國立臺灣大學電機資訊學院資訊網路與多媒體研究所

碩士論文

Institute of Networking and Multimedia
College of Electrical Engineering and Computer Science
National Taiwan University

Master Thesis

透過模擬臉部風阻提升虛擬實境中瞬間移動的體驗

HeadWind: Enhancing Teleportation Experience in VR by Simulating Air Drag during Rapid Motion

曾雋淼
Chun-Miao Tseng

指導教授：陳彥仰博士
Advisor: Mike Y. Chen, Ph.D.

中華民國 110 年 6 月
June, 2021

doi:10.6342/NTU202103120

國立臺灣大學碩士學位論文
口試委員會審定書

透過模擬臉部風阻提升虛擬實境中瞬間移動的體驗
HeadWind: Enhancing Teleportation Experience in VR by Simulating Air Drag during Rapid Motion

本論文係曾雋淼君（學號 R08944033）在國立臺灣大學資訊網路與多媒體研究所完成之碩士學位論文，於民國一百一十年六月廿八日承下列考試委員審查通過及口試及格，特此證明

口試委員：

陳彥仰 (Jun 28, 2021 13:21 GMT+8)　（簽名）

（指導教授）

蔡欣叡 (Jun 28, 2021 12:20 GMT+8)

鄭龍磻 (Jun 28, 2021 13:11 GMT+8)

所　長：施吉昇

誌謝

感謝指導老師陳彥仰老師在這篇論文的指導，像是原型設計、使用者體驗設計、使用者研究、攝影、影片創意腳本、論文寫作。也耐心地指導我怎麼成為一位 Project Leader，使我在專案進度管理、組員工作分派溝通上有明確的方向。更感謝老師提供了相當好的實驗環境以及設備，才能夠順利的完成這篇論文。

我也非常地感謝這篇論文的共同作者們，感謝柏佑努力的建構我們專案所需的大量 3D 模型。感謝詩芩非常熱心的投入這篇研究，一起共同討論、計算模型、規劃使用者研究並執行。兩位高度的參與讓我很難決定這篇的第二作者。感謝在硬體上、電路上、系統評估、論文寫作、進度管理、各項器具採買等包山包海各種事物提供了非常多的幫忙，卻一直要求不要掛作者的佑威 (但我還是掛了)。感謝雨新及沐恩在論文寫作及潤飾上提供了強而有力的後盾，把我寫的一團垃圾變成一朵朵鮮花。感謝永雯跟柏丞在使用者研究上及開發上的幫助，讓當時忙爆的我可以有點喘息的時間。感謝余能豪老師的論文指導、統計分析的方法。

感謝口試委員鄭龍磻教授、陳炳宇教授、蔡欣叡教授及張永儒教授，提供了很多非常不一樣的觀點，非常寶貴的意見。

最後感謝我的女友詩洳在心理上及各種雜事上的支持，以及總是問我餐券還夠不夠的家人們，沒有你們我肯定無法順利完成學業。

doi:10.6342/NTU202103120

摘要

瞬間移動 (Teleportation) 已成為虛擬實境 (VR) 中最受歡迎的移動方式。使用者透過瞬間移動可以快速、瞬間地移動到指定的位置。它讓使用者能夠快速的在 VR 中定位，並降低暈眩的產生，但其代價是大幅降低的沉浸感。我們研發 HeadWind，透過調整吹到臉上的氣流，模擬瞬間移動時快速穿越空氣的觸覺體驗，以提升沉浸感。我們透過三個形成性使用者實驗以了解：1）在瞬間移動時使用者預期的觸覺體驗，2）在 VR 中瞬間移動方向的範圍，以及 3）使用者偏好的氣流強度以及持續時間。依實驗結果，我們將三個氣動噴頭分別放置在左、中、右夾角各 30 度的位置，以產生來自三個方向的氣流，且氣流的強度及持續時間與瞬間移動的距離成正比。我們完成 24 人的使用者體驗評估，顯示 HeadWind 大幅的提升 VR 中瞬間移動的真實感、沉浸感以及娛樂性 (p<.01)，並獲 96% 受測者的偏好。

關鍵字：瞬間移動，虛擬實境觸覺，空氣阻力，運動知覺

doi:10.6342/NTU202103120

Abstract

Teleportation has become the most popular locomotion technique in virtual reality (VR) in which the user instantly (or rapidly) moves from the current location to the target location. It enables fast navigation with reduced VR sickness at the cost of significantly reduced immersion. To understand users' expectation of haptic experiences during teleportation, we conducted a formative study (n=16) and found that the most expected haptic sensation to be air drag. We present HeadWind, a novel approach to improve the experience of teleportation by simulating the haptic experience of rapidly moving through air. Specifically, HeadWind simulates air drag by modulating bursts of directional airflow to the face. To help design HeadWind, we conducted two additional formative studies to design airflow direction (n=12) and airflow speed and duration (n=24). Informed by these studies, HeadWind uses three air nozzles that are positioned 30-degrees apart to create airflow from 3 directions, with faster air speed and longer duration for farther teleportation distances. We conducted a 24-person user experience evaluation, which showed that HeadWind significantly improved realism, immersion, and enjoyment of teleportation in VR ($p<.01$) with large effect sizes ($r>0.5$), and was preferred by 96% of participants.

Keywords: Teleportation; Virtual Reality Haptic; Air Drag; Motion Perception

doi:10.6342/NTU202103120

Contents

doi:10.6342/NTU202103120

doi:10.6342/NTU202103120

List of Figures

doi:10.6342/NTU202103120

doi:10.6342/NTU202103120

Chapter 1

Introduction

Figure 1.1: (a) Point-and-teleport has become the most popular locomotion technique in VR games; (b) HeadWind uses 3 nozzles to provide directional airflow to simulate air drag when teleporting in different directions; (c) HeadWind modulates bursts of compressed air to simulate air drag (note: the white smoke is added for illustrative purposes only, as actual airflow is invisible); (c) air speed and duration models from the participatory design study showed faster airflow with longer duration for longer teleportation distances.

Locomotion is essential in virtual reality (VR) to allow users to navigate beyond the limited physical tracking space. Although continuous locomotion techniques are commonly used for non-VR experiences, it causes significant cybersickness in VR [7, 9]. Thus, there has been extensive explorations of locomotive techniques to reduce VR sickness [18, 34, 33].

doi:10.6342/NTU202103120

Teleportation is a VR locomotion technique that instantly moves the user from the current location to the destination. The visual field briefly blacks out during teleportation, typically using *eye blink* animation. Teleportation enables fast navigation with low VR sickness [29]; however, it significantly reduces immersion [4, 5] and increases spatial disorientation [2, 5], as the experience does not exist in real life. To improve spatial awareness, the *Dash* technique [3, 28] adds optical flow during teleportation, to provide the visual experience of rapidly moving from the current location to the destination.

Our survey of top VR games shows that most (67%) have chosen teleportation as the default locomotion technique. It is about 4 times as popular as the second most-popular technique, which is continuous locomotion using the trackpad/d-pad on controllers (17%). The survey methodology and detailed results are described in the section VR Locomotion Survey.

