (c) 2:1-Turn resetting method corrected the directions of two users to continue the walking process. (b) and (d) represent the RDW visualizations of (a) and (c) respectively.

6 Other Forms of Locomotion

In addition to walking on the flat ground, there are other forms of locomotion which can be redirected in the virtual environment. For example, users tend to use transportation devices such as electric wheelchairs for long distance travel, and redirection can also be applied into these movements in a similar way [44]. Besides, another type of common motion in our daily life could be bipedal jumping, which in some cases can be even more efficient than walking in virtual exploration [114, 115]. Jumping motion can help users get access to a variety of special experiences including ski jumping with indoor devices [116], gravity reduced jumping on Lunar or Martian surfaces provided by the cable-driven system [117], and even skydiving supported by the Virtual Super-Leaping system [118].

Similar to RDW, redirected jumping (RDJ) is also a practical form of redirection techniques, and its imperceptible gain range was proven to be even wider than that of RDW by some studies, which indicates that the RDJ technique can support VR experience in a larger virtual space. The RDJ concept was proposed by Hayashi *et al.* [45] for the first time. They defined horizontal, vertical, and rotation gains of RDJ and conducted user studies to measure the detection thresholds (see Fig.11). Based on their results, the imperceptible gain range for horizontal manipulation is from 0.68 to 1.44, that for the vertical one is from 0.09 to 2.16 and the imperceptible rotation gain can vary from 0.50 to 1.44. Jung *et al.* [46] supplemented the measurement results of curvature gain detection thresholds in RDJ, which indicates that compared with RDW, larger manipulations can be applied for virtual forward jumping. Li *et al.* [119] analyzed the interaction effect of joint horizontal and vertical gains by fitting the data to two-dimensional psychometric functions. Results revealed that the imperceptible range for the horizontal gain could be affected by the value of the vertical gain, and vice versa. They also found horizontal translation gains were significantly smaller in the VE with high visual richness rather than the one with low visual richness, while different self-representations will not significantly affect the perception thresholds [120]. Liu *et al.* studied the effect of virtual alley width on the detection thresholds in RDJ, and found different alley widths can affect the perception on jumping height and rotation [121]. To test the RDJ performance in the VR entertainment or exercising applications, Havlik *et al.* [122] applied the RDJ technique into a virtual factory scene with several moving platforms, where users can jump between these platforms within the size requirement reduced tracking space. Results revealed that the $g_T = 2.0$ translation gain was able to save about 30% space without disturbing the user's virtual exploration. Li *et al.* [119]

Table 2. Brief Summary of Redirected Walking and Key Related Work

Direction	Category	Description	Related Work
Threshold	Subtle	User experiments to measure imperceptible detection thresholds	[15, 51, 57, 59]
	Overt	User experiments to measure noticeable detection thresholds	[53, 54]
Algorithm	View manipulation	Algorithms based on virtual camera view manipulations	[16, 20, 24, 89]
	VE manipulation	Algorithms based on changing the architecture of virtual environment	[26–30]
Platform	Library	Open-source library or benchmark for developing and deploying RDW algorithms	[42, 43]

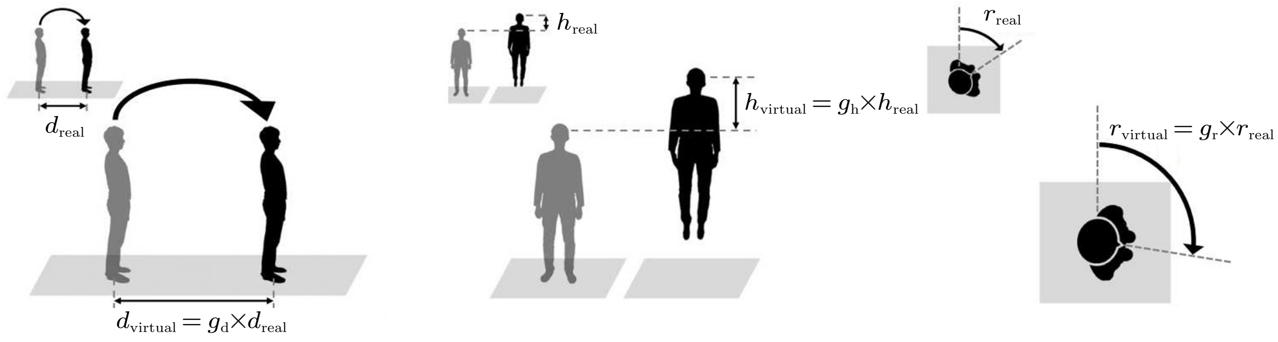


Fig.11. Overview of redirected jumping. (a)–(c) represent horizontal, vertical and rotation gains respectively [45].

built two VR jumping games to validate the estimated joint detection thresholds in RDJ, which proved that joint gains can reduce both the required horizontal and vertical jumping distances.

Other forms or variations of locomotion redirection were also proposed and studied. Inspired by RDJ, Matsumoto *et al.* [47] were interested in vertical movement redirection in stretching and crouching behaviors; therefore they conducted user experiments and found that vertical movements in these two forms could be imperceptibly manipulated both in the VE and telepresence drone environment. Ogawa *et al.* [123] designed two viewpoint-manipulation methods including gain manipulation and peak shifting to allow the user to experience virtual step-up jumping motion by performing a physical jump on a flat floor, which can remain reality and naturalness in most cases. Yukai *et al.* [124] investigated the potential rotation gain manipulation during the user's walking under door-opening behavior by testing two types of interfaces (with and without passive haptic feedback). Results found participants were more likely to notice the redirection manipulation but feel more comfortable under the one which provides the haptic feedback.

