JumpVR: Jump-Based Locomotion Augmentation for Virtual Reality

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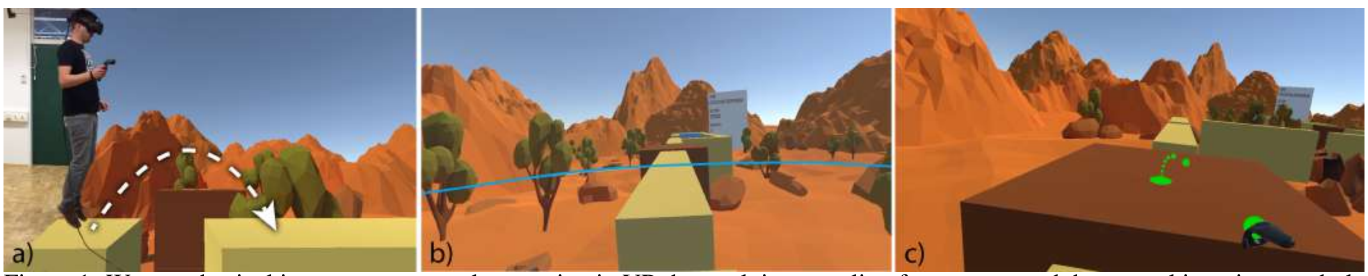

Figure 1: We use physical jumps to augment locomotion in VR, by applying a scaling factor to extend the natural jumping parabola by forward motion (a). The range of the previous jump is indicated to users by a radius indicator (b). We compared this scaled jumping to a teleportation baseline (c).

ABSTRACT

One of the great benefits of virtual reality (VR) is the implementation of features that go beyond realism. Common "unrealistic" locomotion techniques (like teleportation) can avoid spatial limitation of tracking, but minimize potential benefits of more realistic techniques (e.g., walking). As an alternative that combines realistic physical movement with hyper-realistic virtual outcome, we present *JumpVR*, a jump-based locomotion augmentation technique that virtually scales users' physical jumps. In a user study (N=28), we show that jumping in VR (regardless of scaling) can significantly increase presence, motivation and immersion compared to teleportation, while largely not increasing simulator sickness. Further, participants reported higher immersion and motivation for most scaled jumping variants than forward-jumping. Our work shows the feasibility and benefits of jumping in VR and explores suitable parameters for its hyper-realistic scaling. We discuss design implications for VR experiences and research.

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VR; virtual reality; jumping; super human; immersion; hyper realism.

CCS Concepts

•**Human-centered computing** → **Interaction techniques;** *Empirical studies in HCI;*

INTRODUCTION

Modern virtual reality (VR) provides an environment with theoretically unlimited possibilities. We can assume different roles, gain new abilities and explore fictional worlds, in a technologically and emotionally immersive world overlaid on top of real life. While a large body of research focuses on achieving increasingly "realistic" experiences in VR such as feeling haptic feedback when touching virtual walls [4], getting hit by objects [38], or climbing physical steps [32, 23], there is no reason to restrict our imagination to physical limitations set by the world we know. As children, we are often inspired by superheroes, dreaming of gaining similar abilities one day [24]. In growing older, children learn to distinguish between fact and fiction, but we argue that a yearning for this kind of experience never entirely goes away. Thus, we are motivated by the design and implementation of hyper-realistic experiences such as superhuman strength and speed in order to realize a common childhood fantasy, by creating and evaluating unique and engaging user experiences in VR (a motivation termed "*mixed reality empowerment*" in prior work [12]).

Fictional characters with superhuman strength often achieve unnatural jump heights, scaling mountains and roof-tops in the blink of an eye. We aim to give players the chance to experience this exciting and entertaining sensation. For this purpose, we introduce physical jumping as a realistic input technique and apply a virtual forward motion through scaling factors to create a hyper-realistic experience of increased jump strength. We aimed to explore how users experience physical jumping in VR (i.e., while wearing the headset and controllers), to explore its feasibility for VR games and experiences in general. Further, we compared the impact of different scaling factors (i.e., how far the user's jump was scaled in terms of forward motion), and how scaled jumping in VR performs as an alternative to teleportation, currently one of the most common locomotion techniques in VR.

In a within-subjects lab study (N=28), we compared teleportation to scaled jumping and forward-jumping by letting users navigate a virtual parkour scene. Our results show that physical jumping in VR (regardless of scaling) can significantly increase presence, motivation and immersion while largely not increasing simulator sickness. Additionally, most scaled jumping conditions achieved a significantly higher immersion and motivation rating than forward-jumping. Combining these results with participants' self-reported preferences, we found scaling factors that maximize user experience and comfort while minimizing negative effects such as simulator sickness. We conclude with design implications for VR experiences that aim to benefit from hyper-realistic output.

With this work, we contribute an evaluation of the feasibility of physical jumping in VR, including an exploration of the parameters for virtually scaling hyper-realistic jumps. Based on this, we discuss how hyper-realistic jumping can be designed for inclusion in VR games and experiences, as well as other potential hyper-realistic movement representation in VR.

RELATED WORK

Locomotion in VR

Early work has shown that walking in VR is perceived to be more natural than walk-in-place or controller-based techniques [35]. However, then as well as today, walking in virtual environments is restricted by the spatial boundaries of the tracking space. Previous work has explored methods for VR users to walk endlessly in virtual worlds; for example, Razzaquev et al. introduced a redirected walking technique that creates the illusion of an unlimited walking space by tricking users to walk on a curved path [25]. However, curvature gains that are entirely unnoticeable to the user generally still require too much physical space to be practical [27]. In current VR applications, an "unrealistic" locomotion technique is becoming increasingly established: teleportation. With this method, VR users point-and-click to move in virtual space, with a parabola indicating the currently selected new location (see Figure 1c) [3]. This technique creates less simulator sickness than touchpad-based locomotion (i.e., moving the virtual camera forward by moving the finger forward on the touchpad) [8] and avoids spatial restrictions of the tracking space. Another option (closer to real-life locomotion than such button-based techniques) is walk-in-place, i.e., performing swinging gestures with the arms to virtually move forward [34]. Although this remains less realistic than real-life locomotion, it motivated us to explore a jump-in-place technique.

