VR Bridges: Simulating Smooth Uneven Surfaces in VR

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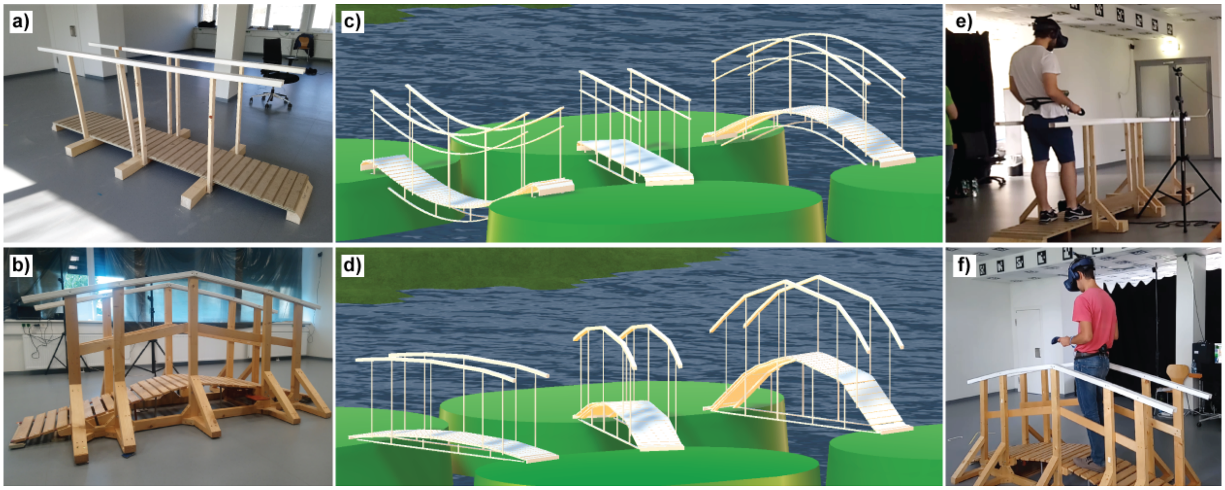

Figure 1: Simulation of smooth uneven surfaces in VR with different physical props: Study 1 (top) - we used a flat physical bridge (a) and simulated hanging (concave) and convex bridges (c). Study 2 (bottom) - we used a convex physical bridge (b) and simulated different convex virtual bridges (d) - lower and higher than the physical bridge. Images (e) and (f) show participants using our VR setups during the studies.

Abstract

Virtual reality (VR) is limited in many ways and often is incomparable to real-world experience. Walkable smooth uneven surfaces are inherent to reality but extremely lacking in VR. At the same time, VR offers a lot of possibilities for manipulations. In this paper, we focus on human height and slant perception of the uneven surfaces with multi-sensory stimulation in VR. By employing viewport manipulations, haptic, and vibrotactile stimuli, we explore the possibility to simulate uneven surfaces different from the physical props used.

Our results suggest that the use of a rounded prop helps to create a more convincing illusion of an uneven surface that is significantly higher than the physical one. The multi-sensory stimulation brings both height and slant estimations closer to the values suggested by the visual cues if there is no conflict with the haptic sensations. The use of a flat prop is less realistic and leads to massive height and slant underestimations as opposed to those suggested by visual cues. However, if the curved prop cannot be used, a flat surface might still be used to simulate small dents and bumps.

Index Terms: Human-centered computing—User studies; Human-centered computing—Virtual reality; Computing methodologies—Perception;

1 Introduction

There is a clear gap between the real and virtual worlds. Virtual reality (VR) is always limited by the size of the physical tracked space. In the ideal VR setup, as conceptualized in the Holodeck from the Star Trek series, the freedom of natural movement is unrestricted both in the horizontal and the vertical directions.

Extensive research has been done for real walking on a flat horizontal surface. To overcome the limits of the physical space, a variety of methods were suggested to compress the virtual space. Some are altering the way users see the results of their motion and are known as redirected walking techniques (RDW) [27]. Others are changing the structure of the VE, creating self-overlapping impossible spaces [39], or bringing the concept to the extreme as dynamically restructuring flexible spaces [42]. A notably smaller number of publications propose techniques also for vertical locomotion. Virtual stairs and ladders [17, 32], elevators [43], as well as the camera viewport manipulations to simulate uneven terrain [19] are still bound to the flat horizontal surfaces.