7 Future Directions

In this section, we present our thoughts on potential future research directions for promoting the RDW region.

7.1 General Benchmark

Although there are a lot of RDW methods proposed from different perspectives, there are few open-source RDW implementations. While it will take other researchers a lot of effort to reproduce the previous methods for comparisons, which may hinder the prosperity and development of this field. Moreover, there are also few common testing datasets here, leading to potential unfairness of evaluation process. Therefore, open-source libraries and benchmarks can provide templates for references and for better developing, deploying and evaluating RDW algorithms, which will greatly promote progress of this field. Besides, the user interfaces of existing open-source platforms can be further improved and more features and functions can be integrated for better development of RDW research.

7.2 Algorithms with Artificial Intelligence

We all witness the progress of the RDW field benefited by artificial intelligence, where more and more learning-based RDW methods have been developed and they can achieve better experimental results than traditional methods under both simple and complex testing conditions. The use of artificial intelligence can be beneficial for prediction tasks, such as using machine learning or deep neural network to predict eye movements, saccades, blinks, and users' intentions. Therefore, the design of novel reward functions, training data preparation, and applicable conditions of this technique need to be further studied. Nevertheless, building a common walking path dataset can be beneficial for both training process and testing fairness.

7.3 Potential Tasks for RDW

RDW is a powerful locomotion technique which can be applied in abundant of VR application scenarios. It allows VR users to naturally walk in the virtual environment with limited physical space. With the development of this active research region, we can be aware of that tasks including multiple co-location user walking, irregular tracking spaces with obstacles, and passive haptics have aroused the interest of the majority of researchers, and we hope there are more potential tasks that can be handled by the RDW technique discovered in the future.

7.4 More Forms of Redirected Locomotion

Redirected walking is one of the most common forms of redirected locomotion techniques. Besides redirected walking, the emergence of other forms like redirected jumping and crouching enabled redirected locomotion to be applied to more application scenarios like reducing the required physical space and rehabilitation training. It is intriguing to explore more potential values from other forms of locomotion, or investigate how to naturally combine different locomotion patterns together for better virtual explorations.

8 Conclusions

Redirected locomotion plays an important role in virtual reality exploration, allowing VR users to naturally move from one place to another place within the limited physical tracking space. This survey presented a reasonable taxonomy of redirected walking, which divided existing work into three major parts: gain perception, algorithm, and platform. Then we systematically reviewed and summarized the existing RDW work based on the taxonomy. Gain perception work is mainly related to the perception range measurement of manipulation, which can be classified into subtle manipulation and overt manipulation. Subtle manipulation is more commonly used while overt manipulation can save more physical space. These evaluated perception ranges can provide reliable quantity references for RDW algorithms. Based on different strategies, these algorithms can be divided into view manipulation algorithms and environment manipulation algorithms. The former type of algorithms is more general to diverse virtual environments but have to be combined with resetting methods, which may break the presence of users. The latter can provide users with coherent movement experiences but may require more manual setting effort or introduce visual distortion effect. With the emergence of various RDW algorithms, common platforms for developing and deploying the RDW technique become more important than before, because they can save a lot of time for algorithm re-implementations and improve algorithm comparison fairness. Besides, more forms of redirected locomotion including redirected jumping have also been proposed, giving users more chances to save physical space and have surreal experience.

In the end, we also revealed the potential research directions in the future, including making RDW platforms more general and easy-to-use, combining artificial intelligence with RDW algorithms to improve efficiency, discovering potential tasks for the RDW technique to extend its applicability, and exploring more redirected locomotion forms for diverse application scenarios. We hope that this survey will encourage all researchers to face the challenges and work together to promote the development of this field.

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References

[1] Usoh M, Arthur K, Whitton M C, Bastos R, Steed A, Slater M, Brooks Jr F P. Walking > walking-in-place > flying, in virtual environments. In *Proc. the 26th Annual Conference on Computer Graphics and Interactive Techniques*, August 1999, pp.359-364. DOI: 10.1145/311535.311589.

[2] Multon F, Olivier A H. Biomechanics of walking in real world: Naturalness we wish to reach in virtual reality. In *Human Walking in Virtual Environments: Perception, Technology and Applications*, Steinicke F, Visell Y, Campos J, Lécuyer A (eds.), Springer, 2013, pp.55-77. DOI: 10.1007/978-1-4419-8432-6_3.

[3] Ruddle R A, Lessels S. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction*, 2009, 16(1): Article No. 5. DOI: 10.1145/1502800.1502805.

[4] Steinicke F. Being Really Virtual. Springer, 2016.

[5] Slater M. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 2009, 364(1535): 3549-3557. DOI: 10.1098/rstb.2009.0138.

[6] Steinicke F, Bruder G. A self-experimentation report about long-term use of fully-immersive technology. In *Proc. the 2nd ACM Symposium on Spatial User Interaction*, Oct. 2014, pp.66-69. DOI: 10.1145/2659766.2659767.