While walk-in-place and jump-in-place are both missing the sensation of vection, a study by Rietzler et al. suggests that missing movement feedback can be substituted by rotational feedback to trick the vestibular system into perceiving a forward motion [28]. We explore whether a similar approach can be used by applying virtual forward movement to scaled vertical-only jumps. We hope that combining a natural movement with hyper-realistic output presentation in VR can make users accept a vertical jump as containing forward momentum, thus yielding user acceptance of jumping in VR and leverage positive side effects of embodied interaction on player experience. Interaction based on whole-body movement in virtual spaces has been shown to have a high potential for engaging and enjoyable user and player experiences [2, 15, 21, 29], suggesting potential benefits from employing physically engaging locomotion techniques.

Highly Physical Movement in Virtual Experiences

There is evidence that embodied interaction and physically highly engaging movements are in themselves beneficial to a human's mood [9], brain plasticity [37] and stress relief [13].

This is increasingly being explored in mixed reality experiences. For example, Finkelstein et al. presented Astrojumper, a CAVE-based experience that required autistic children to physically jump to overcome obstacles [6]. Preliminary results with healthy participants were positive. Mixed reality is also increasingly being used for exergames, i.e., games developed to induce physical exertion and use physical movement as an input mechanism [39]. This has been explored by integrating workout machines into virtual spaces (e.g, a cycling ergometer or rowing machine [5, 17]). It has also led to the inclusion of whole-body movement in the form of functional training sessions in augmented reality (e.g., the ExerCube [22]). In generally exploring whole-body movements in VR, Rogers et al. found that realism is not always necessary; sometimes an approximation of physical challenge is enough or even preferred [29]. Further, highly realistic or physically engaging movements in VR must be designed in consideration of trade-offs with usability (i.e., through "unrealistic" abstraction) and onlooker effects (e.g., feeling self-conscious). These examples show that (fully as well as partially) virtual experiences can incorporate increased physical movements for the purpose of also increasing engagement, enjoyment, and motivation.

Finally, we note that jumping itself has previously been explored in the VR context focusing on exergaming. Ioannou et al. [14] explored a very similar jump-in-place concept with applied forward motion, and found increased immersion and motivation for the addition of augmentation, but also incurred motion sickness when participants were running in VR. While they included different scaling factors of augmenting the jump, they explored a smaller range for jumping in place (theoretically up to 2.5m upwards motion for a physical jump of 10 cm). In contrast, we extend this range to reach up to 30m at our highest scaling factor for jumping in place. However, they only explored effects of jumping alongside effects of running in place in VR, i.e., existing forward motion was preserved or used to augment forward motion. How jumping as an isolated experience affects player experience remains unanswered. Further, likely due to the focus on exergames, they did not compare their system against teleportation, i.e., the de facto standard in VR locomotion.

(Hyper-)Realism in VR

Several related works have explored hyper-realism in VR experiences. For example, Birdly by Max Rheiner is an installation for VR that allows users to experience a sensation of flying like a bird via a wing-flapping mechanism [26]. Although no formal evaluation was conducted, this work has become very popular due to its "realistic" flying, and is a great demonstration of how a seemingly unrealistic experience in VR can elicit a high amount of enjoyment in users. Hämäläinen et al. have termed this "*mixed reality empowerment*" [12], and in particular, lament a scarcity of systems that enable "*superhuman locomotion*" via manipulation of perceived gravity. In a follow-up study in the wild by Lehtonen et al., mixed reality empowerment was explored for exaggerated jumps on a trampoline in a multi-player game [20]. Their results suggest that "movement empowerment may support autonomy, competence, and relatedness". A related project by Granqvist et al. [10] explored hyperrealistic avatar flexibility in a martial arts VR game. They found that a medium degree of hyperrealistic flexibility was preferred over realism or strong exaggeration.

In a more subtle application of hyperrealism, Gugenheimer et al. provided kinesthetic feedback for head movements to create a sensation of increased gravity on an alien planet, by attaching fly-wheels to a head-mounted display (HMD) [11]. Their results indicate that users experienced higher immersion and presence than without kinesthetic feedback, but after virtual jumps (performed by pressing a button, while seated) lacked a sensation of impact when returning to the ground.

In a more physically involved example, Sasaki et al. presented a haptic feedback device for "virtual super-leaping" [31]. An upward directed force is generated by eight rotors in a hand-held prototype to create the sensation of being pulled upwards during a physical jump. Unfortunately, no formal user evaluation has been conducted so far. Also incorporating a physical jump, virtual forward movement was presented in a work by Ishibashi et al. [16]. In this work, a web-shooter prototype for VR creates a pulling-force on the arm and simulates swinging from building to building like the popular comic superhero Spiderman. Preliminary results on user experience were promising. In contrast, Kim et al. proposed a cable-driven system to induce a sense of reduced gravity and enable users to physically take hyper-realistic jumps [19]. Their results show that scaled vertical jumps are accepted by users within a certain scaling range and have the potential to increase user presence. This approach largely increases time spent physically ascending and descending to manipulate perceived gravity while introducing a minor virtual scaling, while our approach leaves the physical jump unaffected and scales only the virtual output which results in a higher virtual jump height and distance.

RESEARCH FOCUS

Based on previous work we can conclude that both hyper-realistic experiences and physical movement in VR can enhance user experience. Additionally, there exists a range of (vertical) scaling factors for physical jumps that is accepted by users in VR. However, previous work has mostly relied on hardware prototypes to create hyper-realistic experiences while software-based solutions remain under-explored, despite benefits in terms of cost. Furthermore, we are interested how a mostly jump-based locomotion technique compares against teleportation which is the state-of-the-art locomotion technique for most VR experiences. To explore this comparison, we implemented a software VR prototype that allows us to evaluate a range of horizontal scaling factors for physical jumps, with the goal to improve player experience without inducing additional simulator sickness. We conducted a lab study to answer the following research question:
How does (scaled) physical jumping in VR compare against teleportation in terms of presence, immersion, enjoyment and simulator sickness?