Simulation of the smooth uneven walking surface poses significantly different challenges than existing horizontal or vertical space extensions. Unlike the techniques mentioned above, the smooth uneven surfaces require consideration for the contributions of different sensory systems to the final perception. A realistic uneven terrain requires the shape and height variations, preferably without regularity. To achieve this goal, the perception of height and slant in VR should be addressed. As any VR simulation is limited by the volume of the workspace, so is the number of the available physical props in it. Consequently, the props should be reused as much as possible. For the effective simulation, we need to know what manipulations might be used to create a believable and not monotonous illusion of an uneven surface using a single prop.

In this paper, we focus on simulation of smooth uneven surfaces and possibilities to variate the perceived height and slant within a VR setup with one physical prop. We explore the cases with two different physical bridges together with visual bridge height manipulation in the virtual environment (VE), camera height and pitch manipulation, and vibrotactile stimulation. Our evaluation methodology allows

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for determining the influence of each stimulus or their combinations together with the added visual height. Thus, our contribution is extending the knowledge about how height and slant perception might be manipulated for a believable vertical traversal within the available physical workspace.

2 Related Work

The world around us is defined by how we perceive it and what instruments are available to us to sense it and to process the acquired information. Sensory integration is a process that brings together the sensory information from different sources to form the final representation of the world [31]. This applies to the real world, but also VR. However, the latter offers a lot more possibilities to interfere and change the perception of the synthetic world.

2.1 Height and Slant Perception

Human perception of height and slant has been extensively researched in the real world, but not fully addressed in VR. In general, people overestimate heights [45]. The overestimation was shown to be dependent on the viewing perspective: looking up from below or looking down from above, where the latter has a significantly stronger effect [34]. States of heightened emotions (arousal, disgust, fear) can also increase the overestimation of height perception [33]. Fear has an especially high impact on the overestimation [8].

People also tend to overestimate the slant in their conscious estimations [10], while visually guided actions are unaffected [25]. The slant perception is also dependent from various factors, such as feeling of fear [35], mood [28], and social factors [30]. Furthermore, a physical state like fatigue might make the hill look more steep [3]. Proffitt et al. found that slant overestimation is not dependent on viewing direction (head-on vs. sideways view) [26]. They conducted experiments in real-world and VE settings and found matching results. It has also been shown that haptic cues can enhance visual slant perception if they are consistent [11].

2.2 Non-flat VEs and Haptics

Uneven surfaces with corresponding haptic sensations are intrinsic parts of the real world and its multi-sensory representation. Unfortunately, both are often lacking in VR.

Marchal et al. evaluated the effectiveness of different camera manipulation techniques for simulating height changes [19]. They proposed four methods to simulate uneven surface with bumps and holes that are not rendered while walking on a flat floor: 1) adjusting the height of the virtual camera to maintaining its relative position to the uneven surface; 2) changing the pitch of the camera according to the tangent of the surface; 3) modifying the camera movement velocity; 4) combining all three methods. This paper is partially building on their findings.

Some techniques rely on electro-mechanical devices to create a physically changing environment. Iwata et al. proposed a device with platforms that trace the user's feet and return them to the neutral position [14]. Nagao et al. combined camera manipulations and passive haptic stimulation to create an infinite stairwell [21–23]. Vasylevska and Kaufmann proposed to use a multi-sensory stimulation platform that vibrates in accordance with the audio recording for the elevator simulation [43]. They showed that the elevator was more natural, increased the sense of presence, and better supported the spatial orientation than magic metaphors of flying [41] or teleportation [4].

2.3 Multi-Sensory Stimulation for VR

Typically, designers of a VR experience can stimulate only some of the sensory systems. Dinh et al. showed that an increase in the number of stimulated sensory systems in accordance with VE contributes to the sense of presence, immersion, and memory [9].

The sensory information from different sources might result in sensory misalignment. That, in turn, might lead to cybersickness [15] or be resolved in favor of dominating senses. With careful design, the sensory misalignment might be used for the benefit of the VR experience. Camera viewport manipulations for heights simulation [19] or space compression via redirection [27] set perfect examples. Marshall et al. made an overview and suggested a typology of creative applications with the purposefully introduced sensory misalignment [20].