[7] Kelly J W, Ostrander A G, Lim A F, Cherep L A, Gilbert S B. Teleporting through virtual environments: Effects of path scale and environment scale on spatial updating. *IEEE Transactions on Visualization and Computer Graphics*, 2020, 26(5): 1841-1850. DOI: 10.1109/TVCG.2020.2973051.

[8] Buttussi F, Chittaro L. Locomotion in place in virtual reality: A comparative evaluation of joystick, teleport, and leaning. *IEEE Transactions on Visualization and Computer Graphics*, 27(1): 125-136. DOI: 10.1109/TVCG.2019.2928304.

[9] Langbehn E, Lubos P, Steinicke F. Evaluation of locomotion techniques for room-scale VR: Joystick, teleportation, and redirected walking. In *Proc. the Virtual Reality International Conference—Laval Virtual*, April 2018, Article No. 4. DOI: 10.1145/3234253.3234291.

[10] Hanson S, Paris R A, Adams H A, Bodenheimer B. Improving walking in place methods with individualization and deep networks. In *Proc. the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2019, pp.367-376. DOI: 10.1109/VR.2019.8797751.

[11] Nilsson N C, Serafin S, Laursen M H, Pedersen K S, Sikström E, Nordahl R. Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In *Proc. the 2013 IEEE Symposium on 3D User Interfaces*, March 2013, pp.31-38. DOI: 10.1109/3DUI.2013.6550193.

[12] Wendt J D, Whitton M C, Brooks F P. GUD WIP: Gait-understanding-driven walking-in-place. In *Proc. the 2010 IEEE Virtual Reality Conference*, March 2010, pp.51-58. DOI: 10.1109/VR.2010.5444812.

[13] Razzaque S, Kohn Z, Whitton M C. Redirected walking. In *Proc. the 22nd Annual Conference of the European Association for Computer Graphics*, Sept. 2001. DOI: 10.2312/egs.20011036.

[14] Razzaque S. Redirected walking [Ph.D. Thesis]. University of North Carolina at Chapel Hill, 2005.

[15] Steinicke F, Bruder G, Jerald J, Frenz H, Lappe M. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 2010, 16(1): 17-27. DOI: 10.1109/TVCG.2009.62.

[16] Sun Q, Patney A, Wei L Y, Shapira O, Lu J, Asente P, Zhu S, McGuire M, Luebke D, Kaufman A. Towards virtual reality infinite walking: Dynamic saccadic redirection. *ACM Transactions on Graphics*, 2018, 37(4): Article No. 67. DOI: 10.1145/3197517.3201294.

[17] Steinicke F, Bruder G, Jerald J, Frenz H, Lappe M. Analyses of human sensitivity to redirected walking. In *Proc. the 2008 ACM Symposium on Virtual Reality Software and Technology*, Oct. 2008, pp.149-156. DOI: 10.1145/1450579.1450611.

[18] Nilsson N C, Peck T, Bruder G, Hodgson E, Serafin S, Whitton M, Steinicke F, Rosenberg E S. 15 years of research on redirected walking in immersive virtual environments. *IEEE Computer Graphics and Applications*, 2018, 38(2): 44-56. DOI: 10.1109/MCG.2018.111125628.

[19] Hodgson E, Bachmann E. Comparing four approaches to generalized redirected walking: Simulation and live user data. *IEEE Transactions on Visualization and Computer Graphics*, 2013, 19(4): 634-643. DOI: 10.1109/TVCG.2013.28.

[20] Bachmann E R, Hodgson E, Hoffbauer C, Messinger J. Multi-user redirected walking and resetting using artificial potential fields. *IEEE Transactions on Visualization and Computer Graphics*, 2019, 25(5): 2022-2031. DOI: 10.1109/TVCG.2019.2898764.

[21] Dong T, Chen X, Song Y, Ying W, Fan J. Dynamic artificial potential fields for multi-user redirected walking. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2020, pp.146-154. DOI: 10.1109/VR46266.2020.00033.

[22] Zmuda M A, Wonser J L, Bachmann E R, Hodgson E. Optimizing constrained-environment redirected walking instructions using search techniques. *IEEE Transactions on Visualization and Computer Graphics*, 2013, 19(11): 1872-1884. DOI: 10.1109/TVCG.2013.88.

[23] Lee D Y, Cho Y H, Lee I K. Real-time optimal planning for redirected walking using Deep Q-Learning. In *Proc. the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2019, pp.63-71. DOI: 10.1109/VR.2019.8798121.

[24] Strauss R R, Ramanujan R, Becker A, Peck T C. A steering algorithm for redirected walking using reinforcement learning. *IEEE Transactions on Visualization and Computer Graphics*, 2020, 26(5): 1955-1963. DOI: 10.1109/TVCG.2020.2973060.

[25] Williams B, Narasimham G, Rump B, McNamara T P, Carr T H, Rieser J, Bodenheimer B. Exploring large virtual environments with an HMD when physical space is limited. In *Proc. the 4th Symposium on Applied Perception in Graphics and Visualization*, July 2007, pp.41-48. DOI: 10.1145/1272582.1272590.

[26] Suma E A, Clark S, Krum D, Finkelstein S, Bolas M, Warte Z. Leveraging change blindness for redirection in virtual environments. In *Proc. the 2011 IEEE Virtual Reality Conference*, March 2011, pp.159-166. DOI: 10.1109/VR.2011.5759455.