IMPLEMENTATION

We implemented a VR prototype called *JumpVR*, for which all virtual scenes were written in Unity3D with use of the *Virtual Reality Toolkit* (VRTK) [7] and displayed on an HTC Vive VR headset (v1.0). Players navigate a virtual platform course via *MoveInPlace*—a locomotion mechanism provided by VRTK, by which users can move through the scene by keeping the touchpad pressed and performing a walking gesture (up-down motions) with their arms. At 14 spots throughout the course, players have to cross differently spaced gaps between platforms by jumping across. Using MoveInPlace would result in players falling between platforms; depending on the game variation, players can either teleport across, or employ scaled jumping[1], as described in the following. While the player is in mid air, a virtual forward movement is applied based on the velocity of the headset calculated frame by frame.

Jumping in VR

While the player is standing or moving through the tracking space a baseline is calculated based on the headset's height. This *headset baseline* consists of the average height of the headset gathered over the last 100 frames of the game and adjusts itself to the players' behaviour. When the player bends their knees (i.e., the headset height decreases), the system is set into a monitoring state. If the headset's subsequent upwards acceleration surpasses the baseline in addition to an empirically defined threshold, the system recognises a jump

[1]Forward-jumping was conducted as an exploratory baseline condition on a smaller course, due to potential fatigue from jumping and to allow for unrealistically far scaled jumps in the main course.

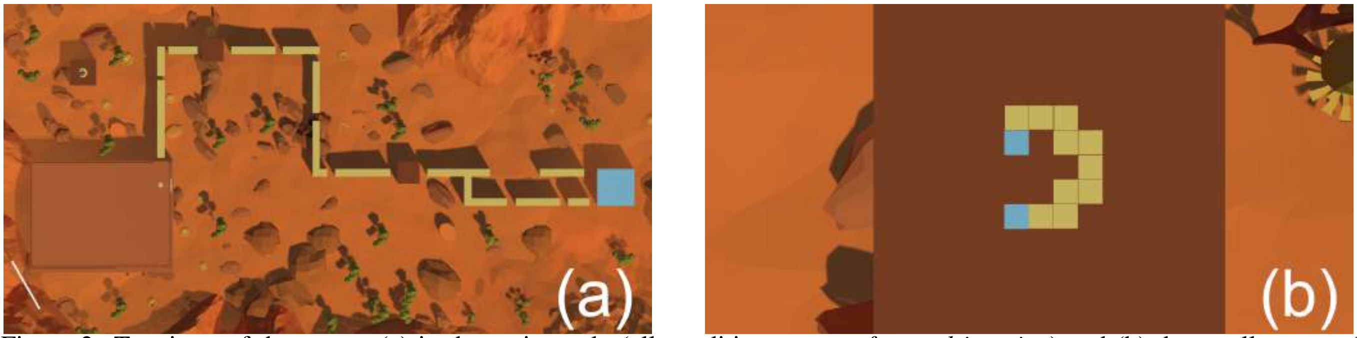

Figure 2: Topviews of the course (a) in the main study (all conditions except *forward-jumping*) and (b) the smaller second course used only for the *forward-jumping* condition. The brown blocks in the main-study course were checkpoints; upon falling, participants were re-set to the last passed checkpoint.

and applies a vertical scaling factor to the actual movement vector. Forward movement is applied linearly by scaling the player's initial forward vector in each frame during the jump phase. A longer airtime therefore results in a longer jump. As a lack of physical feedback during virtual jumps has been lamented in previous work [11], we utilize the natural haptic feedback of physical jumps' take-off and landing to simulate the start and end of a hyper-realistic jump; only the air-time is virtually scaled. To facilitate jump precision and learning, a *range indicator* in the form of a virtual ring around the user was introduced to visualize the jump range from the current position if the player were to repeat the previous jump (see Fig. 1b).

Jump States

The system monitors the current user state to detect when users are physically jumping, and which state of the jump they are in. This allows the virtual jump scaling manipulation to be enabled exactly and only during jumps. To do so, the system detects the following five states based on headset height, velocity, and acceleration:

OnGround

The user is standing or moving inside the tracking space (default state). During this time, a baseline is continuously built.

KneesBent

The headset height is lower than the baseline, i.e., the player is bending their knees. This triggers the system to be aware of a possible upcoming jump. To abort the jump, the user can simply straighten their legs again, bringing their headset to the *OnGround* height and corresponding system state.

Rising

When the user is accelerating upwards, the start of the jump is initiated as soon as the headset's baseline is passed. Virtual jump manipulations can now be applied, based on the position difference to the last frame. The first occurrence of the *Rising*-state triggers the system to log the timestamp and the start position of the physical jump (the moment the user leaves the ground), and to activate the scaling manipulation.

Falling

The user has passed the jump peak and is now falling back towards the ground. The scaling manipulation is now inverted to bring the user back to the ground in the virtual world.

Landing

As soon as they reach the baseline again, the jump is finished and scaling manipulation stops. The system then resets itself; the user is considered to be in the *OnGround*-state again.

EVALUATION

A scaling factor exaggerates the player's actual jump height and creates a sensation of vection due to forward movement. This could potentially induce motion sickness due to the mismatch between players' virtual and physical movements [1]. We conducted an in-lab user experiment to explore a range of scaling factors with regards to their effect on player immersion and presence, as well as simulator sickness.

Method

Our within-subjects experiment had a total of seven conditions, each representing one of the following locomotion variants of our *JumpVR* prototype: jumping scaled with five different factors, teleportation as a state-of-the-art baseline, as well as a secondary baseline of forward-jumping. All conditions were fully counterbalanced.

