Enhancing Agency in Redirected Walking with Haptic Nudges

XINYI YANG, Harvard University, USA

DANIEL HAILS, Massachusetts Institute of Technology, USA

In this paper, we propose "Haptic Nudges", an extension to redirected walking techniques to provide an intuitive, unobtrusive understanding of the real-world space. Haptic Nudges maximize virtual traversal distance while increasing agency. In addition, we update existing open-source redirected walking tool-kits with new redirection algorithms and expose artificial potential fields for all techniques. The combination of these techniques can be applied as a drop-in addition to any existing Unity project. It could help us to understand better whether this haptic nudges method can not only give a real sense of feedback in a virtual environment but also largely influence/manipulate the user behavior in the physical environment using a sensory mode that is under-utilized in existing virtual reality setups.

CCS Concepts: • **Human-centered computing → Haptic devices**.

Additional Key Words and Phrases: haptic distractor, navigation-by-haptics techniques, redirected walking, mobile computing, artificial potential field

ACM Reference Format:
Xinyi Yang and Daniel Hails. 2022. Enhancing Agency in Redirected Walking with Haptic Nudges. 1, 1 (November 2022), 8 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

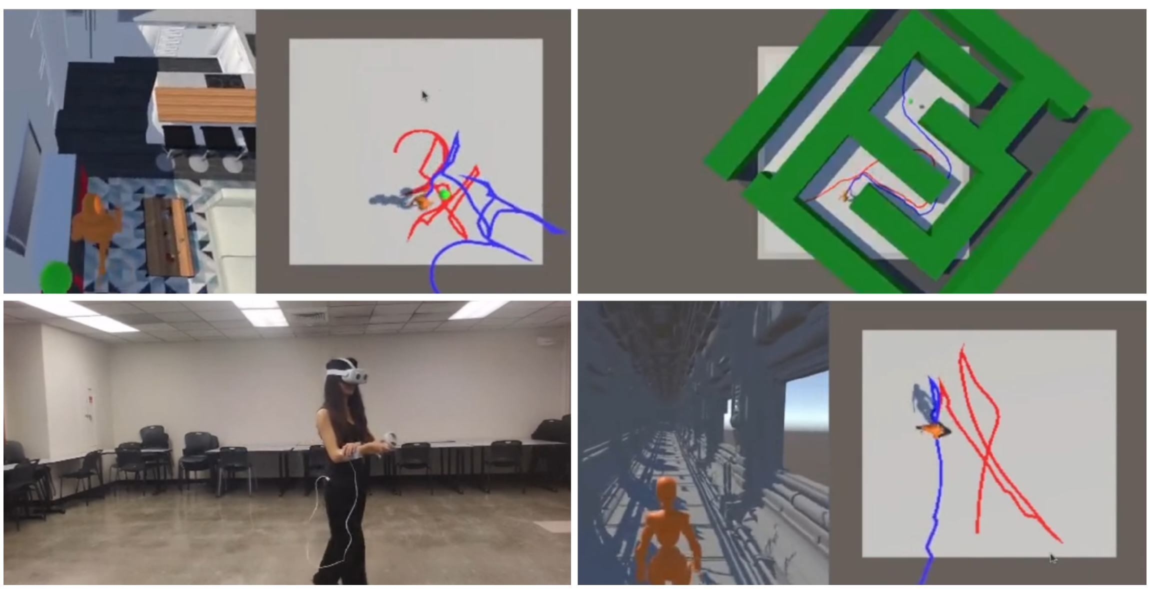

Fig. 1. Our experiments about our technique in different testing unity scenes. A. House Tour Scene with Virtual Avatar; B. Classical Maze Example; C.Haptic device and redirection in 7x7 meter space; D. Corridor redirection.

Authors' addresses: Xinyi Yang, xinyiyang@gsd.harvard.edu, Harvard University, Cambridge, Massachusetts, USA, 02138; Daniel Hails, hails@mit.edu, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 02138.

2022. Manuscript submitted to ACM

1 INTRODUCTION

Virtual Reality has been described as " the substitution of the interface between a person and their physical environment with an interface to a simulated environment" [6]. In other words, it provides a new medium to break the boundary between physical spaces and makes imaginations more realistic. Some existing VR projects mainly focus on the visual effect, bringing amazing virtual scenes to the user while at the same time, more and more researchers are researching audio and haptic feedback and creating a more immersive experience by involving more senses of the users [2]. However, there is still a lack of study on how haptic feedback can change and manipulate people's behavior in a virtual environment. In this research, we provide a new haptic system as a distractor (we call it "haptic nudges") to help to redirect people's movement in virtual reality based on the open-source OpenRDW library[7]. In this paper, our main contributions include:

(1) Provide an innovative methodology and framework for adopting haptic distractors in virtual reality, taking redirected walking as an example.
(2) Creating a haptic nudge system that can manipulate people's walking behavior in virtual reality.
(3) Providing demos to evaluate the impact of haptic nudges in redirected walking for further research and user study.