In order to understand what haptic feedback enhances the experience of teleportation, we conducted a formative interview study with 16 participants on the types of haptic sensations users expect when using teleportation. Results showed that the most common sensation is wind (41%), followed by acceleration/deceleration (25%), and feet landing (16%). Although participants all used the term ”wind” to describe the experience of air moving relative to them, they were technically describing *air drag* or *air resistance* as it is the user that is moving through still air.

Based on these findings, we present HeadWind, a novel approach to improve the experience of teleportation in VR by simulating the haptic experience of rapidly moving through air. Specifically, HeadWind modulates bursts of compressed air to the face in the opposite direction of teleportation to simulate the sensation of air drag.

In order to design realistic airflow direction, coverage, speed, and duration, we conducted two more formative studies: 1) a teleportation direction study to help understand the range of directional airflow HeadWind needs to support, and 2) a participatory design study to model realistic airflow speed and duration for different teleportation distances.

For the teleportation direction study, we collected teleportation data of 12 players while playing several top VR games. Analysis showed that 90% of teleportation was between

doi:10.6342/NTU202103120

-27° to 27° relative to users' heading. Based on the range of teleportation directions, we explored the design space of nozzle placement and nozzle coverage. We balanced several competing goals of airflow realism, device weight, and system complexity, with a design that uses three nozzles mounted in front of the VR headset at -30°, 0°, and 30°, as shown in Figure 1.1. HeadWind's pneumatic system is inspired by prior compressed air systems, including VaiR [20] and HeadBlaster [13]'s head-mounted nozzles, and JetController's mobile, high-speed pneumatic control system [30].

To model realistic airflow speed and duration for different teleportation distances, we conducted a 16-person participatory design study (n=16), which showed faster air speed and longer duration when teleporting over longer distances. Finally, we evaluated the user experience of HeadWind for both types of teleportation: Blink and Dash through a 24-person study. Compared to visual-audio feedback, HeadWind significantly improved realism, immersion, and enjoyment of teleportation in VR ($p<.01$) with large effect sizes ($r>0.5$), and was preferred by nearly all (96%) participants.

Our key contributions are as follows: 1) proposing the novel use of airflow-based haptic feedback to significantly improve the experience of the most popular VR locomotion technique, 2) designing a light-weight, wearable system that provides realistic haptic experience for teleportation, and 3) modeling of airflow speed and duration vs. teleportation distances.

doi:10.6342/NTU202103120

Chapter 2

Related Work

We discuss how HeadWind relates to and differs from prior approaches to providing haptic feedback for VR locomotion, followed by different approaches to simulating wind and air drag.

2.1 Haptic Feedback for VR Locomotion

2.1.1 VR Teleportation

AoEs [10] provides the haptic experience of changing environmental conditions by using a ceiling mounted, steerable device that simulates the haptic experience of being in hot and cold environments. The device consists of 3 cold modules on one end: mist, rain drop, and wind, and 2 hot modules on the other end: heat and hot air. AoEs enhances the experience of walking through a teleportation portal from a hot environment to a cold environment while users physically walk from the hot-module side of the room to the cold-module side of the room, and vice versa.

While AoEs enhances the before/after experience of *changing environmental conditions* from moving through a teleportation portal, HeadWind enhances the locomotion experience itself, i.e. motion *during* teleportation. Therefore, HeadWind can be used to enhance any VR games and experiences that use teleportation, rather than being limited to only experiences that transition between hot/cold environments. Another difference is

doi:10.6342/NTU202103120

how AoEs uses airflow, in that it simulate environmental wind, whereas HeadWind uses airflow to simulate air drag during teleportation.

2.1.2 Continuous VR Locomotion

Haptic feedback has been used to improve continuous locomotion experience in VR, including reducing VR sickness and improving realism. Weech et al. [31] used bone-conducted transducers for vestibular stimulation during large angular acceleration to effectively reduce VR sickness. PhantomLegs [14] used two servos to alternatingly tap the region in front of the ears in synchrony with footsteps to reduce VR sickness while walking in VR. WalkingVibe [18] improves realism and comfort, as well as reduce VR sickness, for walking in VR by using vibration motors behind the ears to provide vibrotactile feedback that is synchronized with footsteps.

Whereas PhantomLegs and WalkingVibe simulated vibration from footsteps, HeadWind simulates the haptic sensation of air drag. Also, these approaches improve the experience of continuous VR locomotion, which is much less popular than teleportation for VR games.

2.2 Simulating Wind and Air Drag

Wind and air drag are common everyday experiences, and researchers have explored air-based haptic feedback using fans and more recently, compressed air, in wearable and environment mounted form factors.

2.2.1 Wearable: Compressed Air

VaiR [20] is a VR headset-mounted device with 2 servo-controlled arrays of compressed air nozzles, with a total of 10 nozzles. It is designed to be a general-purpose device capable of providing airflow from a wide range of directions spanning the entire head.

HeadWind is inspired by VaiR's approach, and we designed it for a novel use case, haptic feedback for VR teleportation. Through our application-specific design process

doi:10.6342/NTU202103120

and optimization, we significantly reduced the complexity and weight of the system. The weight of the headset-mounted device was reduced by 84% (119 vs. 766 grams), such that it can be worn comfortably for typical VR sessions. As a reference, Oculus Quest 2 weighs 503g and HTC Vive Pro weighs 803g. Moreover, we reduced the weight of the pneumatic system in the backpack by 50% (2.0 vs. 4.0 Kg), further improving portability and usability of the system.

Our main contribution is not the device, but in proposing, designing, and demonstrating a novel use of airflow-based feedback to significantly improve the experience of the most popular VR locomotion technique. We achieved this through a series of formative studies, in addition to a participatory design study to developed the perceptual modeling of air speed and duration for different teleportation distances.

2.2.2 Environment: Compressed Air and Air Vortex

Environment-mounted single air nozzles [27, 21, 25] and nozzle arrays [24, 23] have been used to provide tactile feedback, such as touching virtual objects. This approach eliminates the need for devices to be placed on users. However, the latency for air to travel from the nozzle to the user is too slow for teleportation, in addition to severely constraining the play area size. For example, the typical jogging speed is 8Km/hr, which is equivalent to light breeze on the Beaufort wind scale [8]. To simulate such air drag, it would take 225ms for the air leaving the nozzle to reach the user over a distance of 50cm, which is the experimental setup used by AIREAL [21]. This latency exceeds the duration of teleportation, which ranges between 80-180ms in top VR games, such that the air will arrive after the end of teleportation.

2.2.3 Fans and Propellers

Wearable [6, 19, 32] and environment-mounted fans [16, 12] have been used to simulate wind from the environment. Because of the need to physically spin up propellers, which takes 300ms or longer [11], the latency of this approach is too slow for teleportation. In addition, the wearable weight of fans added to the HMD is significantly heavier than

doi:10.6342/NTU202103120

compressed air approach. For example, HMWind [6] uses a multi-fan design that weights about one kilogram. FaceHaptics [32] uses a single fan mounted on a robotic-arm, which weights 405 grams with a weight-bag of 654 grams attached to the back of the HMD to counterbalance, resulting in also over one kilogram of weight. In contrast, HeadWind's HMD weight is much more practical and comfortable at 119 grams.

doi:10.6342/NTU202103120

Chapter 3

VR Locomotion and Teleportation Surveys

3.1 VR Locomotion Survey

To understand the popularity of locomotion techniques in today's VR experiences, we surveyed top VR games to see which techniques they support and which are set as the default. We surveyed the VR game recommendation lists from 9 popular gaming and technology news sites[1], then ranked the games by popularity in terms of the number of publications that recommended it. Overall, 22 games were recommended by four or more publications[2], of which 12 games have locomotion.