Jump Prototype Variants

The prototype was implemented with different sets of parameters, to compare varying degrees of manipulation applied to jumping in VR against two baselines: "realistic", i.e., unscaled physical jumping in VR, and a teleportation alternative without any jumping (state-of-the-art VR locomotion technique).

- *Forward-jumping*: Participants had to complete (a smaller version of) the parkour without virtual jump manipulation, teleportation, or *MoveInPlace*; every locomotion except for physical movement was disabled. Moving over gaps required realistic physical jumping (including forward motion) that was represented without manipulation in the virtual world. The parkour for this variant was smaller, constrained both by the tracking space, and due to the higher expected fatigue for realistic jumping (see Figure 2b).

Figure 3: The different scaled jumping conditions in comparison, visualizing the range of each scaling for an average jump on the yellow square to the left.

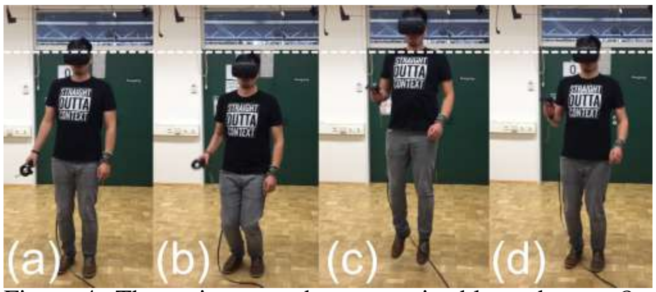

Figure 4: The main states the system is able to detect: *On-Ground* (a), *KneesBent* (b), *Rising/Falling* (c), *Landing* (d). The dashed line symbolises the measured baseline.

- *Teleportation*: In this baseline condition, players were asked to use teleportation only to navigate the main parkour (Figure 2a). Teleportation was implemented using the default mechanism provided by VRTK. Pressing and holding the trigger on the controller enabled an indicator showing the currently selected future position. Upon release of the trigger, users are teleported to the selected position. The maximum range was limited so that users were not able to teleport for more than two blocks at once. Participants were instructed not to jump; *MoveInPlace* was disabled.
- *Scaled Jumping*: vertical physical jumping was required, while forward motion was applied virtually through different scaling factors (SFs) in five different variants: *SF 1.4* (corresponding to ~2 m in real world), *SF 1.8* (~5 m), *SF 2.2* (~10 m), *SF 2.6* (~18 m), and *SF 3.0* (~30 m). The different conditions are illustrated in Figure 3 (all shown jumps were executed with a mean airtime of 250ms). For each of these forward vectors in terms of scaled horizontal motion, corresponding vertical factors were applied to achieve a close-to-natural jump parabola. For the sections on the platforms of the main parkour (Figure 2a), *MoveInPlace* was also enabled.

Along the main parkour, three checkpoints were defined: the start, and the two small brown blocks seen in Figure 2a. If participants virtually fell between platforms, they were transported back to the last passed checkpoint prior to reaching the ground of the virtual world.

Technical Setup
The experiment was conducted with the HTC Vive HMD and controllers in a tracking space sized 3.2 x 3.5 meters. We used a computer equipped with an i5-6600k (stock) processor and an Nvidia GTX 1080 graphics card. The software ran with 60 frames per second.

Participants
We recruited 28 participants (10 female, 18 male, 0 other) from our institution with a mean age of 25.90 (*SD*=2.63). All participants had normal or corrected-to-normal vision. With regards to VR experience, 2 participants reported owning a VR headset themselves and 9 reported having access to a VR headset[2]. For those with VR experience (*N*=21), the mean duration of their VR sessions was reported as 1.92 hours (*SD*=0.76), with a mean of 1.77 breaks per hour (2.17 generally, 1.36 due to discomfort of some kind—three participants reported the headset weight as a reason for taking breaks).

Measures
Participants' experiences were assessed via questionnaires at the end of each study condition. This post-condition set of questionnaires covered simulator sickness (Simulator Sickness Questionnaire (SSQ) [18], 16 items on a 4-point scale), motivation (interest/enjoyment from the Intrinsic Motivation Inventory (IMI) [30], 7 items on a 7-point scale), presence (Inter Group Presence Questionnaire [33], 14 items on a 7-point scale), and immersion and mastery (two subscales with corresponding names of the Player Experience Inventory (PXI) [36], 4 items each on a 7-point scale).

A final questionnaire at the end of the study recorded the perceived number of jumps during the study, custom questions about general comfort with the HMD (7-point scale, 7 items) and the usability of the range indicator (7-point scale, 4 items), as well as participants' general playing habits, e.g., whether they enjoy physically engaging games (7-point scale, 3 items). Finally, we asked them to choose their preferred condition and to give general feedback on the prototype.

Procedure
After an introduction to the concept of *JumpVR* and the study, and the completion of consent forms, participants provided information on their demographic background, as well as their VR experience and habits. They were then asked to experience the prototype seven times, followed by questionnaires. Depending on the current condition, participants were asked to

[2] 6 HTC Vive, 1 Oculus Rift/Go, 1 Pimax 8k, 1 Oculus Quest, 1 Google Cardboard, 1 Sony Playstation VR.

reach the end of the parkour by either jumping or teleporting over the gaps between platforms (see Figure 1). A condition was considered finished if the target platform was reached, or a maximum of three minutes had passed. If a participant fell from a platform, they were automatically teleported back to the last checkpoint they had passed. All conditions were balanced with a Latin Square. Between conditions (after questionnaires), participants could take an optional break in case of fatigue. All movement data including jump height, duration, and frequency was logged. After the last condition, participants additionally filled out the final questionnaire covering general feedback and their preferred condition.

RESULTS

A summary of the results of the SSQ, IMI, IPQ and PXI questionnaires can be found in Table 1. The following paragraphs contain only significant results.