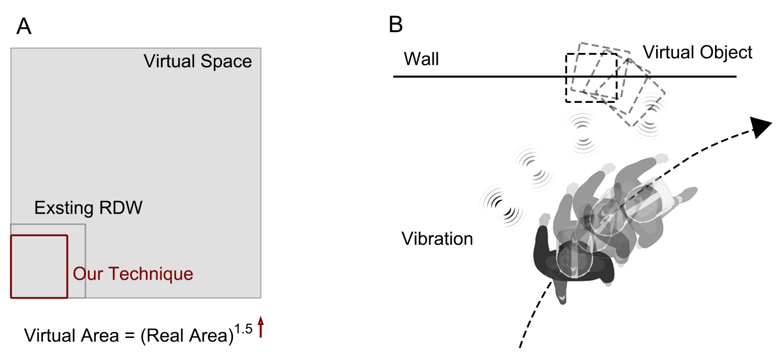

Fig. 2. A. Traditional virtual Space compression example with a 1.5 exponential factor. With our technique, we expect we can achieve unlimited walking in the physical space with the dimension of less than 10m * 10m; B. Concept Diagram: we hope the haptic nudges help people to redirect their path both visually and physically

2 BACKGROUND AND RELATED WORK

Three VR topics can be further developed and formed the foundation of our research:

2.1 Haptics and Embodiment

Haptic perception can enhance the immersion of the virtual environment for users by providing additional information. There are two kinds of haptic perception in virtual reality: the kinesthetic and the tactile senses [9]. The former one can help the user get a sense of their posture and body parts within the space, while the latter can create contact between the body and the objects. In this research, we want to focus on vibro-tactile devices, which mainly generate tactile sensations. By manipulating the tactile sensation, we create "tactile dislocation" to confuse people's sense of objects in the virtual environment, thus changing the movement behavior in virtual reality.

2.2 Distractor in Virtual Reality

In the previous study, distractors in virtual reality are mainly adopted as a technique for psychological and physical medical treatment [5] [1]. These studies demonstrate the successful translation of traditional paradigms and manipulations into immersive VR and lays a foundation for future research on attention and distraction in VR. Meanwhile, some studies provide new ideas of using distractors in manipulating human behavior in VR, but mainly focus on visual distractors. For example, a moving dot with bright colors can help people rotate their heads as they are more likely to pay more attention to the dot and move their heads without noticing. Some research also discusses the sound/audio distractor in redirected walking [12]. In this paper, we focus on exploring the haptic distractor in redirected walking, and will make a comparison with other distractors (visual/ audio) in future work.

2.3 Redirected Walking

"How far can you walk in a straight line, blindfolded?" This well-studied problem shows the dominance and reliance of the visual system when determining straight lines; proprioceptive senses are insufficient and result in drifting. However, the dual of this problem allows for the visual system to manipulate otherwise straight motion imperceptibly. In virtual reality, based on this psychological phenomenon based on inattentional blindness, some techniques enable users to locomote naturally within a virtual environment that is larger than the available physical space [11] [8]. Traditional research on redirected walking in virtual reality has focused on predictive algorithms [4]; it is often necessary to utilize reactive approaches when the user's path is unconstrained. And more and more researchers started to use haptic devices to enhance the performance of traditional algorithms. Navigation by haptic can increase the efficiency of collision avoidance as well as to help to improve the accessibility of disabled people in virtual environments [10]. In this research, we not only extend the concepts of navigation by haptic but also see haptic feedback as the distractor instead of the guidance.

3 MANIPULATION TECHNIQUES

Our technique is built based on the existing subtle gain-based redirection technique and developed into the new haptic nudges to increase the efficiency of rotating angles in virtual reality, thus minimizing the area of physical space that should be used in VR. It involves both visual and haptic systems in our body [See Fig.03].