Figure 3.1 shows the summary of locomotion techniques in use by these top VR games with locomotion. Teleportation (67%) is by far the most popular default technique, being 4 times as popular as the second-place technique, joystick/trackpad-based continuous locomotion (17%).

In terms of supported techniques, as many games support multiple locomotion modes, both teleportation and joystick/trackpad are the most popular (67%). Moreover, 50% of

[1]PC Gamer, GamesRadar, PCGamesN, Tom's Guide, CNET, TechRadar, PCMag, Digital Trends, and Popular Mechanics, as retrieved on July 10, 2020.

[2]Beat Saber, Half-Life: Alyx, Superhot VR, Keep Talking And Nobody Explodes, Moss, Tetris Effect, No Man's Sky VR, Eve: Valkyrie, Rez Infinite, Star Trek: Bridge Crew, The Elder Scrolls V: Skyrim VR, Fallout 4 VR, Resident Evil 7: Biohazard, Space Pirate Trainer, L.A. Noire: The VR Case Files, Thumper, Batman: Arkham VR, Minecraft VR/Minecraft: Gear VR Edition, Robo Recall, The Climb, Arizona Sunshine, and I Expect You To Die.

doi:10.6342/NTU202103120

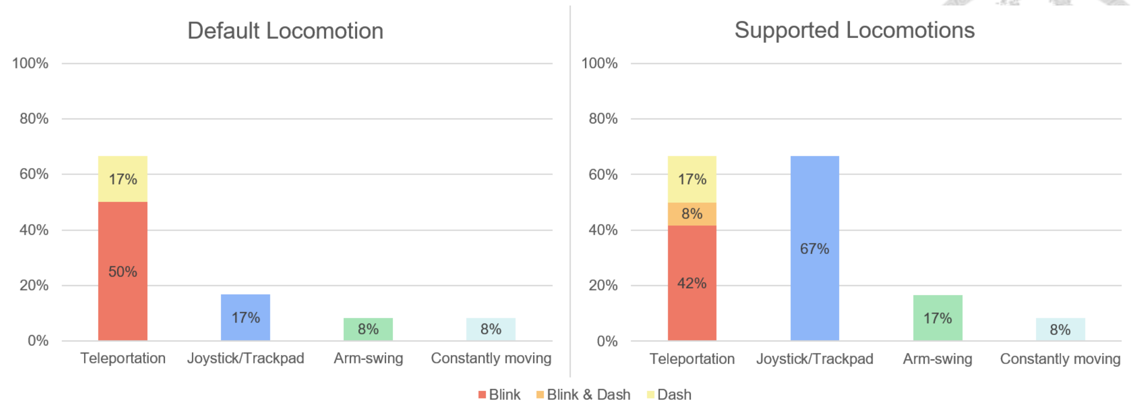


Figure 3.1: Locomotion techniques used in top VR games. Teleportation, in both Blink and Dash modes, is the default locomotion technique by majority of games at 67%, which is 4 times as popular as joystick/trackpad-based continuous locomotion (17%). Many games support multiple techniques, with teleportation and joystick/trackpad being the most popular. For games that support both of these techniques, all chose teleportation as its default technique.

games support both techniques, and all of them have chosen teleportation as the default technique over joystick/trackpad.

3.2 Haptic Expectations for Teleportation

To understand what types of haptic feedback users expect during VR teleportation, we conducted a formative study using semi-structured interviews with 16 users (age 20-59, mean=24.7, SD=12.8, 10 male, 6 female). We asked participants to play Half-Life: Alyx, which is the all-time highest-rated VR game according to the most popular game rating aggregator Metacritic [15]. Participants played the game using both Blink and Dash teleportation modes in counter-balanced ordering, followed by semi-structured interviews. We grouped the interview responses into the following 4 types of haptic feedback: 1) wind (air drag), 2) acceleration/deceleration, 3) feet landing, and 4) heat. While participants all used the term ”wind” to describe the sensation of air moving relative to them, they were actually describing *air drag* (or *air resistance*) as it is the player that is moving relative to air that is stationary.

As shown in Table 3.1, the most common haptic expectation is the sensation of wind (41%), followed by acceleration/deceleration (25%), and feet landing on the ground (16%).

doi:10.6342/NTU202103120

	Wind (Air Drag)	Acceleration/Deceleration	Feet Landing	Heat
Blink	38%	19%	25%	0%
Dash	44%	32%	6.3%	6.3%

Table 3.1: Types of expected haptic sensations for Blink and Dash teleportation modes.

Motivated by these findings, we focused on designing airflow haptic experience to enhance the VR teleportation experience.

doi:10.6342/NTU202103120

Chapter 4

Designing Air Drag Feedback for Teleportation

Being the first work to design air drag feedback for teleportation, we detail the iterative design process we took to explore the design space of airflow direction and airflow coverage.

4.1 Direction of Teleportation and Airflow

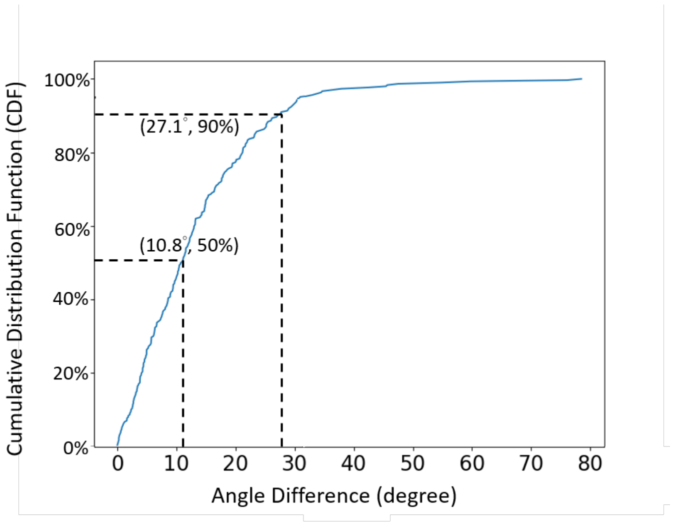


Figure 4.1: Cumulative distribution function (CDF) of the angles between the heading of the HMD and the teleportation directions from the formative study. Results show that 50% of teleportation were within 10.8° of the heading of HMD, and that 90% were within 27.1°.

doi:10.6342/NTU202103120

When teleporting, users first point at the target destination, then move there by initiating teleportation. While the pointing phase can be accomplished using any pointing technique, such as gaze, head, and controller, all the top VR games we surveyed used controller-based pointing followed by pressing a controller button to initiate teleportation. To help users visualize and confirm the target destination and direction of teleportation, trajectory visualization and destination highlighting are typically used, as shown in Figure 1.1 (a).