Simulator Sickness (SSQ)

A Friedman's ANOVA revealed significant differences in the SSQ total score (SSQ_TS) between the conditions, $X^2(6)$=24.517, $p<.001$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). SSQ_TS scores were significantly higher for the *scaled-1.4* condition than for the *teleportation* condition (see Table 2 for an overview of the descriptive statistics).

Interest/Enjoyment (IMI)

A Friedman's ANOVA revealed significant differences in the IMI's interest/enjoyment score between conditions, $X^2(6)$=68.889, $p<.001$). Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Interest/enjoyment scores were significantly higher for *scaled-1.8*, *scaled-2.2*, *scaled-2.6*, and *scaled-3.0* than for the *teleportation* condition. Further, the *forward-jumping* condition yielded significantly lower interest/enjoyment than conditions *scaled-1.8*, *scaled-2.2*, *scaled-2.6*, and *scaled-3.0* (see Table 2 for an overview of the descriptive statistics).

Presence (IPQ)

A Friedman's ANOVA indicated significant differences in the presence between conditions, $X^2(6)$=45.021, $p<.001$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Presence scores were significantly lower for *teleportation* than for the *forward-jumping* condition, for *scaled-1.4*, for *scaled-1.8*, for *scaled-2.2*, for *scaled-2.6*, and *scaled-3.0* (see Table 2 for an overview of the descriptive statistics).

Immersion and Mastery (PXI)

A final Friedman's ANOVA reported significant differences in the immersion score between conditions, $X^2(6)$=62.078, $p<.001$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Immersion was reported as significantly lower for the *teleportation* condition than for conditions *scaled-1.4*, for *scaled-1.8*, for *scaled-2.2*, for *scaled-2.6*, and *scaled-3.0*. Immersion was also significantly lower for the *forward-jumping* condition than for conditions *scaled-1.4*, for *scaled-1.8*, for *scaled-2.2*, for *scaled-2.6*, and *scaled-3.0*.

A final Friedman's ANOVA reported significant differences in the mastery scores between conditions, $X^2(6)$=16.864, $p<.05$. Dunn's pairwise tests with Bonferroni correction were carried out for each pair of groups (all Z and p values of these comparisons are listed in Table 1). Mastery scores were significantly higher for the condition *scaled-1.8* than for conditions *scaled-1.4* and *forward-jumping* (see Table 2 for an overview of the descriptive statistics).

An overview of the components of player experience components (immersion, interest/enjoyment, and presence) across conditions is displayed in Figure 5.

Performance: Jumps and Falls

On average, participants guessed they had jumped a total of 85 times over all conditions (*SD*=44.37). Results on actual jumps, falls and fall/jump ratios per condition (and total) can be found in Table 3.

Perceived Comfort

The majority of participants were comfortable jumping while wearing the HMD, although they did feel its weight, and they felt it applied pressure to their face. Participants mostly denied being afraid of damaging or losing the HMD during their experience; in fact, many had at some point forgotten about the HMD. The results for these custom comfort questions are shown in Figure 7.

Range Indicator

Participants mostly agreed that "*the range indicator helped to understand the system faster*" (M=5.07, SD=0.93), and mostly disagreed that the "*the range indicator was confusing*" (M=1.29, SD=0.96) or "*[...] affected the game experience negatively*" (M=1.07, SD=0.68). Further, they mostly disagreed that "*the indicator was unnecessary after [they] understood the mechanic*" (M=2.18, SD=1.60).

Preferred Condition

The most preferred condition was *scaled-1.8* (32.14%), followed by *scaled-2.2* (25%) and *scaled-2.6* (25%), see Figure 6.

Qualitative Feedback

With regards to preferences, only a single participant preferred the *teleportation* condition, as it eliminated the "*risk of falling*" (P4). Others, however, perceived it as "*unrealistic and boring*" (P5), "*less immersive*" (P21), or "*felt like the actual jumping was way more fun than the teleportation, although exhausting. It felt like the movement was real.*" (P14). Additionally, P28 reportedly experienced less simulator sickness with this condition: "*tend to get simulator sickness from teleportation, which I didn't experience [with physical jumps]*". None of the participants preferred the *forward-jumping* condition. According to P7, "*[m]oving through the actual room in the [*forward-jumping*] condition did not feel as comfortable/secure as just jumping up and down*". For some this was due to a "*fear to collide with something*" (P23) in the