[27] Suma E A, Lipps Z, Finkelstein S, Krum D M, Bolas M. Impossible spaces: Maximizing natural walking in virtual environments with self-overlapping architecture. *IEEE Transactions on Visualization and Computer Graphics*, 2012, 18(4): 555-564. DOI: 10.1109/TVCG.2012.47.

[28] Vasylevska K, Kaufmann H, Bolas M, Suma E A. Flexible spaces: Dynamic layout generation for infinite walking in virtual environments. In *Proc. the 2013 IEEE Symposium on 3D User Interfaces*, March 2013, pp. 39-42. DOI: 10.1109/3DUI.2013.6550194.

[29] Sun Q, Wei L Y, Kaufman A. Mapping virtual and physical reality. *ACM Transactions on Graphics*, 2016, 35(4): Article No. 64. DOI: 10.1145/2897824.2925883.

[30] Dong Z C, Fu X M, Zhang C, Wu K, Liu L. Smooth assembled mappings for large-scale real walking. *ACM Transactions on Graphics*, 2017, 36(6): Article No. 211. DOI: 10.1145/3130800.3130893.

[31] Dong Z C, Fu X M, Yang Z, Liu L. Redirected smooth mappings for multiuser real walking in virtual reality. *ACM Transactions on Graphics*, 2019, 38(5): Article No. 149. DOI: 10.1145/3345554.

[32] Cao A, Wang L, Liu Y, Popescu V. Feature guided path redirection for VR navigation. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2020, pp.137-145. DOI: 10.1109/VR46266.2020.00032.

[33] Messinger J, Hodgson E, Bachmann E R. Effects of tracking area shape and size on artificial potential field redirected walking. In *Proc. the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2019, pp.72-80. DOI: 10.1109/VR.2019.8797818.

[34] Lee D Y, Cho Y H, Min D H, Lee I K. Optimal planning for redirected walking based on reinforcement learning in multi-user environment with irregularly shaped physical space. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2020, pp.155-163. DOI: 10.1109/VR46266.2020.00034.

[35] Chen H, Chen S, Rosenberg E S. Redirected walking strategies in irregularly shaped and dynamic physical environments. In *Proc. the 25th IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2018, pp.523-524. DOI: 10.1109/VR.2018.8446563.

[36] Thomas J, Rosenberg E S. A general reactive algorithm for redirected walking using artificial potential functions. In *Proc. the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2019, pp.56-62. DOI: 10.1109/VR.2019.8797983.

[37] Kohli L, Burns E, Miller D, Fuchs H. Combining passive haptics with redirected walking. In *Proc. the 2005 International Conference on Augmented Tele-Existence*, Dec. 2005, pp.253-254. DOI: 10.1145/1152399.1152451.

[38] Chen Z Y, Li Y J, Wang M, Steinicke F, Zhao Q. A reinforcement learning approach to redirected walking with passive haptic feedback. In *Proc. the 2021 IEEE International Symposium on Mixed and Augmented Reality*, Oct. 2021, pp.184-192. DOI: 10.1109/ISMAR52148.2021.00033.

[39] Wang L, Zhao Z, Yang X, Bai H, Barde A, Billinghurst M. A constrained path redirection for passive haptics. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops*, March 2020, pp.651-652. DOI: 10.1109/VRW50115.2020.00176.

[40] Thomas J, Pospick C H, Rosenberg E S. Towards physically interactive virtual environments: Reactive alignment with redirected walking. In *Proc. the 26th ACM Symposium on Virtual Reality Software and Technology*, Nov. 2020, Article No. 10. DOI: 10.1145/3385956.3418966.

[41] Steinicke F, Bruder G, Kohli L, Jerald J, Hinrichs K. Taxonomy and implementation of redirection techniques for ubiquitous passive haptic feedback. In *Proc. the 2008 International Conference on Cyberworlds*, Sept. 2008, pp.217-223. DOI: 10.1109/CW.2008.53.

[42] Azmandian M, Grechkin T, Bolas M, Suma E. The redirected walking toolkit: A unified development platform for exploring large virtual environments. In *Proc. the 2nd IEEE Workshop on Everyday Virtual Reality*, March 2016, pp.9-14. DOI: 10.1109/WEVR.2016.7859537.

[43] Li Y J, Wang M, Steinicke F, Zhao Q. OpenRDW: A redirected walking library and benchmark with multiuser, learning-based functionalities and state-of-the-art algorithms. In *Proc. the 2021 IEEE International Symposium on Mixed and Augmented Reality*, Oct. 2021, pp.21-30. DOI: 10.1109/ISMAR52148.2021.00016.

[44] Bruder G, Interrante V, Phillips L, Steinicke F. Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 2012, 18(4): 538-545. DOI: 10.1109/TVCG.2012.55.

[45] Hayashi O, Fujita K, Takashima K, Lindernan R W, Kitarnura Y. Redirected jumping: Imperceptibly manipulating jump motions in virtual reality. In *Proc. the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2019, pp.386-394. DOI: 10.1109/VR.2019.8797989.