When using controller pointing, users are free to move their gaze and head independently from the direction of the controllers, which result in a delta angle between users' heading and the direction of teleportation. This means that the directional air drag should be perceived as coming from that delta angle relative to users' faces.

In order to understand the range of airflow direction we need to simulate, we conducted a formative user study (n=12) to collect and analyze the teleportation delta angles during actual VR usage. We recruited 12 participants to play 3 highly-rated VR games: Half-Life: Alyx, No Man's Sky, and The Elder Scrolls V: Skyrim VR, for a minimum of 5 minutes each game, and recorded the delta angles between teleportation vs. users' HMD heading using OpenVR API [22]. Overall, we recorded a total of 3014 teleportations. After normalization across users and games, results showed that 50% of all teleportation were within 10.8°of the heading of the HMD and 90% were within 27.1°. The cumulative distribution function (CDF) of the angles is shown in Figure 4.1.

Prior studies on human's ability to identify directions of wind on the face have found that the absolute pointing error, without any visual redirection, averaged 14.5° [32]. These results suggest that a range of airflow of -13.6°-13.6°would be needed to support typical VR teleportation usage.

4.2 Airflow Coverage and Nozzle Blowing Angle

During rapid motion, air drag is primarily perceived through exposed skin surface, including face, neck, and hands. Wearable airflow feedback systems have focused on providing feedback to the face, in order to balance user experience and system weight and complex-

doi:10.6342/NTU202103120

ity. For HeadWind, we also focus on the face, and our goal is to design air nozzles and nozzle layout that expand the coverage area of the face while supporting directional cues for teleportation.

There are user experience tradeoffs between nozzle distance from the face, coverage area size, weight/torque on the head, airflow latency, and interference with hand movement. As we move the nozzle farther from the face, the coverage area increases, but the weight, torque, and airflow latency would increase, in addition to increased interference with users' hands when performing gestures and using controllers. Based on VR ergonomics guidelines [17], the comfortable hand gesture and controller distance from the body is the length of elbow and hand. To minimize interference, our goal for the nozzle distance is to be less than the length of the elbow, which range 27-30cm based on anthropometry studies [1].

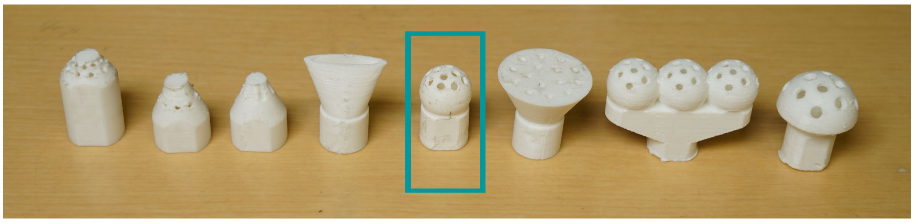


Figure 4.2: A variety of nozzle designs we explored and evaluated to maximize airflow coverage and uniformity.

To maximize blowing coverage area, we first surveyed the two nozzles used by Head-Blaster [13] and also air nozzles by two well-known nozzle manufacturers, Silvent and EXAIR. For nozzles suitable for wearable systems, the widest blowing coverage we found was a circular blowing angle of 22° (approx. 8cm diameter at 20cm distance), as these off-the-shelf nozzles are designed to focus air jets to improve air efficiency for manufacturing and factory automation. We also acquired and tested wide-angle nozzles designed for water, but they do not work well for air as their viscosity differ by 50 times. After consulting experts in fluid dynamics, we designed and 3D-printed 8 nozzle designs, as shown in Figure 4.2. We measured the blowing angle and air uniformity across the coverage area using an anemometer, and selected the design with 48 °blowing angle (approx. 18cm diameter at 20cm distance), which is 2.2x in blowing angle and 4.8x in blowing area.

doi:10.6342/NTU202103120

4.3 Nozzle Layout

To provide airflow for different teleportation directions, we explored multiple nozzle layout designs. The user experience tradeoffs include coverage area size, range of airflow directions, and weight/torque on the head.

To explore the designs space, we designed a flexible nozzle mounting platform with 9 nozzle mounts at 15° intervals with adjustable distance to the face and nozzle angles, as shown in Figure 4.3. We asked 3 haptic designers to explore layout designs with 3, 5, 7 nozzles at various angles and distance. After experiencing the haptic feedback for various configurations while teleporting in VR, all 3 designers recommended the layout with 3 nozzles at 30° apart, which achieved a good balance between sense of direction, coverage, and weight/torque. The 3-nozzle layout is shown in Figure 4.4, with a center nozzle directly in front of the face and left/right nozzles at -30° and +30° heading, respectively.

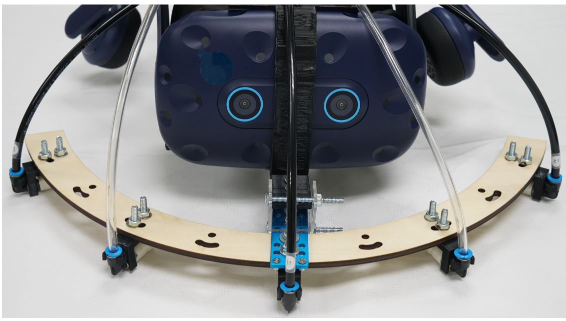


Figure 4.3: Nozzle platform with adjustable nozzle distance and angles used in our design process to explore difference layout designs.

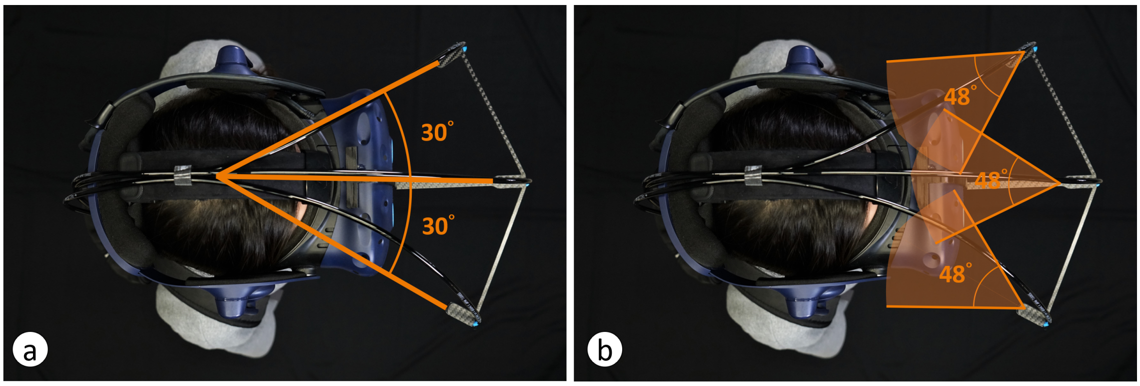


Figure 4.4: HeadWind's nozzle layout and airflow coverage: (a) 3 nozzles at 0°, -30°, and 30° heading, (b) each nozzle has a 48°blowing angle, and multiple nozzles are actuated together to further expand the coverage area.

doi:10.6342/NTU202103120

Even with the wide-angle nozzles, the designers still found the coverage area to be too limited and suggested actuating multiple air nozzles at the same time. Specifically, actuating all 3 nozzles together when teleporting in front of the user, and actuating the center nozzle and a side nozzle together when teleporting off to the side. We implemented +-15° teleportation angle as the threshold to determine whether to actuate all 3 nozzles vs. center+left or center-right nozzles. We invited the designers back for a another design session, and all reported that the multi-nozzle design improved the teleportation experience.