Vibration has also been used in VR for various purposes: to provide a sensation of touch [6], to augment the interaction with the VE through a full-body vibrotactile suit [18], improve the sense of presence [43], or to reduce cybersickness [44]. Harazin and Grzesik showed that the floor vibrations are propagating through the whole body up to the head [13]. The vestibular system is sensitive towards low and high-frequency vibrations [40, 44]. That suggests that the floor vibrations might be used to alter the sense of touch, proprioception, and vestibular system.

2.4 Locomotion and Redirection

Real walking in VR has been shown to have a positive influence on user's sense of presence [41], spatial updating [7], search task performance [29], attention [38] and higher mental processes [46]. However, as the real workspace for the VR setup is often limited, the user's senses are subject to manipulations in order to fit the VE into it. To avoid the breaks in presence in VR, it is desirable that the manipulations stay unnoticed. Bruder et al. covered the periphery of the user with a grey overlay for a few frames, during which they unnoticeably reoriented the virtual camera [5]. Peck et al. suggested a more continuous version of redirection. They applied rotation while the user was distracted by a hummingbird flying around him [24]. Redirected walking (RDW) uses gains to control the mapping of real and virtual spaces from the user's perspective. These gains should be applied within thresholds, exceeding which will make the RDW noticeable and might induce cybersickness [12, 36, 37]. To integrate RDW into research and entertainment projects, Azmandian et al. developed a free toolkit for the Unity 3D game engine [2]. Our experiments use the redirection to create an illusion of locomotion through a large VE with the different uneven walking surfaces.

3 General Design

To address the issue of uneven surfaces in VR, we choose to use bridges for several reasons: 1) the bridge is a real-world object that can be integrated into VR, 2) bridges allow ascending and descending, 3) physical props will provide safe and controlled usage by design. Based on the previous research, we selected the following factors for investigation: visual height of the virtual bridge, camera pitch manipulation according to the virtual bridge, vibrotactile stimulation.

Our hypotheses are: H1. An uneven physical surface will allow for larger height manipulations. H2. Pitch manipulation will increase the perceived slant, especially with an uneven physical surface. H3. Vibrotactile stimulation will increase the perceived height and slant and even more so for an uneven physical surface.

To evaluate the chosen factors, we chose a within-participants experimental design with several visual heights and all possible combinations with the other binary independent variables (present or not). The sequences of virtual bridges were generated using a balanced Latin square. Additionally, each bridge sequence was counter-balanced to compensate for the potential learning effect. Finally, we decided to perform two independent user studies, each with a different physical bridge: one flat and one curved.

3.1 Virtual Environment

The virtual environment is implemented as a scene with a mountain lake and small islands on it. VE features ambient sound (splashing waves and bird noises) to aid immersion and mask the sounds unrelated to the experience, such as location and movement of the experimenter, or the sound of the working audio transducer. The islands are positioned in a zig-zag pattern and connected by the bridges with a maximum of two per island. Two neighboring bridges always are at an angle of 30 degrees to each other. To reach the final island, the participant has to cross all bridges and perform the tasks to progress. We chose to avoid the usage of realistic visuals in favor of a better frame rate, as visual fidelity does not have a profound effect on the sense of presence and the forming of memories [9].

For the virtual bridges, we use a self-made bridge model that allows for precise parametrization in height, length, width, and curvature of the bridge and railings. It allows us to control the visual shape of a bridge precisely and corresponding camera height and orientation manipulations. While walking from one island to the next, the participant is crossing the virtual bridges. Each virtual bridge features a unique combination of the manipulations applied. Meanwhile, in the real world, the participant is redirected back onto the very same physical bridge. Fig. 1 shows the physical bridges used (a & b) and VEs with sample bridges from Study 1 with the flat bridge (c) and Study 2 with the arched bridge (d), as well as users in the workspace during the studies (e & f).