[46] Jung S, Borst C W, Hoermann S, Lindeman R W. Redirected jumping: Perceptual detection rates for curvature gains. In *Proc. the 32nd Annual ACM Symposium on User Interface Software and Technology*, Oct. 2019, pp.1085-1092. DOI: 10.1145/3332165.3347868.

[47] Matsumoto K, Langbehn E, Narumi T, Steinicke F. Detection thresholds for vertical gains in VR and drone-based telepresence systems. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2020, pp.101-107. DOI: 10.1109/VR46266.2020.00028.

[48] Suma E A, Bruder G, Steinicke F, Krum D M, Bolas M. A taxonomy for deploying redirection techniques in immersive virtual environments. In *Proc. the 2012 IEEE Virtual Reality Workshops*, March 2012, pp.43-46. DOI: 10.1109/VR.2012.6180877.

[49] Langbehn E, Steinicke F. Redirected walking in virtual reality. In *Encyclopedia of Computer Graphics and Games*, Lee N (ed.), Springer, 2019. DOI: 10.1007/978-3-319-08234-9_253-1.

[50] Bishop I, Abid M R. Survey of locomotion systems in virtual reality. In *Proc. the 2nd International Conference on Information System and Data Mining*, April 2018, pp.151-154. DOI: 10.1145/3206098.3206108.

[51] Langbehn E, Lubos P, Bruder G, Steinicke F. Bending the curve: Sensitivity to bending of curved paths and application in room-scale VR. *IEEE Transactions on Visualization and Computer Graphics*, 2017, 23(4): 1389-1398. DOI: 10.1109/TVCG.2017.2657220.

[52] Cho Y H, Min D H, Huh J S, Lee S H, Yoon J S, Lee I K. Walking outside the box: Estimation of detection thresholds for non-forward steps. In *Proc. the 2021 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 27-April 1, 2021, pp.448-454. DOI: 10.1109/VR50410.2021.00068.

[53] Schmitz P, Hildebrandt J, Valdez A C, Kobbelt L, Ziefle M. You spin my head right round: Threshold of limited immersion for rotation gains in redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 2018, 24(4): 1623-1632. DOI: 10.1109/TVCG.2018.2793671.

[54] Rietzler M, Gugenheimer J, Hirzle T, Deubzer M, Langbehn E, Rukzio E. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *Proc. the 2018 IEEE International Symposium on Mixed and Augmented Reality*, Oct. 2018, pp.115-122. DOI: 10.1109/ISMAR.2018.00041.

[55] Steinicke F, Bruder G, Hinrichs K, Jerald J, Frenz H, Lappe M. Real walking through virtual environments by redirection techniques. *Journal of Virtual Reality and Broadcasting*, 2009, 6: Article No. 2. DOI: 10.20385/1860-2037/6.2009.2.

[56] Kim D, Shin J, Lee J, Woo W. Adjusting relative translation gains according to space size in redirected walking for mixed reality mutual space generation. In *Proc. the 2021 IEEE Virtual Reality and 3D User Interfaces*, March 27-April 1, 2021, pp.653-660. DOI: 10.1109/VR50410.2021.00091.

[57] Grechkin T, Thomas J, Azmandian M, Bolas M, Suma E. Revisiting detection thresholds for redirected walking: Combining translation and curvature gains. In *Proc. the ACM Symposium on Applied Perception*, July 2016, pp.113-120. DOI: 10.1145/2931002.2931018.

[58] Kruse L, Langbehn E, Steinicke F. I can see on my feet while walking: Sensitivity to translation gains with visible feet. In *Proc. the 2018 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2018, pp.305-312. DOI: 10.1109/VR.2018.8446216.

[59] Langbehn E, Steinicke F, Lappe M, Welch G F, Bruder G. In the blink of an eye: Leveraging blink-induced suppression for imperceptible position and orientation redirection in virtual reality. *ACM Transactions on Graphics*, 2018, 37(4): Article No. 66. DOI: 10.1145/3197517.3201335.

[60] Zhang J, Langbehn E, Krupke D, Katzakis N, Steinicke F. Detection thresholds for rotation and translation gains in 360 video-based telepresence systems. *IEEE Transactions on Visualization and Computer Graphics*, 2018, 24(4): 1671-1680. DOI: 10.1109/TVCG.2018.2793679.

[61] Williams N L, Peck T C. Estimation of rotation gain thresholds considering FOV, gender, and distractors. *IEEE Transactions on Visualization and Computer Graphics*, 2019, 25(11): 3158-3168. DOI: 10.1109/TVCG.2019.2932213.

[62] Neth C T, Souman J L, Engel D, Kloos U, Bulthoff H H, Mohler B J. Velocity-dependent dynamic curvature gain for redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 2012, 18(7): 1041-1052. DOI: 10.1109/TVCG.2011.275.

[63] Zhang S, Wang C, Zhang Y, Zhang F L, Pantidi N, Hu S M. Velocity guided amplification of view rotation for seated VR scene exploration. In *Proc. the 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops*, March 27-April 1, 2021, pp.504-505. DOI: 10.1109/VRW52623.2021.00134.

[64] Paludan A, Elbaek J, Mortensen M, Zobbe M, Nilsson N C, Nordahl R, Reng L, Serafin S. Disguising rotational gain for redirected walking in virtual reality: Effect of visual density. In *Proc. the 2016 IEEE Virtual Reality*, March 2016, pp.259-260. DOI: 10.1109/VR.2016.7504752.