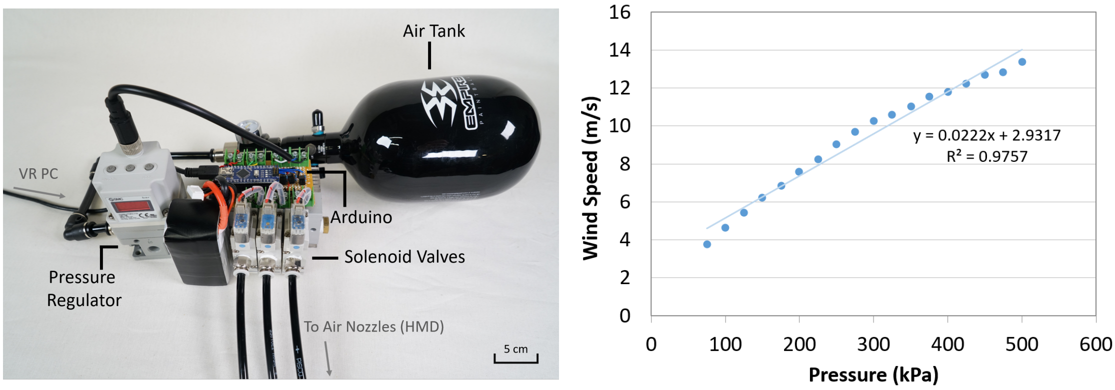
doi:10.6342/NTU202103120

Chapter 5

Implementation and System Validation

5.1 Pneumatic Control System

To achieve fast response time and light weight, we combined JetController's high-speed circuitry [30] with the light-weight solenoid valves used by HeadBlaster [13] to reduce the entire system weight to 2Kg. As shown in Figure 5.1a, our system controls airflow speed using a high-speed electro-pneumatic pressure regulator (SMC ITV2050) and modulates airflow duration using three solenoid valves (SMC SYJ712) connected to the 3 nozzles. The entire control system fits inside a small backpack. The pressure regulator use 0-10V control signal for output pressure of 5-900kPa, which is supplied via a PWM-voltage converter controlled by Arduino Nano using 255 PWM steps.



(a) (b)

Figure 5.1: (a) HeadWind's pneumatic control system with a high-pressure air tank, showing the high-speed pressure regulator and three solenoid valves controlled via Arduino. (b) Experimental measurements of airflow speed vs. air pressure.

doi:10.6342/NTU202103120

5.2 Nozzle Mount

Our goal for the HMD nozzle mounts is to achieve high structural strength while minimizing weight. We iterated through several nozzle mount designs with materials ranging from acrylic, wood, PLA, and carbon fiber that were created using laser cutting, 3D printing, and CNC machining. We found that 2mm carbon fiber plate custom cut via CNC machining had the highest structural strength and torsional rigidity with the lightest weight. We then attached the carbon fiber plate to a 3D-printed mount that clips onto the front of a VR headset. Three sets of custom 3D-printed nozzles and mounts are attached to the nozzle platform, as shown in Figure 1.1b. The nozzles connect to the pneumatic system in the backpack via 6mm tubing of 1 meter in length. The entire head-mounted portion of HeadWind, including tubing, weights 119 grams, which is about 12-24% of the weight of a VR headset, e.g. HTC Vive Pro: 955g (including a 129g wireless adapter) and Oculus Quest 2: 503g.

5.3 System Validation

5.3.1 Airflow Speed

To measure the airflow speed reaching users' faces, we set up a Testo 405i anemometer at the same distance as the face from the nozzle. We varied air pressure from 75-500 kPa with a step size of 25 kPa, and measurements showed strong linear correlation ($R^2 = 0.9757$) with air speed, as shown in Figure 5.1b. The air speed ranged from 3.8-13.7 m/s, and are considered as ”gentle breeze” to ”strong breeze” on the Beaufort wind scale [8].

5.3.2 Actuation Latency

Actuation latency is the time between Arduino receiving a command to the time that compressed air actually leaves the nozzle. We used a high-speed 960fps camera to record the time that Arduino turns on an LED, which has an extremely low turn-on time in microseconds, to the time that a small piece of paper in front of the nozzle moves. Visual analysis of

doi:10.6342/NTU202103120

the recorded frames over 10 trials showed an average of 28 frames, or 29ms, of actuation latency.

doi:10.6342/NTU202103120

Chapter 6

Modeling Realistic Airflow Speed and Duration

To model airflow speed and duration for teleportation, we conducted a 16-person user study using participatory design methodology and also collected qualitative feedback.

6.1 Study Procedure

Participants first became familiar with the HTC Vive Pro VR headset, controllers, HeadWind device, and teleportation in VR. To ensure that participant have experienced different airflow speed and duration, we selected 2 settings for each parameter: slow vs. fast speed and short vs. long duration, and had participants experience the 4 combinations of them, before asking the participants to freely explore different parameter settings. For ease of parameter adjustment, participants held an Xbox One controller in their dominant hand, and used the up/down buttons to adjust airflow speed and the left/right buttons to adjust the airflow duration.

Participants were then asked to design the most realistic airflow experience for short vs. long teleportation distances: 0.5m and 4.5m, for both teleportation modes: Blink and Dash, in counter-balanced ordering. For each distance, participants were able to teleport and experience the haptic feedback for as many times as needed. After designing the parameters for the two distances, participants then teleported freely to experienced the

doi:10.6342/NTU202103120

haptic feedback for the two distances, and were able to make adjustments until they were satisfied with the parameter settings.

6.1.1 VR Scene

We used Half-Life: Alyx as our VR scene for the participatory design study as it supports both Blink and Dash teleportation modes. To help participants focus on the haptic experience without getting distracted by other game characters, we used HL:A's Workshop Tools to create an area outside of the regular gameplay. The open area allowed participants to freely teleport in any direction.

Teleportation in HL:A uses the standard point-and-teleport interaction, which consists of the following 3 phases: 1) press the controller touchpad to display a trajectory showing the destination, 2) aim the controller to adjust the destination, and 3) release the touchpad to initiate teleportation. To track the teleportation direction, distances, and heading that are necessary for haptic feedback, we implemented game mods which are supported by Half-Life: Alyx to monitor player's position and heading, and used OpenVR [22] to monitor the VR headset and controller's orientation and status.

6.1.2 System Setup

We used an air compressor to eliminate the possibility of needing to re-fill portable air tanks during the studies. To minimize the effects of noise from the air jets and the compressor, we used the same mitigation method as HeadBlaster [13], and had participants wear an active noise-canceling headphone playing white noise in the background so that the noise is not noticeable.