3.2 Physical Bridges

To fit a physical bridge into our workspace and leave enough space for redirection, we chose the following parameters for both studies: length - 3m, width (between the railings) - 55cm, railings height - 90 cm. As the primary construction material, we chose wood. The walking surfaces of the bridges are covered with wooden planks with spacing between them. This way, we provide a better grip for the shoes and additional haptic sensations. For sturdiness and better distribution of the vibrations of the audio transducer, we put metal planks under the entire length of each bridge and positioned it along the center-line. The audio transducer is mounted in the middle of each bridge in direct contact with the metal. To avoid splinters, we made the railings from the plastic cable tunnels. The resulting constructions are shown in Fig. 1 (a & b).

3.3 Manipulations

We use multi-sensory stimulation: change of height (positive or negative) and pitch rotation of the viewport, as well as vibrotactile stimuli. Additionally, the physical bridges provide passive haptic feedback of actually stepping onto/off from a real bridge and touching the railings. The curved bridge in Study 2 also provides the proprioceptive cues of a tilted surface. Our height and pitch manipulations are inspired by the previous work by Marchal et al. [19]. However, our manipulations are strictly based on visuals, while their approach targeted an abstract bump or hole simulations without visual distinction between them.

3.3.1 Height Adjustment

The head and torso are continuously on the move even while standing. Their positions are not ideal for height adjustment, as during the leaning forward or interacting with the VE the manipulation might become unnatural and obvious. We also could not use the feet for it. Even though previous research suggests that their visual representation is beneficial for the sense of presence [1], the high degree of occlusion created by the props' railings made the feet tracking unreliable. Therefore, for the height adjustment of the virtual camera, we placed a tracker on the tailbone. Its positioning is more stable than the head and more reliable than the calculations based on the feet positions. That resulted in the adequate height adjustment and allowed the user to freely interact with the bridges without visual artifacts.

The height adjustment is calculated from a function that describes the shape of the bridge. The function is evaluated at the users' position along the center-line of the bridge. Additionally, we defined short transition areas (0.5m) at the ends of the bridge, where the adjustment was gradually introduced and scaled-down. This is done to prevent a noticeable change of camera position when getting onto/off the physical bridge. For the safety and more natural experience, the hand-held controllers are also adjusted in height but based on their specific position in the workspace. This way, the visual and haptic stimuli always match, and the physical railings can be easily reached.

3.3.2 Pitch Manipulation

The additional pitch rotation is representing the angle between the real bridge center-line and the tangent line to the function describing the curvature at the corresponding point. After preliminary testing, we reduced the manipulation to the 50% of the calculated angle to avoid overstimulation, mentioned in [19]. Similar to the height adjustment, our pitch rotation has the same transition area to prevent sudden changes in orientation. Furthermore, we apply it depending on the angle between the participant's viewing direction and the bridge's center-line. Application of the calculated pitch smoothly transitions between the maximum of the additional pitch rotation when the viewing direction is parallel to the bridge's center-line, and down to 0 of extra pitch rotation when the viewing direction is perpendicular to it. Preliminary testing showed that this mitigates disorientation and cybersickness issues when looking around the VE. Otherwise, the view gets unnaturally tilted.

3.3.3 Vibrotactile Stimuli

To create the vibrotactile stimuli, we used an audio transducer. As an input signal, we use an audio file containing a uniform sound wave. We tested frequencies in the range of 20-60Hz. Based on our unofficial observations, a frequency of 40Hz was chosen. It was not as disturbing as 20Hz but still perceived as whole-body vibrations, unlike the higher frequencies. The latter might depend on the material used in our setup. The transducer was turned on before the user steps on a bridge ($\approx$ 2s) and turned off when the user left the bridge. We used volume fade in/out to avoid the detection of the start/stop of the transducer by the user. Due to the differences in physical bridges, the amount of signal amplification was adjusted. We aimed at a slightly noticeable but not disturbing or destabilizing effect that is comparable between the bridges.

3.3.4 Redirection

To be able to use one physical bridge while crossing multiple virtual bridges, we use the existing Redirected Walking Toolkit by Azmandian et al. [2]. Our redirection phase is disguised as a game of "pop the balloons." Colorful balloons are spawned pseudo-randomly one-by-one based on the maximum redirection potential on the current island. The participant has to locate a balloon, then walk up to it and pop it by touching it with a controller.