[65] Schmelter T, Hernadi L, Störmer M A, Steinicke F, Hildebrand K. Interaction based redirected walking. *Proceedings of the ACM on Computer Graphics and Interactive Techniques*, 2021, 4(1): Article No. 9. DOI: 10.1145/3451264.

[66] Serafin S, Nilsson N C, Sikstrom E, De Goetzen A, Nordahl R. Estimation of detection thresholds for acoustic based redirected walking techniques. In *Proc. the 2013 IEEE Virtual Reality*, March 2013, pp.161-162. DOI: 10.1109/VR.2013.6549412.

[67] Nilsson N C, Suma E, Nordahl R, Bolas M, Serafin S. Estimation of detection thresholds for audiovisual rotation gains. In *Proc. the 2016 IEEE Virtual Reality*, March 2016, pp.241-242. DOI: 10.1109/VR.2016.7504743.

[68] Meyer F, Nogalski M, Fohl W. Detection thresholds in audio-visual redirected walking. In *Proc. the 13th Sound and Music Computing Conference*, August 31-September 3, 2016. DOI: 10.5281/zenodo.851258.

[69] Gao P, Matsumoto K, Narumi T, Hirose M. Visual-auditory redirection: Multimodal integration of incongruent visual and auditory cues for redirected walking. In *Proc. the 2020 IEEE International Symposium on Mixed and Augmented Reality*, Nov. 2020, pp.639-648. DOI: 10.1109/ISMAR50242.2020.00092.

[70] Sakono H, Matsumoto K, Narumi T, Kuzuoka H. Redirected walking using continuous curvature manipulation. *IEEE Transactions on Visualization & Computer Graphics*, 2021, 27(11): 4278-4288. DOI: 10.1109/TVCG.2021.3106501.

[71] Hutton C, Ziccardi S, Medina J, Rosenberg E S. Individualized calibration of rotation gain thresholds for redirected walking. In *Proc. the 2018 International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments*, Nov. 2018, pp.61-64. DOI: 10.2312/egve.20181315.

[72] Rothacher Y, Nguyen A, Lenggenhager B, Kunz A, Brugger P. Visual capture of gait during redirected walking. *Scientific Reports*, 2018, 8(1): Article No. 17974. DOI: 10.1038/s41598-018-36035-6.

[73] Bölling L, Stein N, Steinicke F, Lappe M. Shrinking circles: Adaptation to increased curvature gain in redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 2019, 25(5): 2032-2039. DOI: 10.1109/TVCG.2019.2899228.

[74] Chen W, Ladevèze N, Hu W, Ou S, Bourdot P. Comparison between the methods of adjustment and constant stimuli for the estimation of redirection detection thresholds. In *Proc. the 16th EuroVR International Conference on Virtual Reality and Augmented Reality*, Oct. 2019, pp.226-245. DOI: 10.1007/978-3-030-31908-3_14.

[75] Congdon B J, Steed A. Sensitivity to rate of change in gains applied by redirected walking. In *Proc. the 25th ACM Symposium on Virtual Reality Software and Technology*, Nov. 2019, Article No. 3. DOI: 10.1145/3359996.3364277.

[76] Simeone A L, Nilsson N C, Zenner A, Speicher M, Daiber F. The space bender: Supporting natural walking via overt manipulation of the virtual environment. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2020, pp.598-606. DOI: 10.1109/VR46266.2020.00082.

[77] Interrante V, Ries B, Anderson L. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *Proc. the 2007 IEEE Symposium on 3D User Interfaces*, March 2007, Article No. 35. DOI: 10.1109/3DUI.2007.340791.

[78] Reimer D, Langbehn E, Kaufmann H, Scherzer D. The influence of full-body representation on translation and curvature gain. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops*, March 2020, pp.154-159. DOI: 10.1109/VRW50115.2020.00032.

[79] Nguyen A, Rothacher Y, Lenggenhager B, Brugger P, Kunz A. Effect of sense of embodiment on curvature redirected walking thresholds. In *Proc. the 2020 ACM Symposium on Applied Perception*, Sept. 2020, Article No. 16. DOI: 10.1145/3385955.3407932.

[80] Heeter C. Being there: The subjective experience of presence. *Presence: Teleoperators & Virtual Environments*, 1992, 1(2): 262-271. DOI: 10.1162/pres.1992.1.2.262.

[81] Slater M, Usoh M, Steed A. Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction*, 1995, 2(3): 201-219. DOI: 10.1145/210079.210084.

[82] Lin J W, Duh H B L, Parker D E, Abi-Rached H, Furness T A. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Proc. the 2002 IEEE Virtual Reality Conference*, March 2002, pp.164-171. DOI: 10.1109/VR.2002.996519.

[83] Stanney K, Salvendy G. Aftereffects and sense of presence in virtual environments: Formulation of a research and development agenda. *International Journal of Human-Computer Interaction*, 1998, 10(2): 135-187. DOI: 10.1207/s15327590ijhc1002_3.

[84] Kolasinski E M. Simulator Sickness in Virtual Environments. US Army Research Institute for the Behavioral and Social Sciences, 1995.

[85] Kennedy R S, Lane N E, Berbaum K S, Lilienthal M G. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, 1993, 3(3): 203-220. DOI: 10.1207/s15327108ijap0303_3.