CONDITION PAIR	SSQ		IMI		IPQ		PXI-IMMERSION		PXI-MASTERY	
	Z	*Adj. Sig.*	*Z*	*Adj. Sig.*	*Z*	*Adj. Sig.*	*Z*	*Adj. Sig.*	*Z*	*Adj. Sig.*
teleportation - forward-jumping	.875	1.000	-.179	1.000	1.821	**.034**	.161	1.000	-1.375	1.000
teleportation - scaled-1.4	-2.464	**.000**	-1.554	.150	-2.625	**.000**	-2.036	**.009**	1.339	.427
teleportation - scaled-1.8	-1.750	.051	-2.768	**.000**	-3.321	**.000**	-2.679	**.000**	-.429	1.000
teleportation - scaled-2.2	-1.107	1.000	-2.679	**.000**	-3.036	**.000**	-2.911	**.000**	.607	1.000
teleportation - scaled-2.6	-1.661	.084	-3.107	**.000**	-2.393	**.001**	-2.571	**.000**	.482	1.000
teleportation - scaled-3.0	-1.393	.333	-3.089	**.000**	-2.804	**.000**	-2.268	**.002**	.625	1.000
forward-jumping - scaled-1.4	-1.589	.124	-1.375	.362	-.804	1.000	-1.875	**.024**	-.036	1.000
forward-jumping - scaled-1.8	-.875	1.000	-2.589	**.000**	-1.500	.197	-2.518	**.000**	-1.804	**.037**
forward-jumping - scaled-2.2	-.232	1.000	-2.500	**.000**	-1.214	.744	-2.750	**.000**	-.768	1.000
forward-jumping - scaled-2.6	-.786	1.000	-2.929	**.000**	-.571	1.000	-2.411	**.001**	-.893	1.000
forward-jumping - scaled-3.0	-.518	1.000	-2.911	**.000**	-.982	1.000	-2.107	**.006**	-.750	1.000
scaled-1.4 - scaled-1.8	.714	1.000	-1.214	.744	-.696	1.000	-.643	1.000	-1.768	**.046**
scaled-1.4 - scaled-2.2	1.357	.394	-1.125	1.000	-.411	1.000	-.875	1.000	-.732	1.000
scaled-1.4 - scaled-2.6	.804	1.000	-1.554	.150	.232	1.000	-.536	1.000	-.857	1.000
scaled-1.4 - scaled-3.0	1.071	1.000	-1.536	.164	-.179	1.000	-.232	1.000	-.714	1.000
scaled-1.8 - scaled-2.2	.643	1.000	.089	1.000	.286	1.000	-.232	1.000	1.036	1.000
scaled-1.8 - scaled-2.6	.089	1.000	-.339	1.000	.929	1.000	.107	1.000	.911	1.000
scaled-1.8 - scaled-3.0	.357	1.000	-3.21	1.000	.518	1.000	.411	1.000	1.054	1.000
scaled-2.2 - scaled-2.6	-.554	1.000	-.429	1.000	.643	1.000	.339	1.000	-.125	1.000
scaled-2.2 - scaled-3.0	-.286	1.000	-.411	1.000	.232	1.000	.643	1.000	.018	1.000
scaled-2.6 - scaled-3.0	.268	1.000	.018	1.000	-.411	1.000	.304	1.000	.143	1.000

Table 1: Pair-wise comparisons between conditions for simulator sickness (SSQ), interest/enjoyment (IMI), presence (IPQ), immersion and mastery (PXI).

CONDITION	SSQ		IMI		IPQ		PXI-IMMERSION		PXI-MASTERY	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
forward-jumping	17.63	20.66	4.16	1.29	3.40	.79	4.80	1.12	4.77	1.17
teleportation	10.55	16.26	3.74	1.48	2.81	.83	4.72	1.18	5.21	1.07
scaled-1.4	21.10	20.31	5.31	1.16	3.87	.90	5.66	.85	4.64	.92
scaled-1.8	17.63	17.48	5.69	0.98	4.01	.83	5.87	.65	5.46	.90
scaled-2.2	14.96	14.54	5.60	1.02	3.94	.91	5.90	.69	5.10	1.27
scaled-2.6	18.43	20.68	5.72	1.07	3.78	.88	5.79	.84	5.02	1.06
scaled-3.0	17.90	20.16	5.82	1.10	3.79	.83	5.76	.80	4.94	.90

Table 2: Descriptive statistics by condition for simulator sickness (SSQ), interest/enjoyment (IMI), presence (IPQ), immersion and mastery (PXI).

CONDITION	JUMPS		FALLS		FALL/JUMP	
	M	*SD*	*M*	*SD*	*M*	*SD*
forward-jumping	7.36	3.27	–	–	–	–
scaled-1.4	49.93	32.48	3.64	2.90	0.10	0.09
scaled-1.8	27.36	10.30	1.21	1.13	0.04	0.04
scaled-2.2	28.82	10.32	5.46	3.29	0.17	0.08
scaled-2.6	27.43	10.63	8.43	5.12	0.28	0.11
scaled-3.0	21.93	8.14	8.86	4.34	0.39	0.11
Total	163.82	54.85	27.82	10.51	0.17	0.05

Table 3: Player jump statistic by condition. The lowest fall/jump ratio for scaled jumping was achieved in scaled-1.8.

forward-jumping condition, wherein the physical space was mostly realistically utilised.

For scaled jumping, while some participants liked "*the physical challenge to achieve a longer jump*" (P17), the smallest scaling factor (*scaled-1.4*) was the least preferred scaled jumping condition (e.g., "*required more jumps [and thus] more effort*" P27). This trade-off between between exertion and accuracy is likely what led to *scaled-1.8* being preferred by most participants: a "*sweet spot between too exhausting and too imprecise*" (P25). It allowed them to feel "*more in control of the length of a jump*" (P1). Interestingly, this condition was often referred to as "*natural*" (P15) even though the virtual jump was much longer than possible for most in real life. P14 summarised it as "*not too far of a [j]ump that seemed like i could not do it in real life, but it was also far enough that i could feel like some kind of superhuman.*"

Condition *scaled-2.2* came second in preference, considered "*the most controllable out of all the jumping conditions [where] larger jumps where still possible*" (P26). P27 could "*reach the blocks with less effort*" in this condition while "*[l]arger jumps were difficult to control*". In contrast, *scaled-2.6* "*allows [you] to do more than [you] can in real life but is still manageable*" (P22). "*The longer range gave [them] the feeling of being faster which makes [them] feel better*" (P6). Generally, the "*higher difficulty of guessing the jump range made the task more challenging*" (P10). For some, this yielded greater interest and enjoyment in the strongest manipulation (*scaled-3.0*): it "*allowed the most interesting jumps*" (P7), and "*[j]umping really far just feels good if you hit the track*" (P23).