The redirection is achieved using two different methods, separated by the time when they are activated. The first method is a classic steer-to-center type redirection. It is applied while participants look around to locate the balloons and walk up to them. We set the gains' thresholds to the 50% of those described in [36] to guarantee the safety and imperceptible redirection within our limited free space (2x4m). This way, we minimize the risk of collision with the prop in case of redirection malfunction or user's misbehavior.

To ensure both fast and accurate overlay of the real bridge with the next virtual model, we implemented our second method. It combines change blindness and optical flow simulation as in [5] to introduce additional unperceived redirection. When the participant fixates his/her view on the balloon and touches it, the balloon's position relative to the virtual camera is stored. On touch, the field of view is filled with dense, colorful spherical particles, simulating confetti. At the same time, extra rotation ($\leq 5°$) and translation ($\leq$30 cm) are

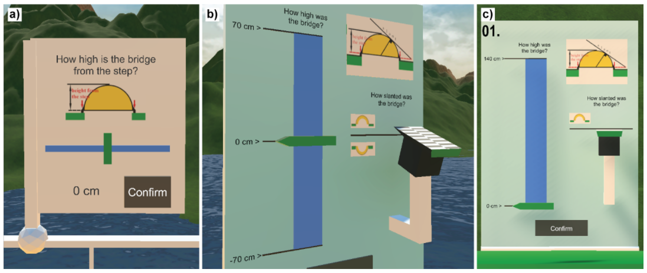

Figure 2: Experience reporting interfaces inside the VE. a) Reporting interface on the bridge. b) A reporting station on the island, close-up view of the height slider (left), and the slant estimation pad (right) as used in Study 1. The slant pad is already tilted from a neutral horizontal position upwards at 20 degrees. c) Reporting interface after the bridges, full view as used in Study 2. The scales of the height sliders used for visual estimations differ to match the experimental conditions: Study 1 scale [-70..70] cm, Study 2 scale [0..140] cm.

added to the camera pose to achieve the planned position for each redirection step. The particle emission center is moved together with the camera maintaining the previously-stored relative position to keep the manipulation unperceived.

3.4 Measures

For our analysis, we asked the participants to estimate the height twice per each virtual bridge: once at the center of the bridge, and once after the bridge was crossed. On the bridge, we asked them to estimate the height in centimeters using a simple horizontal slider, as shown in Fig. 2 (a).

At the island we created a reporting station (see Fig. 2 b & c). First, participants were asked to visually estimate the height of the experienced bridge using a vertical slider. This scale contained markings only at zero and at maximum scale values in cm (the very same were used on the bridge), and its length matched the real-world scale exactly. Then, we asked participants to tilt the measuring pad from a neutral horizontal position to visually set a maximum slant they experienced on the bridge. After that, participants answered the following questions about their subjective experience of the recent bridge. All answers to the questions were given via a 7-point float Likert-like scaled sliders. The main points were annotated from very positive, through neutral, to very negative. We enquired about the general state of the participant by asking "How do you feel after this bridge?", about the preferences - "How did you like this bridge?", and about the naturalness of the experience - "How natural was the movement on the bridge?".

4 General Procedure

For the successful creation of an illusion, the participants did not see the workspace until the end of the experiment. Participants were greeted outside the laboratory and briefed about health and safety, privacy, and data protection details. They read and signed the informed consent form, confirming that they are physically fit to participate, understood the risks and general recommendations for the VR exposure. Next, participants filled out Kennedy's simulator sickness pre-test [16] and a general information questionnaire, screening for age, gender, and VR experience.

After that, the experimental procedure was explained. Participants were asked to cross the virtual bridges one by one and report their experience. We specifically addressed how to step on/off from the bridges and how to use the reporting posts in VR. Participants were allowed to take a break between tasks or discontinue the experiment at any moment. They were also asked to comment verbally on their experience or ask questions while they are in VR. Then, the participants were fitted with the equipment and led to the starting position in the workspace, with the head-mounted display (HMD) occluding the real world. In VR, they were first trained to use the reporting interface using hand-held controllers. When participants confirmed that they are comfortable with controlling the interface and that they understood the task, the experiment commenced.