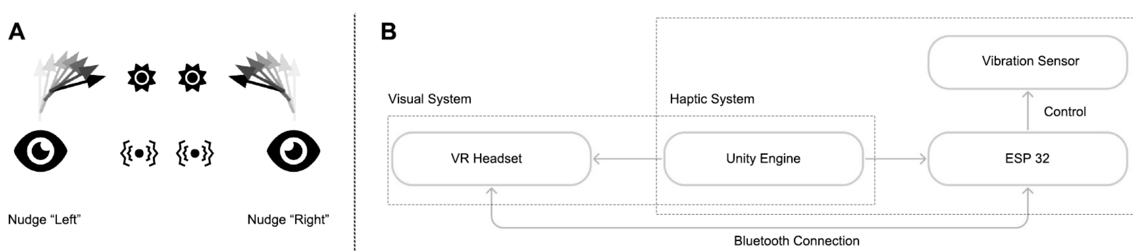

Fig. 3. Framework for our system. A.our technique involves both "visual" and "haptic" redirection. B. The structure of the hardware device of the system.

3.1 Subtle Gain-based Redirection

The most well-studied technique for redirection that maintains coherency in virtual space is "Gain based" redirection. A "gain" describes a relative difference between real and virtual motion. Traditional locomotion techniques will enforce a one-to-one mapping and a gain of: (1). A translation gain manipulates the virtual velocity of the user causing the user to walk faster or slower in the real world. (2). Rotational gains cause the viewpoint in the virtual space to rotate faster or slower relative to the tracked head rotation. (3). Curvature-based techniques apply rotation to the world during forward motion causing straight lines to curve alongside this vibration.

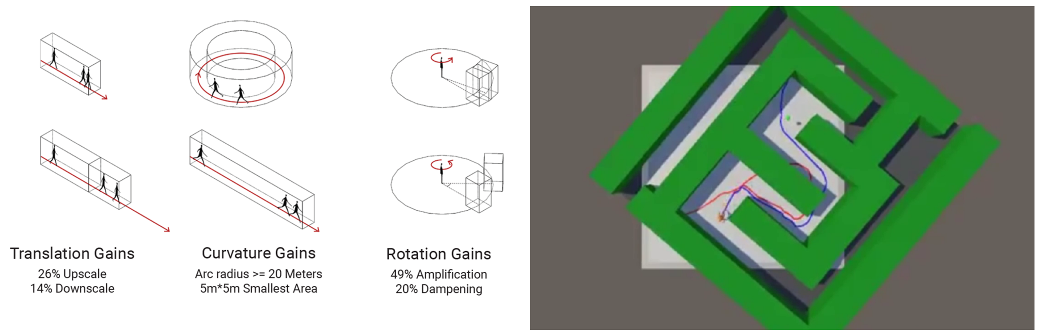

Fig. 4. Redirected walking algorithms: One the right: The existing "gain based" technique that are used in redirected walking; On the right: Our extension of OpenRDW / RDWTK, which performs Gain-based redirected walking, and supply “Resetters” such as the 2-1 turn. As part of these changes, the setup was updated for modern Unity releases and XRTK HMD, allowing for additional Headset types.

However, subtle gain-based techniques only apply when there is existing motion and have limits to their redirected force. In essence, they are under-actuated dynamic control systems. As such, we often need an overt technique to add additional motion to produce additional input. The primary technique we use is the 2-1 rotation that converts a 360-degree virtual rotation into a 180-degree physical rotation. This technique is imperceptible (beyond the overt command to spin) and allows for rapid direction change at the cost of observability [See Fig.05].

These redirection techniques are best applied with some awareness of the tracking space and the “ideal” points for which to be located to maximize both the current trajectory and possible future trajectories. The redirection then directs the user to these optimal points. For instance, an unobstructed square will have a center point as the minimum potential point that allows for the maximum distance given no current motion. This notion can be formalized as Artificial Potential Fields [See Fig.05] [3]. This provides a gradient vector for optimal movement, and we use this for all redirection algorithms for our haptic nudges that we show below.