Overall, the jump-in-place concept was well received and allowed participants "*to forget that [they were] in the laboratory because [they] didnt fear to collide with something*" (P23) in scaled jumping. The combination of walk-in-place and jump-in-place was considered "*really good*" (P21). Walk-in-place

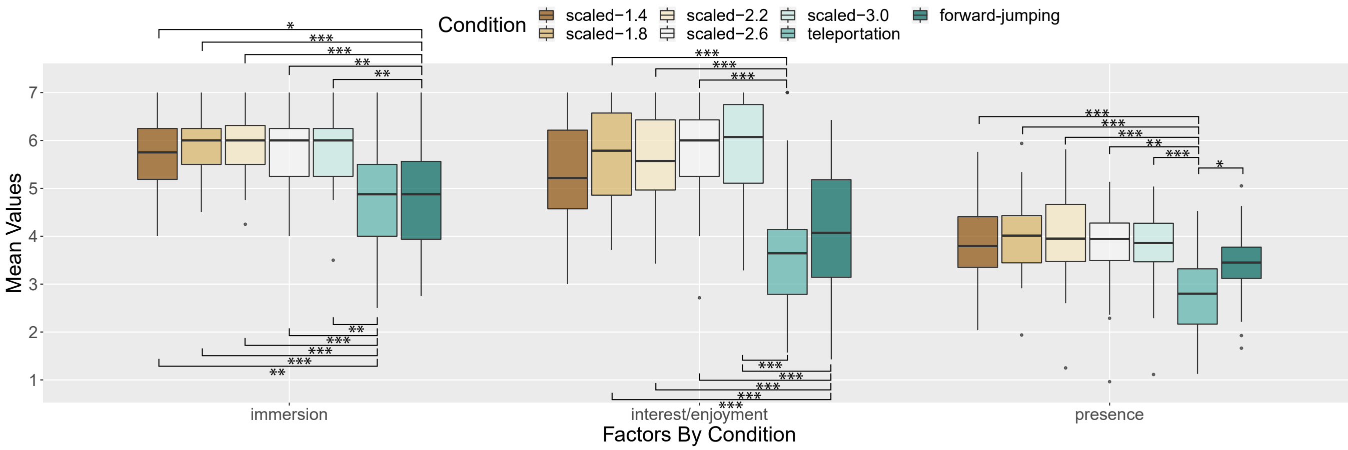

Figure 5: Immersion, interest/enjoyment, and presence were rated higher for the scaled jumping conditions than compared to teleportation (and largely also compared to forward-jumping). Significant differences are highlighted with ∗ (p<.05), ∗∗ (p<.01) and ∗∗∗ (p<.001).

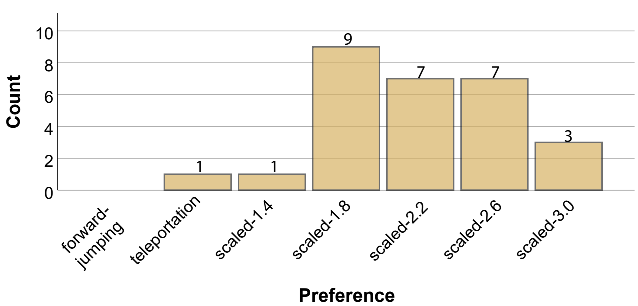

Figure 6: Results of participants' most preferred condition.

enabled staying "*in the correct space to not collide with obstacles of the outside*", i.e., granular refinement of position. In contrast, "*jumping on the other hand gave [...] the feeling of being really in the game. It made a lot of fun*" (P21). Some participants would like to see *JumpVR* "*integrated into games*" (P10) and "*exergames in VR*" (P22), as they "*like doing extraordinary stuff inside a game*" (P23). P16 considered *JumpVR* as a "*very innovative way of moving in VR*" but would "*not like this as [the] only option of travelling in the virtual world*". Similarly, P17 would like to see jumping interaction in specific scenarios where "*you have to jump across a gap or want to climb something / reach something atop*".

Discussion

Our results showed that *JumpVR* was very well received by participants. With the exception of the *scaled-1.4* condition, all scaled jumping conditions elicited significantly higher presence, interest/enjoyment, and immersion in comparison to teleportation. For the most part, scaled jumping thus showed significant benefits in comparison to the state-of-the-art locomotion technique in most VR experiences. It therefore represents a viable extension or augmentation of existing walk-in-place locomotion techniques [34].

Scaled Jumping: Scaled-1.4 vs. Other SFs

All physical jump conditions except for *scaled-1.4* did not significantly increase simulator sickness in comparison to teleportation. This indicates that the manipulation of participants' forward motion was largely accepted by our VR users and was even considered natural by many. This suggests that we successfully built on previous findings that a missing stimulus in VR (e.g., forward movement) can be replaced or roughly substituted with another (in our case, upwards-only movement), without compromising user or player experience [28, 29].

It is interesting to note that *scaled-1.4* was the only condition to increase simulator sickness compared to teleportation. This may provide insight with regards to mismatch theories of simulator sickness [1], i.e., ascribing simulator sickness symptoms to a mismatch between participants' visual and vestibular input (what they see vs. what they feel). The lack of significantly increased simulator sickness for the scaled jumping conditions with stronger manipulation is surprising from this perspective, as they represent a greater mismatch. However, we argue that it could be precisely because of the more obvious mismatch that participants accepted scaled jumping with factors higher than 1.4 as its own technique, rather than interpreting it as noise in their perceived visual and vestibular input. Alternatively, the higher simulator sickness for condition *scaled-1.4* could be related to the relatively high number of jumps performed in that condition compared to the others (this did not translate to a similarly high number of falls).