[86] Bruder G, Lubos P, Steinicke F. Cognitive resource demands of redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 2015, 21(4): 539-544. DOI: 10.1109/TVCG.2015.2391864.

[87] Nguyen A, Rothacher Y, Efthymiou E, Lenggenhager B, Brugger P, Imbach L, Kunz A. Effect of cognitive load on curvature redirected walking thresholds. In *Proc. the 26th ACM Symposium on Virtual Reality Software and Technology*, Nov. 2020, Article No. 17. DOI: 10.1145/3385956.3418950.

[88] Razzaque S, Swapp D, Slater M, Whitton M C, Steed A. Redirected walking in place. In *Proc. the 8th Eurographics Workshop on Virtual Environments*, May 2002, pp.123-130. DOI: 10.2312/EGVE/EGVE02/123-130.

[89] Field T, Vamplew P. Generalised algorithms for redirected walking in virtual environments. In *Proc. the 2nd International Conference on Artificial Intelligence in Science and Technology*, Nov. 2004, pp.58-63.

[90] Nescher T, Huang Y Y, Kunz A. Planning redirection techniques for optimal free walking experience using model predictive control. In *Proc. the 2014 IEEE Symposium on 3D User Interfaces*, March 2014, pp.111-118. DOI: 10.1109/3DUI.2014.6798851.

[91] Azmandian M, Yahata R, Bolas M, Suma E. An enhanced steering algorithm for redirected walking in virtual environments. In *Proc. the 2014 IEEE Virtual Reality*, March 29-April 2, 2014, pp.65-66. DOI: 10.1109/VR.2014.6802053.

[92] Azmandian M, Grechkin T, Bolas M, Suma E. Automated path prediction for redirected walking using navigation meshes. In *Proc. the 2016 IEEE Symposium on 3D User Interfaces*, March 2016, pp.63-66. DOI: 10.1109/3DUI.2016.7460032.

[93] Xie X, Lin Q, Wu H, Narasimham G, McNamara T P, Rieser J, Bodenheimer B. A system for exploring large virtual environments that combines scaled translational gain and interventions. In *Proc. the 7th Symposium on Applied Perception in Graphics and Visualization*, July 2010, pp.65-72. DOI: 10.1145/1836248.1836260.

[94] Yu R, Duer Z, Ogle T *et al*. Experiencing an invisible World War I battlefield through narrative-driven redirected walking in virtual reality. In *Proc. the 2018 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2018, pp.313-319. DOI: 10.1109/VR.2018.8448288.

[95] Zhang S H, Chen C H, Fu Z, Yang Y, Hu S M. Adaptive optimization algorithm for resetting techniques in obstacle-ridden environments. *IEEE Transactions on Visualization and Computer Graphics*. DOI: 10.1109/TVCG.2021.3139990.

[96] Zhang S H, Chen C H, Zollmann S. One-step out-of-place resetting for redirected walking in VR. *IEEE Transactions on Visualization and Computer Graphics*. DOI: 10.1109/TVCG.2022.3158609.

[97] Bahill A T, Clark M R, Stark L. The main sequence, a tool for studying human eye movements. *Mathematical Biosciences*, 1975, 24(3/4): 191-204. DOI: 10.1016/0025-5564(75)90075-9.

[98] Bolte B, Lappe M. Subliminal reorientation and repositioning in immersive virtual environments using saccadic suppression. *IEEE Transactions on Visualization and Computer Graphics*, 2015, 21(4): 545-552. DOI: 10.1109/TVCG.2015.2391851.

[99] Langbehn E, Bruder G, Steinicke F. Subliminal reorientation and repositioning in virtual reality during eye blinks. In *Proc. the 2016 Symposium on Spatial User Interaction*, Oct. 2016, pp.213. DOI: 10.1145/2983310.2989204.

[100] Nguyen A, Kunz A. Discrete scene rotation during blinks and its effect on redirected walking algorithms. In *Proc. the 24th ACM Symposium on Virtual Reality Software and Technology*, November 28-December 1, 2018, Article No. 29. DOI: 10.1145/3281505.3281515.

[101] Peck T C, Fuchs H, Whitton M C. Evaluation of reorientation techniques and distractors for walking in large virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 2009, 15(3): 383-394. DOI: 10.1109/TVCG.2008.191.

[102] Peck T C, Fuchs H, Whitton M C. Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments. In *Proc. the 2010 IEEE Virtual Reality Conference*, March 2010, pp.35-38. DOI: 10.1109/VR.2010.5444816.

[103] Rewkowski N, Rungta A, Whitton M, Lin M. Evaluating the effectiveness of redirected walking with auditory distractors for navigation in virtual environments. In *Proc. the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2019, pp.395-404. DOI: 10.1109/VR.2019.8798286.

[104] Bachmann E R, Holm J, Zmuda M A, Hodgson E. Collision prediction and prevention in a simultaneous two-user immersive virtual environment. In *Proc. the 2013 IEEE Virtual Reality*, March 2013, pp.89-90. DOI: 10.1109/VR.2013.6549377.

[105] Azmandian M, Grechkin T, Rosenberg E S. An evaluation of strategies for two-user redirected walking in shared physical spaces. In *Proc. the 2017 IEEE Virtual Reality*, March 2017, pp.91-98. DOI: 10.1109/VR.2017.7892235.