Task The participants had to reach the last island. Each bridge crossing cycle consisted of the following steps: 1) observe the bridge from the island; 2) walk halfway over the bridge; 3) estimate the height of the bridge in centimeters (also to focus the participant on the experience); 4) finish crossing the bridge and go to the reporting station; 5) report the height and slant estimations; 6) report subjective experiences; 7) play the pop-the-balloon mini-game (redirection to the next bridge); 8) observe and continue to the next bridge. After the experiment was completed, participants were led out of the laboratory. They filled out the SSQ post-test and answered a few additional questions: 1) How did you estimate the height of the bridge? 2) How many virtual bridges of different height did you notice? (same heights count as one) 3) How many real bridges were used? 4) Was there anything that contributed or took away from the experience? Finally, participants could also leave any further comments they considered necessary.

5 Technical Setup

The participants were equipped with the HTC Vive Pro HMD in a wireless configuration. We used the HTC wireless adapter battery placed in a belt bag. The tailbone of the participant was tracked with an HTC tracker. Finally, participants were provided with two Vive Pro Controllers to allow task performance and support a more confident interaction with the physical bridge. We used four 2^{nd} generation HTC Lighthouse tracking stations to create a workspace 6 x 10 meters. To ensure a seamless VR experience, a second HTC tracker was used to ensure a fixed floor height due to occasional Steam VR glitches. The VE was rendered using the Unity 3D game engine on a desktop PC with an Intel Core i7 9900K CPU and an NVidia RTX 2080Ti graphics card. The audio transducer affixed to the bottom center of the physical bridges (Buttkicker LTE) was controlled from a notebook, connected to the transducer's amplifier.

6 User Study 1

This study followed the general design and measures described above. Only one physical bridge was used to simulate different virtual bridges.

6.1 Design

For Study 1, we used a flat physical bridge (for construction details see Sect. 3.2). The walkway surface of the bridge is equally elevated from the floor by 12 cm to ensure stability and accommodate structural elements (audio transducer and vibration conducting metal). Our bridge model included this peculiarity so that participants saw that a step up should be taken for every virtual bridge.

For the task performance, we asked the participants to regard the step on the bridge (12 cm from the floor level) as a starting (zero) point of height and slant estimations. The graphic depiction of how to do the estimations was used during the instruction process and placed on all the reporting stations in VE (see Fig. 2).

We set up a VE with 17 virtual bridges (see Fig. 3 for a partial view of the VE). Five levels of added visual heights have been selected in preliminary testing, with an interval of 20 cm for height manipulations. Forming a set of the hanging (concave) bridges with -40 cm and -20 cm added visual heights, and upwards curved (convex) bridges with 20 cm and 40 cm maximum deviation from the flat surface of the real bridge. Height and curvature for the 3D models of bridges with manipulations are calculated and set via a scaled sine function. Finally, there was a flat bridge identical in form to the physical bridge.

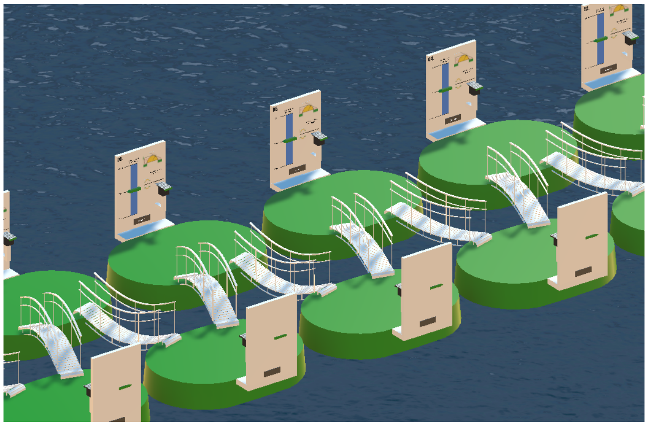

Figure 3: Birds view of the VE used in Study 1 with a flat physical bridge. The whole scene contains 17 virtual bridges that differ in heights and the multi-sensory manipulations applied. Note that during the study the participants saw only one bridge at a time.

This ground truth flat bridge without any manipulations was placed at the end of all sequences, as it was too revealing for the setup and would have biased any other virtual bridge coming after it. Moreover, the results of this bridge were problematic for the statistical analysis, as pitch manipulations and height manipulations could not be applied to it.