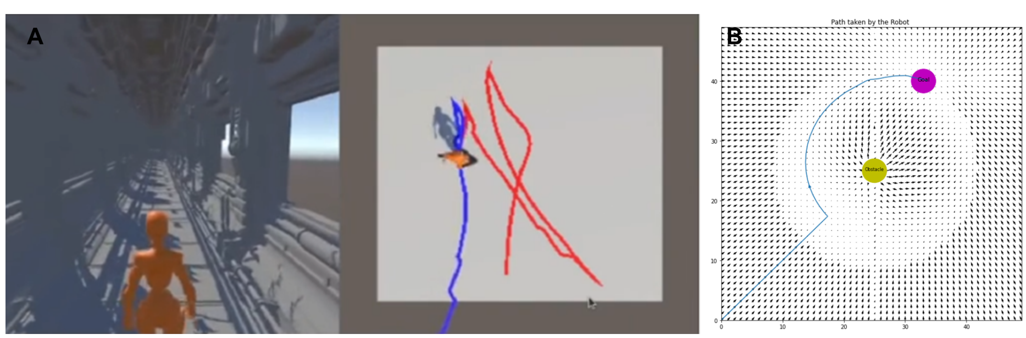

Fig. 5. Limitation and the potential solution for redirected walking algorithms. A. 2-1 Spin used to continue a 21m straight-line path despite a 7x7 tracking space; B. An example of APF used for robotic planning by AslanDevbrat.

3.2 Haptic nudges

All the techniques discussed so far use the visual system primarily. However, we could apply additional senses - not just rotating the viewpoint but also suggesting a direction to the way that minimizes the potential field alongside vibration. We call this "Haptic Nudging" because, unlike redirection, we do not directly control where the user goes; we merely aid them in decision-making. Consider moving around a house in virtual reality. There are often multiple decision points where you could move in multiple ways. Typically this choice occurs by chance or by whichever direction is most desired visually. However, sometimes a direction will lead to a tracking space boundary and cause an overt redirection, often, the preference is to avoid these overt redirections, and we can allow the user to choose a different circulation. When applied alongside gain redirection, the user can often return to the same point in virtual space and instead be nudged to the alternative direction they did not originally pick (as their position in the real world is different). This increases agency because, unlike redirection the user is in control. Due to the haptic feedback, this redirection is subtle and ignorable if desired for a particular game-play element. In addition, after usage the user will often subconsciously prefer directions that lack vibration, allowing for nudging without the user paying conscious attention to the feeling.

However, the key disadvantage of this technique is that it requires choice to be influential. It applies well in high complexity environments where multiple pathways exist, but not in simple environments such as the straight line corridor. That isn't to say it is un-utilised in such an environment as it can still encourage wandering paths and head rotation that can be utilized by subtle gain-based techniques.

We apply Haptic Nudges by considering the global space top-down vectors X_{dir} (the normalized direction from current user pose) and$X_{mingrad}$ the vector to the nearest local minimum in the APF field. Together these encode the haptic amplitude A(t), and signal frequency F(t) at time t. Note that R here denotes the "bounding" circle of the tracking space.

$$A(t) = A_{Max}\frac{|X_{dir}(t)X_{mingrad}(t)|}{180}$$

$$F(t) = 1 + F_{Max}\frac{|X_{mingrad}(t)|}{R}$$

These signal commands are serialised with a simple convention of <device_name>:O<dc_offset>A<amplitude> F<frequency> and broadcasted via Bluetooth serial to connected device. The ESP32s render the given waveform by adjusting the duty cycle of a PWM-controlled ERM motor on a maximum period of 1ms. This allows up to 1000Hz frequencies to be rendered. We use it to denote the loop counter. Therefore:

$$D(t) = O + |Asin(\frac{2(n mod 1000)\pi f}{1000})|$$

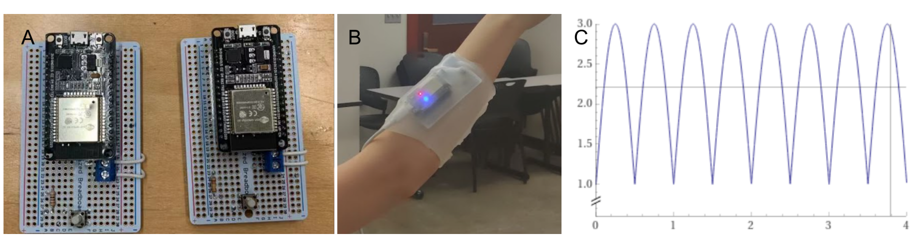

Fig. 6. Haptic nudges A. Our hardware device includes the ESP32, the vibration motor, and the control button to let the player stop the vibration manually if necessary); B. The device is attached to the arm of the player when they interact with the virtual environment; C. Haptic Rendering of "Bump" wave given the input O1A2F1 (offset 1V, amplitude 2V and frequency 1Hz)

4 APPLICATION AND FINDINGS

In this session, we create two VR demos to verify our techniques. These two demos involve the existing algorithms in redirected walking that we choose from the precedents and the haptic nudges we proposed. The two scenes are:

(1) A long corridor walking (14 meters total), which helps us to understand the impact of our proposed distractor in the linear back-and-forth walking patterns in virtual reality [See Fig.07];
(2) A house tour (with one bedroom, one living room, one kitchen, one balcony, and one bathroom inside of the virtual environment) helps us to understand the performance of the haptic distractor in the dynamic visual environment [See Fig.08].