6.1.3 Participants

We recruited 16 participants (7 male, 9 female, age 20-34, mean=23.3, SD=3.2) with a wide range of VR experiences: 1 without any VR experience, 4 experienced VR once a year, 4 several times a year, 1 once a month, and 6 several times a month.

doi:10.6342/NTU202103120

6.2 Airflow Modeling Results

The speed and duration of airflow vs. teleportation distances are shown in Figure 6.1 for both teleportation modes. The three colored arrows show the 25th-, 50th-, and 75th-percentile of settings across all participants, with the non-pointy end showing the speed and duration values for the shorter distance, and the pointy end showing the settings for the longer teleportation distance. Each thinner, grey arrow corresponds to the speed and duration settings designed by a single participant.

Overall, speed and duration both increase with teleportation distance for both teleportation modes, as visualized by the results of the 3 quartile lines all pointing to the upper right. However, there were a wide range of settings chosen across all participants, meaning that a general model may differ from a few participants' personal models. To mitigate this effect, we recommend that participants be allowed to experience and select from one of the three quartile settings, similar to how games and motion platforms support customization of motion levels, volume of background music, and sound effects.

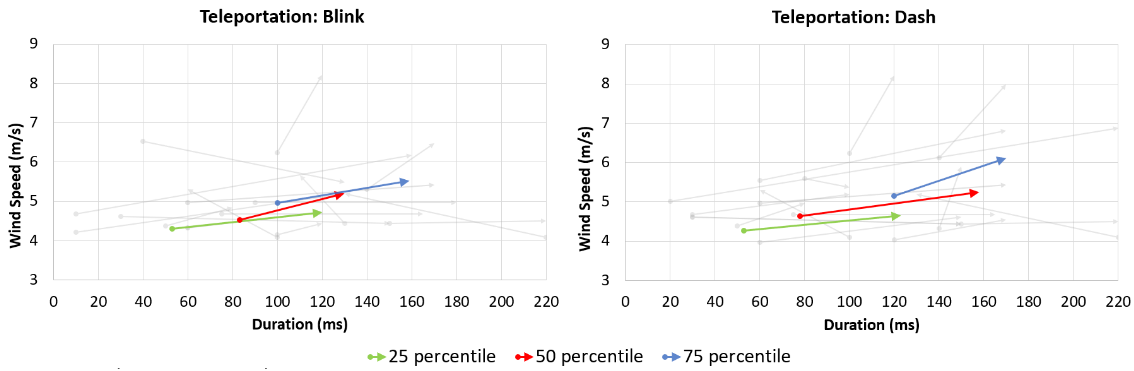


Figure 6.1: Airflow speed and duration vs. teleportation distances for both teleportation modes. The three bolded, arrowed lines show the 25th-, 50th-, and 75th-percentile of settings across all participants. The origin end of a line shows the speed/duration for the short teleportation distance, and the arrowed end shows the speed/duration for the long teleportation distance. Each thinner arrowed line corresponds to the speed and duration settings designed by a single participant.

doi:10.6342/NTU202103120

6.3 Qualitative Feedback

Participants commented on their thought process when designing the haptic experience and how they felt about the feedback: ”teleportation is like running through the air in a flash, so duration should increase as distances increase” (P5). For the Dash mode, participants designed the settings ”based on my real-life running experience” (P3, P15). For the Blink mode, ”the wind provides a hint to remind me that I have completed the task” (P4).

doi:10.6342/NTU202103120

Chapter 7

User Experience Evaluation

To understand how HeadWind affects the user experience of teleportation, we conducted a user study and compared HeadWind to the standard VR experience (ie. visual and audio feedback) using within-subject study design.

7.1 VR Scenes

We initially experimented with using Half-Life: Alyx as the VR experience, but found that it was difficult to find two similar stages and to control the VR experience to be consistent across users, due to computer controlled non-player characters (NPC) and game AI. To ensure a consistent experience across conditions and users, we developed a VR game using Unity 3D that provided the same teleportation experience as Half-Life: Alyx. It supports both Blink and Dash teleportation modes, and uses the same controller interaction, scaling, and teleportation distances. Screenshots of VR scenes and visual cues for teleportation interaction are shown in Figure 1.1. Players were tasked to navigate to randomly generated target zones to earn points.

7.2 Participants

In order to reduce priming effects across the two teleportation modes, each participant only experienced one of the two modes. Therefore, we recruited a total of 24 participants and

doi:10.6342/NTU202103120

randomly assigned 12 to Blink mode and 12 to Dash mode. We recruited 24 participants (15 male, 9 female, age 20-25, mean=22.8, SD=1.3) with a wide range of VR experiences: 2 without any VR experience, 10 experienced VR once a year, 2 several times a year, 5 once a month, and 5 several times a month.

7.3 Study Procedure

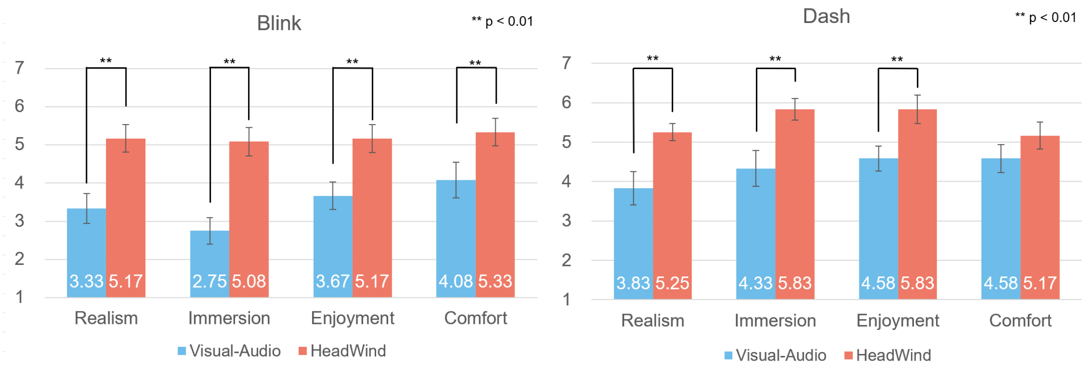
The study used a with-in subject design to compare HeadWind vs. the standard VR visual-audio experience. Each participant would experience one of the two teleportation modes, with and without HeadWind in counter-balanced ordering. At the beginning of the session, participants first practiced teleportation to become familiar with the VR setup. Participants then experienced the three airflow speed and duration settings from the participatory design study (ie. the 25th-, 50th-, and 75th-percentile settings), and selected their most preferred setting. After completing a condition, participants were asked to rate the realism, immersion, enjoyment, and comfort of the teleportation experience using 7-point Likert scale. At the end of study, participants reported their preference and provided qualitative feedback.

7.4 Results

Overall, participants rated HeadWind to have higher realism, immersion, enjoyment, and comfort vs. the standard VR visual and audio feedback, as shown in Figure 7.1. Wilcoxon signed-rank analysis showed that HeadWind significantly improved realism, immersion, and enjoyment for both Blink and Dash teleportation modes ($p<.01$ for all), and significant improved comfort for the Blink mode ($p<.01$). In addition, the effect sizes were large ($r>0.5$) for all metrics that were statistically significant. The exact results were, Blink: realism ($p=0.003$, $r=0.568$), immersion ($p=0.002$,$r=0.586$), enjoyment ($p=0.002$,$r=0.579$) and comfort ($p=0.003$,$r=0.555$); Dash: realism ($p=0.002$,$r=0.587$), immersion ($p=0.002$,$r=0.586$), and enjoyment ($p=0.003$,$r=0.554$).