[106] Krogh B. A generalized potential field approach to obstacle avoidance control. In *Proc. the 1st World Conference on Robotics Research,* Aug. 1984, pp.11-22.

[107] Dong T, Shen Y, Gao T, Fan J. Dynamic density-based redirected walking towards multi-user virtual environments. In *Proc. the 2021 IEEE Virtual Reality and 3D User Interfaces*, March 27-April 1, 2021, pp.626-634. DOI: 10.1109/VR50410.2021.00088.

[108] Min D H, Lee D Y, Cho Y H, Lee I K. Shaking hands in virtual space: Recovery in redirected walking for direct interaction between two users. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2020, pp.164-173. DOI: 10.1109/VR46266.2020.00035.

[109] Azmandian M, Grechkin T, Bolas M T, Suma E A. Physical space requirements for redirected walking: How size and shape affect performance. In *Proc. the 25th International Conference on Artificial Reality and Telexistence and 20th Eurographics Symposium on Virtual Environments*, Oct. 2015, pp.93-100. DOI: 10.2312/egve.20151315.

[110] Williams N L, Bera A, Manocha D. ARC: Alignment-based redirection controller for redirected walking in complex environments. *IEEE Transactions on Visualization and Computer Graphics*, 2021, 27(5): 2535-2544. DOI: 10.1109/TVCG.2021.3067781.

[111] Williams N L, Bera A, Manocha D. Redirected walking in static and dynamic scenes using visibility polygons. *IEEE Transactions on Visualization and Computer Graphics*, 2021, 27(11): 4267-4277. DOI: 10.1109/TVCG.2021.3106432.

[112] Thomas J, Rosenberg E S. Reactive alignment of virtual and physical environments using redirected walking. In *Proc. the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops*, March 2020, pp.317-323. DOI: 10.1109/VRW50115.2020.00071.

[113] Peck T C, Fuchs H, Whitton M C. The design and evaluation of a large-scale real-walking locomotion interface. *IEEE Transactions on Visualization and Computer Graphics*, 2011, 18(7): 1053-1067. DOI: 10.1109/TVCG.2011.289.

[114] Bolte B, Steinicke F, Bruder G. The jumper metaphor: An effective navigation technique for immersive display setups. In *Proc. Virtual Reality International Conference*, April 2011.

[115] Wolf D, Rogers K, Kunder C, Rukzio E. JumpVR: Jump-based locomotion augmentation for virtual reality. In *Proc. the 2020 CHI Conference on Human Factors in Computing Systems*, April 2020. DOI: 10.1145/3313831.3376243.

[116] Yoshida N, Ueno K, Naka Y, Yonezawa T. Virtual ski jump: Illusion of slide down the slope and gliding. In *Proc. SIGGRAPH ASIA 2016 Posters*, Nov. 2016, Article No. 4. DOI: 10.1145/3005274.3005282.

[117] Kim M, Cho S, Tran T Q, Kim S P, Kwon O, Han J. Scaled jump in gravity-reduced virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 2017, 23(4): 1360-1368. DOI: 10.1109/TVCG.2017.2657139.

[118] Sasaki T, Liu K H, Hasegawa T, Hiyama A, Inami M. Virtual super-leaping: Immersive extreme jumping in VR. In *Proc. the 10th Augmented Human International Conference*, March 2019, Article No. 18. DOI: 10.1145/3311823.3311861.

[119] Li Y J, Jin D R, Wang M, Chen J L, Steinicke F, Hu S M, Zhao Q. Detection thresholds with joint horizontal and vertical gains in redirected jumping. In *Proc. the 2021 IEEE Virtual Reality and 3D User Interfaces*, March 27-April 1, 2021, pp.95-102. DOI: 10.1109/VR50410.2021.00030.

[120] Li Y, Wang M, Jin D, Steinicke F, Hu S, Zhao Q. Effects of virtual environment and self-representations on perception and physical performance in redirected jumping. *Virtual Reality & Intelligent Hardware*, 2021, 3(6): 451-469. DOI: 10.1016/j.vrih.2021.06.003.

[121] Liu X, Wang L. Redirected jumping in virtual scenes with alleys. *Virtual Reality & Intelligent Hardware*, 2021, 3(6): 470-483. DOI: 10.1016/j.vrih.2021.06.004.

[122] Havlík T, Hayashi D, Fujita K, Takashima K, Lindeman R W, Kitamura Y. JumpinVR: Enhancing jump experience in a limited physical space. In *Proc. SIGGRAPH Asia 2019 XR*, Nov. 2019, pp.19-20. DOI: 10.1145/3355355.3361895.

[123] Kumpei O, Kazuyuki F, Kazuki T, Yoshifumi K. PseudoJumpOn: Jumping onto steps in virtual reality. In *Proc. the 2022 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2022, pp.635-643. DOI: 10.1109/VR51125.2022.00084.

[124] Yukai H, Kazuyuki F, Kazuki T, Morten F, Yoshifumi K. RedirectedDoors: Redirection while opening doors in virtual reality. In *Proc. the 2022 IEEE Conference on Virtual Reality and 3D User Interfaces*, March 2022, pp.464-473. DOI: 10.1109/VR51125.2022.00066.

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