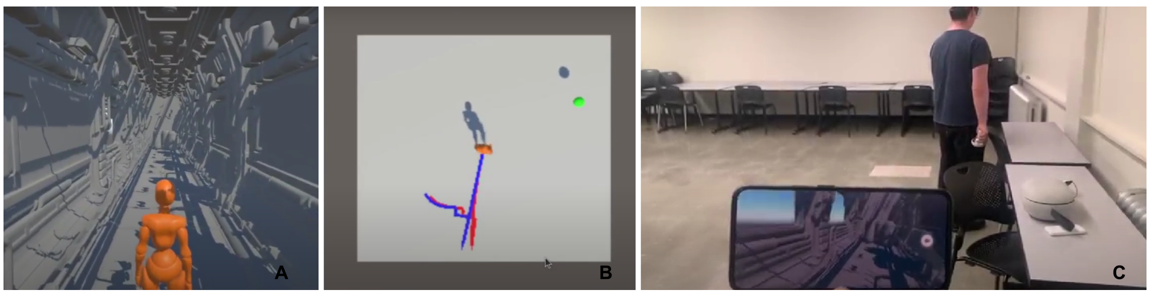

Fig. 7. Corridor VR demo and testing: A. The VR scene that we create to allow players to experience; B. The recording of the walking path of the player during the interaction (the Red line represents the path of the virtual movement while the Blue line represents the physical movement); C. The photo is taken when the player is in the VR scene.

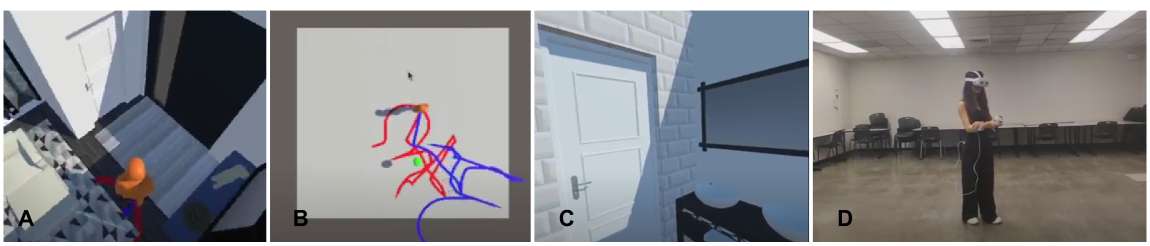

Fig. 8. House Tour VR demo and testing: A. The VR scene that we provide for our players; B. The recording of the walking path of the player during the interaction(the Red line represents the path of the virtual environment while the blue line represents the physical movement); C. The actual view of the player in the virtual environment; D. The photo taken when the player is in the VR scene.

There are several findings that we get from these two demos:

- **For the linear back-and-forth movement in virtual reality:** There is not much improvement in the redirected walking system by adding our proposed haptic nudges in the corridor demo. That is because when the user is slightly moving to the left or the right, the distractor on the arm vibrates and gives the alarm to the user. But there is no harm for the user to move on the right/left side (as there is still plenty of room in physical space). Moreover, when the user is at the end of the corridor, the algorithms will be actuated, and the virtual world will be rotated to 180 degrees, which will make the user not get an immersive feeling during the interaction.

- **For the wandering behavior in virtual reality:** our system works pretty well. We know that the existing redirected walking algorithms can help people to get unlimited walking experience in 10m * 10 m space. And after adding our haptic nudges, it could achieve our expectation for unlimited walking within 7m * 7m space. The player can continuously hang around the virtual home repeatedly to any direction in the immersive VR environment.
- **The performance of the player:** Players respond differently toward the haptic nudges during the interaction. Some people might be distracted by our VR scene and might ignore the vibration alert from the haptic nudges, or people focus more on the vibration instead of the VR visual scene.
- **The dilemma of choice:** Sometimes, the player might be trapped in a small room (for example, the bathroom) and not get out of the space until they ignore the vibration alert from the haptic nudges. That is because when the player stands at the corner of the physical room, the vibration will become intense in two directions. Hence, people get confused when they want to turn in the direction without the vibration alert, but at the same time, there is no way to go out(the direction is blocked by the wall) in the virtual world.