Participants also significantly preferred HeadWind for both Blink and Dash teleporta-

doi:10.6342/NTU202103120



(a) (b)

Figure 7.1: Average rating of realism, immersion, enjoyment and comfort on a 7-point Likert-Scale from 2 kinds of teleportation approaches using 1) visual-audio, 2) HeadWind. (a) HeadWind significantly improved realism, immersion, enjoyment and comfort in Blink (p<.01). (b) HeadWind significantly improved realism, immersion and enjoyment in Dash (p<.01).

tion modes (p<.01), as shown in Figure 7.2. All participants preferred HeadWind in Blink mode and 92% of participants preferred HeadWind in Dash mode.

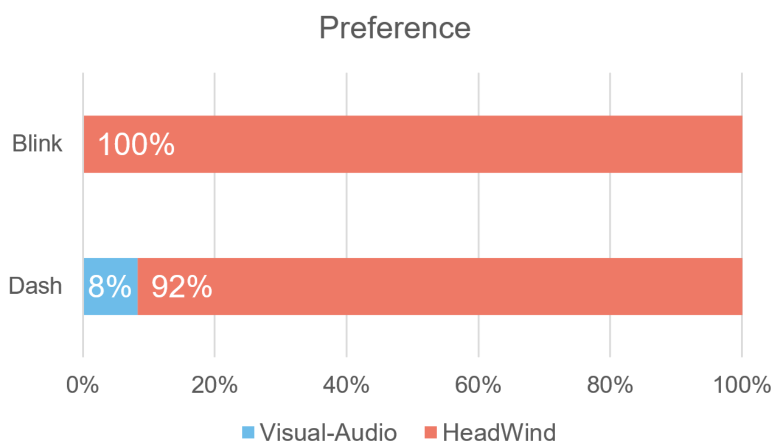


Figure 7.2: Preference ranking between HeadWind vs. visual-audio feedback for Blink and Dash teleportation modes.

7.4.1 Qualitative Feedback

Participants were overall positive about the airflow feedback, and commented that it was ”entertaining and realistic” (P6, P11), ”comfortable” (P1, P3, P7, P11), and ”matched my expectations” (P1, P17, P19). In terms of improvement opportunities, some participants commented that ”the difference between different wind direction was too subtle” (P19,

doi:10.6342/NTU202103120

P24). In addition, the only participant that did not prefer HeadWind commented that ”I expected the wind to cover the entire head and the direction of all wind to be parallel when moving forward” (P23). These are related to the need of using multiple nozzles to achieve wider coverage area. To address these without adding significant weight to the headset and pneumatic system, nozzles with much wider blowing angle would need to be developed. Also, participants reported that ”the air setting I chose at the beginning was too strong during the later, extended gameplay” (P15), suggesting that players' preferred settings may change based on playing duration and we should support setting adjustment at any time.

doi:10.6342/NTU202103120

Chapter 8

Discussion, Limitations, and Future work

8.1 Extended and Long-term Usage

While no participant reported discomfort, one participant asked about the effects of using HeadWind for extended gaming sessions and whether it would lead to dry skin. To assess the effect of airflow for extended sessions, say several hours, we discuss HeadWind's airflow speeds in the context of real world experiences.

HeadWind's medium air speed is 4.7m/s and 4.8m/s for Blink and Dash modes, which is slower than the 5.8m/s (21km/hr) average speed of bicycling [26]. On the Beaufort wind scale [8], HeadWind is categorized as between "Gentle breeze" and "Moderate breeze".

Furthermore, the duty cycle of HeadWind's airflow is extremely low. To estimate the airflow exposure during gameplay, we recruited 9 people to complete the first of six chapters of Half-Life: Alyx, and observed an average of 692 teleportations per hour. Therefore, HeadWind would have a total cumulative duration of 1.2 minutes of airflow exposure for one hour of playing Half-Life: Alyx. In summary, the effects of using HeadWind for one hour is likely comparable to cycling or being in a breezy outdoor environment for a few minutes.

doi:10.6342/NTU202103120

8.2 Air Tank and Battery Life

The air tank HeadWind currently uses is a 4500psi tank designed for paintball, and has a capacity of 0.78 liter at a weight of 709g. Our measurements show that it can support 1100 teleportations at the median airflow speed and duration, which is about 1.6 hours of playing Half-Life: Alyx.

For longer gaming sessions, there are several approaches to extend the gameplay. First, the airflow speed and duration can be reduced (e.g. from 50th-% to 25th-%), similar to how notebooks throttle CPU/GPU while on battery. Second, air tanks can be swapped, similar to paintball. Third, larger air tanks are readily available in a wide range of capacities (e.g. air tank with 2x capacity is 453g heavier). Fourth, if the player is already tethered to a PC, then using air compressor via longer tubing may be an option to support unlimited gameplay, which has the additional benefit of eliminating the weight the portable air tank.

In terms of battery life, the solenoid valves and the pressure regulator are powered by a 24V 650mAh rechargeable Li-Po battery that weighs 115 grams. Using an 1000Hz ampere meter, we measured the current of the pneumatic system to be 0.04A during standby and 0.08A during airflow. Based on the teleportation frequency and airflow duration for Half-Life: Alyx, we estimate that a 650mAh battery can support 16 hours of gameplay.

8.3 Comfort and VR Sickness

VR sickness, or cybersickness, occurs when human brain receives conflicting sensory signals between virtual scenes and body movement. Because teleportation already has low VR sickness, we did not expect significant improvement in comfort. However, participants not only reported higher comfort ratings for HeadWind for both modes, the improvement was statistically significant ($p<.01$) for Blink mode. Participants commented that the improvement in comfort was less significant for Dash mode, because Dash mode was more comfortable than Blink mode, as reflected in its higher comfort rating (4.58 vs. 4.08).

To further enhance the experience of teleportation, we are exploring way to support

doi:10.6342/NTU202103120

the second-most requested sensation, acceleration/deceleration. Such haptic feedback provides vestibular stimulation, which has the potential to reduce VR sickness. We are currently exploring designs that supports both motion simulation and air drag simulation.

doi:10.6342/NTU202103120

Chapter 9

Conclusion

We have proposed, designed, and evaluated a novel use of airflow-based haptic feedback to significantly improve the experience of the most popular VR gaming locomotion technique, teleportation. Our motivation and design exploration were based on surveys and several formative user studies with a total of more than 50 participants. User experience evaluation ($n=24$) showed that HeadWind significantly improved realism, immersion, and enjoyment of teleportation in VR ($p<.01$) with large effect sizes ($r>0.5$), and was preferred by nearly all participants.

doi:10.6342/NTU202103120

Bibliography

[1] Anthropometry. Chapter 2-definition and applicability of anthropometric data. [Online; accessed 26-July-2021].