Scaled vs. Forward Jumps

Scaled jumps elicited higher interest/enjoyment and immersion than forward-jumping, while not significantly increasing simulator sickness. This indicates that the hyperrealism of jumping further than in real life—compared to what is either possible at all, or possible for that degree of effort—is what significantly improved player experience. If the *forward-jumping* condition had been just as well received, the higher immersion and interest/enjoyment could have been caused by either the hyperrealism, or the embodied interaction, i.e., the enjoyment of physical engagement in VR. However, while

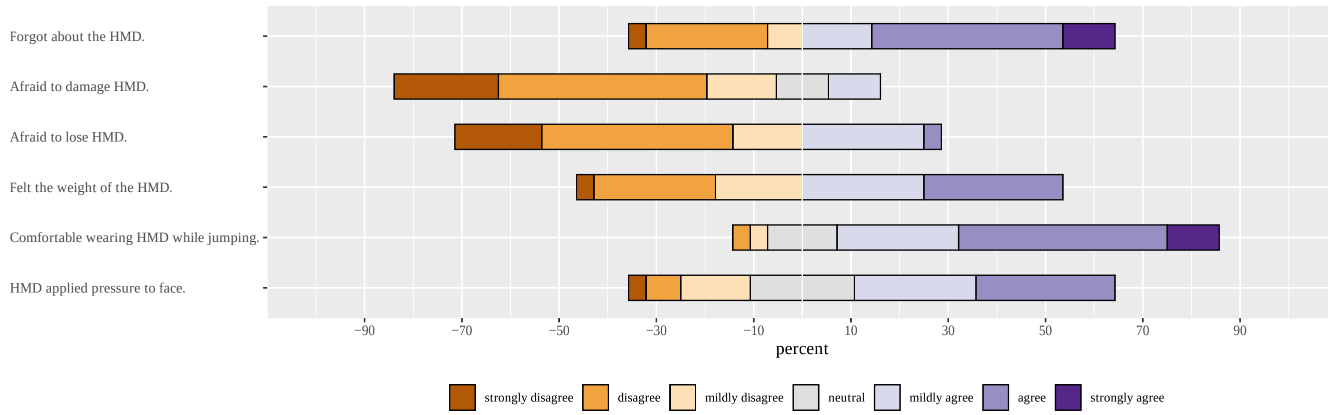

Figure 7: Comfort with HMD.

we do believe that physical engagement remains an important experiential factor in VR [29], it appears that here, hyperrealism was the decisive one for improved player experience. Furthermore, the qualitative feedback indicates that moving through the tracking space in a physically realistic manner made some participants feel "*insecure*" (P7). Jump-in-place thus has a minimizing effect on risk of physical collisions, which likely affected participant preferences. We argue that the decrease in perceived risk could have mitigated distraction from this worry, thus increasing immersion. Our results are particularly interesting in the context of related work by Granqvist et al. [10] on hyperrealistic avatar flexibility; here too, a moderate degree of hyperrealism was preferred over realism (as well as stronger degrees of hyperrealism).

Design Implications for Jumping in VR

Overall, condition *scaled-1.8* was preferred by most participants, described as balancing exhaustion and accuracy while allowing them to feel like a "*superhuman*" (P14). This is consistent with its high presence, immersion, and mastery score and lowest fall-to-jump ratio. We thus suggest this factor as the most suitable for applications and research employing scaled physical jumping. The range indicator was generally considered helpful even after multiple conditions of usage, although some participants asked for an option to deactivate it. For some, this was explained by a preference for increased challenge in accurately reaching platforms via a higher scaling factor—i.e., further away—without help from the range indicator. As such, we suggest implementing a feature of this kind as (optional) scaffolding. Overall, *JumpVR* could thus be employed as either an alternative locomotion technique to teleportation (when increased exertion is not an issue), or as an additional one, to introduce a more physically engaging, hyperrealistically augmented element to a VR experience.

Further Extending Hyperrealism in VR

Although *scaled-1.8* was considered a balanced condition between accuracy and exhaustion, there may be value in exploring larger scaling factors to find the break-even-point where increased simulator sickness outweighs the benefit of increased enjoyment. Since participants considered large scaling factors to make landing on a target spot more challenging, higher scaling factors could be evaluated on a parkour that focuses more on free exploration rather than precise jumps, e.g., a canyon where users can perform Hulk-like super-jumps without aiming at a specific platform. In first exploratory tests, we have seen that the moment of virtual landing can be delayed somewhat from the real landing, to create a perception of longer jumps without the user noticing a mismatch. This concept could be explored further to find the maximum viable delay before a decrease in immersion is observed (and potentially, an increase in simulator sickness).

While we explored *JumpVR* as a pure locomotion augmentation, we believe that it shows further potential as a more general game mechanic. For example, it could be adapted to let players virtually experience jumping in a heavy mech suit, by simulating the force of a take-off blast and landing impact that destroys or stuns surrounding objects.

Limitations

The HMD weight and the attached cable could both have influenced the conditions in this study; while all conditions had the same weight and cable, it is possible that they were experienced differently while physically jumping (especially if the headset had not been properly fastened, or if the cable moved while the participant jumped). Further, it must be noted that exposure time slightly differed between conditions, i.e., in the teleportation condition, participants usually completed the course faster than in the scaled jumping conditions. We argue that this is a faithful representation of a strength of teleportation (faster completion time), however it must be noted that it is accompanied by a difference in exposure time to the condition in our experiment. Furthermore, the order of presentation might bias those participants that experienced a scaled condition first to believe that the scaled conditions are "normal". While the fact that participants could be accepting our hyper-realistic experience as normal is favourable for our experiment, it might have biased the results.

A fairly large number of our participants had some degree of prior VR experience, i.e., they were likely already familiar with teleportation as a locomotion technique. Compared to

VR novices, the jumping techniques could have thus yielded a stronger novelty effect than teleportation. Future work will have to explore user acceptance over prolonged exposure.

Finally, we acknowledge that our forward-jumping constitutes a weaker baseline, as it was operationalized with a smaller parkour. However, we note that it thus represents features inherent to the condition: forward-jumping is limited by the physical tracking space, while teleportation and scaled jumping enable users to roam a much larger virtual space than is physically available.

CONCLUSION

In this work, we have introduced and evaluated *JumpVR*, a jump-in-place locomotion augmentation technique for VR that scales physical jumps into virtual super-jumps in order to create the sensation of being a superhuman. Our user experiment (N=28) evaluated the impact of physical jumping in VR on user immersion, motivation, presence and simulator sickness in comparison to teleportation. Both quantitative and qualitative results indicate that most scaled physical jump conditions elicited a higher immersion and motivation while largely not increasing simulator sickness. We present insights on user preference and design implications that will help to incorporate physical jumping into future VR games and research.

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