5 DISCUSSION AND FUTURE WORK

In this section, we discuss the limitations of our approach and lay out directions for future work.

- **Improving the algorithms:** All the algorithms for redirection currently implemented is tracking-space aware but virtual-space blind. This means they do not consider the variations in virtual space to reduce potential trajectories and hence optimize the redirection because of it. The blind algorithm will attempt to optimize the position to the center point, assuming that all possible trajectories are equally likely [See Fig.9]. Meanwhile, a virtual-space-aware algorithm will adjust the possible trajectories to realign the desired tracking-space, virtual-space mapping to support the right-wards movement at the detriment of left-wards movement blocked by a virtual wall.
- **Improve the haptic nudges:** Based on the above testing, we figured out that people might not be able to sense the vibration when they choose to focus on the visual input. Thus, we should study how to build a link between haptic nudges and the visual environment. By then, our proposed technique not only can help players to redirect but also enhance the immersive experience by giving the haptic feedback of the visual objects.
- **Conducting user study:** When putting the haptic nudges on different body parts, the same player might respond differently in each test. Moreover, even when the haptic nudges are put on the same part of the body of two people with the same stimulus intensity, they may have different feelings due to different response standards. Therefore, a user study should be conducted to avoid deviations due to individual differences and the impact of this equipment on the health of players.

(a) Virtual Environment Blind Algorithm

(b) Virtual Environment Aware Algorithm

Fig. 9. Virtual Environment Awareness

REFERENCES

[1] Rania R Ali, Ali Osman Selim, Mohamed A Abdel Ghafar, Osama Ragaa Abdelraouf, and Olfat Ibrahim Ali. 2022. Virtual reality as a pain distractor during physical rehabilitation in pediatric burns. *Burns* 48, 2 (2022), 303–308.

[2] Grigore C Burdea. 1996. *Force and touch feedback for virtual reality.* John Wiley & Sons, Inc.

[3] Tianyang Dong, Xianwei Chen, Yifan Song, Wenyuan Ying, and Jing Fan. 2020. Dynamic artificial potential fields for multi-user redirected walking. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR).* IEEE, 146–154.

[4] Linwei Fan, Huiyu Li, and Miaowen Shi. 2022. Redirected Walking for Exploring Immersive Virtual Spaces with HMD: A Comprehensive Review and Recent Advances. *IEEE Transactions on Visualization and Computer Graphics* (2022).

[5] Jonathan Gershon, Elana Zimand, Rosemarie Lemos, Barbara Olasov Rothbaum, and Larry Hodges. 2003. Use of virtual reality as a distractor for painful procedures in a patient with pediatric cancer: a case study. *CyberPsychology & Behavior* 6, 6 (2003), 657–661.

[6] Jaron Lanier. 2017. *Dawn of the new everything: Encounters with reality and virtual reality.* Henry Holt and Company.

[7] Yi-Jun Li, Miao Wang, Frank Steinicke, and Qinping Zhao. 2021. Openrdw: A redirected walking library and benchmark with multi-user, learning-based functionalities and state-of-the-art algorithms. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR).* IEEE, 21–30.

[8] Michael Rietzler, Jan Gugenheimer, Teresa Hirzle, Martin Deubzer, Eike Langbehn, and Enrico Rukzio. 2018. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR).* IEEE, 115–122.

[9] Abdulmotaleb El Saddik, Mauricio Orozco, Mohamad Eid, and Jongeun Cha. 2011. Human haptic perception. In *Haptics Technologies.* Springer, 45–66.

[10] Alexa F Siu, Mike Sinclair, Robert Kovacs, Eyal Ofek, Christian Holz, and Edward Cutrell. 2020. Virtual reality without vision: A haptic and auditory white cane to navigate complex virtual worlds. In *Proceedings of the 2020 CHI conference on human factors in computing systems.* 1–13.

[11] Qi Sun, Anjul Patney, Li-Yi Wei, Omer Shapira, Jingwan Lu, Paul Asente, Suwen Zhu, Morgan McGuire, David Luebke, and Arie Kaufman. 2018. Towards virtual reality infinite walking: dynamic saccadic redirection. *ACM Transactions on Graphics (TOG)* 37, 4 (2018), 1–13.

[12] Rene Weller, Benjamin Brennecke, and Gabriel Zachmann. 2022. Redirected walking in virtual reality with auditory step feedback. *The Visual Computer* 38, 9 (2022), 3475–3486.