[2] N. H. Bakker, P. O. Passenier, and P. J. Werkhoven. Effects of head-slaved navigation and the use of teleports on spatial orientation in virtual environments. *Human Factors*, 45(1):160–169, 2003. PMID: 12916588.

[3] J. Bhandari, P. MacNeilage, and E. Folmer. Teleportation without spatial disorientation using optical flow cues. In *Proceedings of the 44th Graphics Interface Conference*, GI '18, page 162–167, Waterloo, CAN, 2018. Canadian Human-Computer Communications Society.

[4] C. Boletsis and J. E. Cedergren. Vr locomotion in the new era of virtual reality: An empirical comparison of prevalent techniques. *Advances in Human-Computer Interaction*, 2019:7420781, Apr 2019.

[5] D. A. Bowman, D. Koller, and L. F. Hodges. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of the 1997 Virtual Reality Annual International Symposium (VRAIS '97)*, VRAIS '97, page 45, USA, 1997. IEEE Computer Society.

[6] S. Cardin, D. Thalmann, and F. Vexo. Head mounted wind. In *In proceeding of the 20th annual conference on Computer Animation and Social Agents (CASA2007)*, pages 101–108, 2007.

doi:10.6342/NTU202103120

[7] P. Caserman, A. Garcia-Agundez, A. Gámez Zerban, and S. Göbel. Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. *Virtual Reality*, Apr 2021.

[8] N. S. P. Center. Beaufort wind scale, 2021.

[9] J. Clifton and S. Palmisano. Effects of steering locomotion and teleporting on cybersickness and presence in hmd-based virtual reality. *Virtual Reality*, 24(3):453–468, Sep 2020.

[10] P.-H. Han, C.-E. Hsieh, Y.-S. Chen, J.-C. Hsiao, K.-C. Lee, S.-F. Ko, K.-W. Chen, C.-H. Chou, and Y.-P. Hung. Aoes: Enhancing teleportation experience in immersive environment with mid-air haptics. In *ACM SIGGRAPH 2017 Emerging Technologies*, SIGGRAPH '17, New York, NY, USA, 2017. Association for Computing Machinery.

[11] S. Heo, C. Chung, G. Lee, and D. Wigdor. *Thor's Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force*, page 1–11. Association for Computing Machinery, New York, NY, USA, 2018.

[12] K. Ito, Y. Ban, and S. Warisawa. Alteredwind: Manipulating perceived direction of the wind by cross-modal presentation of visual, audio and wind stimuli. In *SIGGRAPH Asia 2019 Emerging Technologies*, SA '19, page 3–4, New York, NY, USA, 2019. Association for Computing Machinery.

[13] S.-H. Liu, P.-C. Yen, Y.-H. Mao, Y.-H. Lin, E. Chandra, and M. Y. Chen. Headblaster: A wearable approach to simulating motion perception using head-mounted air propulsion jets. *ACM Trans. Graph.*, 39(4), jul 2020.

[14] S.-H. Liu, N.-H. Yu, L. Chan, Y.-H. Peng, W.-Z. Sun, and M. Y. Chen. Phantomlegs: Reducing virtual reality sickness using head-worn haptic devices. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 817–826, 2019.

[15] MetaCritic. Best all-time pc video games - metacritic, 2020.

doi:10.6342/NTU202103120

[16] T. Moon and G. J. Kim. Design and evaluation of a wind display for virtual reality. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, VRST '04, page 122–128, New York, NY, USA, 2004. Association for Computing Machinery.

[17] Oculus. User interface components, 2021.

[18] Y.-H. Peng, C. Yu, S.-H. Liu, C.-W. Wang, P. Taele, N.-H. Yu, and M. Y. Chen. Walkingvibe: Reducing virtual reality sickness and improving realism while walking in vr using unobtrusive head-mounted vibrotactile feedback. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–12, New York, NY, USA, 2020. Association for Computing Machinery.

[19] N. Ranasinghe, P. Jain, S. Karwita, D. Tolley, and E. Y.-L. Do. *Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions*, page 1731–1742. Association for Computing Machinery, New York, NY, USA, 2017.

[20] M. Rietzler, K. Plaumann, T. Kränzle, M. Erath, A. Stahl, and E. Rukzio. Vair: Simulating 3d airflows in virtual reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, page 5669–5677, New York, NY, USA, 2017. Association for Computing Machinery.

[21] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr. Aireal: Interactive tactile experiences in free air. *ACM Trans. Graph.*, 32(4), July 2013.

[22] V. Software. Open vr sdk, 2021.

[23] Y. Suzuki and M. Kobayashi. Arrayed air jet based haptic display: Implementing an untethered interface. In *Adjunct Proceedings of the 16th annual ACM Symposium on User Interface Software and*, pages 1–2, 2003.

[24] Y. Suzuki and M. Kobayashi. Air jet driven force feedback in virtual reality. *IEEE Computer Graphics and Applications*, 25(1):44–47, 2005.

doi:10.6342/NTU202103120

[25] Y. Suzuki, M. Kobayashi, and S. Ishibashi. Design of force feedback utilizing air pressure toward untethered human interface. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '02, page 808–809, New York, NY, USA, 2002. Association for Computing Machinery.

[26] C. o. C. Traffic Department. Bicycle statistics, 2013.

[27] M. Y. Tsalamlal, P. Issartel, N. Ouarti, and M. Ammi. Hair: Haptic feedback with a mobile air jet. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 2699–2706, 2014.

[28] Valve. Half-life: Alyx - locomotion deep dive, 2020.

[29] S. Vlahović, M. Suznjevic, and L. S. Kapov. Subjective assessment of different locomotion techniques in virtual reality environments. In *2018 Tenth International Conference on Quality of Multimedia Experience (QoMEX)*, pages 1–3, Cagliari, Italy, 2018. IEEE.

[30] Y.-W. Wang, Y.-H. Lin, P.-S. Ku, Y. Miyatake, Y.-H. Mao, P. Y. Chen, C.-M. Tseng, and M. Y. Chen. *JetController: High-Speed Ungrounded 3-DoF Force Feedback Controllers Using Air Propulsion Jets*. Association for Computing Machinery, New York, NY, USA, 2021.

[31] S. Weech, J. Moon, and N. F. Troje. Influence of bone-conducted vibration on simulator sickness in virtual reality. *PLOS ONE*, 13(3):1–21, 03 2018.

[32] A. Wilberz, D. Leschtschow, C. Trepkowski, J. Maiero, E. Kruijff, and B. Riecke. Facehaptics: Robot arm based versatile facial haptics for immersive environments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–14, New York, NY, USA, 2020. Association for Computing Machinery.

[33] D. Wolf, K. Rogers, C. Kunder, and E. Rukzio. Jumpvr: Jump-based locomotion augmentation for virtual reality. In *Proceedings of the 2020 CHI Conference on*

doi:10.6342/NTU202103120

Human Factors in Computing Systems, CHI ’20, page 1–12, New York, NY, USA, 2020. Association for Computing Machinery.

[34] D. Yi, K. Chang, Y. Tai, I. Chen, and Y. Hung. Elastic-move: Passive force feedback devices for virtual reality locomotion. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 766–767, Atlanta, GA, USA, March 2020. IEEE.

doi:10.6342/NTU202103120