6.2 Population

22 persons took part in study 1: 10 female and 12 male, aged 21-64 years old with a mean of 38.5 (standard deviation SD = 11.68). Twelve participants (54.4%) indicated that they had no prior experience with VR. The rest declared to have some experience, and only one participant indicated being a VR expert. Participants were recruited via Facebook and a mailing list for VR research recruitment on a volunteer basis. They were required to be over 18 years old, not suffering from severe motion sickness, epilepsy, or any other critical condition, as well as contact-transmitted diseases. All of the participants had normal or corrected to normal vision.

6.3 Results

To analyze the data, we mainly used a 3-way Factorial ANOVA. For the cases when the assumption of sphericity was violated, we report the F-values according to the conservative Greenhouse-Geisser correction (ε). Contrasts and T-tests are done with the Bonferroni adjustment for multiple comparisons, where it is appropriate.

For the quantitative measure of the strength of a phenomenon, we rely on the measure independent Pearson's correlation coefficient (r) for effect size estimation and Cohen's benchmark for interpretation ($r \approx 0.1$ - small, $r \approx 0.3$ - medium, and $r \approx 0.5$ - large effect).

Data representation. For Kennedy's SSQ, the strength of each symptom was encoded on a scale: 0 – none, 1 – slight, 2 – moderate, 3 – severe. Answers to questions with sliders and 7-point Likert-like scales were encoded as float values from +3 (for the most positive answer) to -3 (for the most negative answer).

6.3.1 Height Perception

For the analysis, we used the data collected at the reporting stations due to the completeness of the experience. A boxplot with the height estimation results clustered according to the multi-sensory simulations used is shown in Fig. 4.

The sphericity test determined the assumption was violated for the height estimations ($\chi^2(5) = 80.092, p < 0.001, \varepsilon = 0.371$). There was a significant main effect of visual height on height judgements made ($F(1.112) = 34.373, p < 0.001$). Other independent parameters did not produce any trends or statistically significant effects. Contrasts showed that the height estimations differed significantly between different added visual heights (all $p < 0.001, M_d$ stands for mean difference):

- -40 and -20 cm ($F(1) = 28.908, r = 0.76, M_d = 10.44$ cm),
- -20 and +20 cm ($F(1) = 30.142, r = 0.77, M_d = 17.02$ cm),
- +20 and +40 cm ($F(1) = 25.681, r = 0.74, M_d = 11.66$ cm).

6.3.2 Slant estimations

A boxplot with the slant estimation results clustered according to the multi-sensory simulations used is shown in Fig. 4.

The Maulchly's test showed that the sphérisity assumption was violated for the visual height variable ($\chi^2(5) = 78.988, p < 0.001, \varepsilon = 0.381$) as well as for the interactions of visual height and vibrotactile stimulation ($\chi^2(5) = 12.643, p = 0.027, \varepsilon = 0.72$) and visual height, vibrotactile, and camera pitch manipulation ($\chi^2(5) = 13.462, p = 0.02, \varepsilon = 0.788$). There was a significant main effect of visual height on slant estimations ($F(1.144) = 35.763, p < 0.001$).

Contrasts showed that the slant estimations differed significantly between different visual heights in favor of the higher ones (unless stated otherwise $p < 0.001$):

- -40 and -20 ($F(1) = 17.762, p = 0.002, r = 0.68, M_d = 6.3°$),
- -20 and +20 ($F(1) = 30.821, r = 0.77, M_d = 12.77°$),
- +20 and +40 ($F(1) = 35.879, r = 0.79, M_d = 6.5°$).

6.3.3 Questions

Bridge Post-exposure Physical State Self-reports. Camera pitch manipulation had a main effect on the participants' state self-report values with a large effect size ($F(1) = 8.787, p = 0.008, r = 0.55$). That suggests that pitch manipulation might slightly contribute to the cybersickness. After the bridges without slant, participants' self-reports were slightly higher than with it ($M_d = 0.26$ of a point).

Bridge Preferences. Camera pitch manipulation also showed the ability to influence the preferences by lowering the scores on average by 0.22 of a point, resulting in a trend for significance with medium-sized effect ($F(1) = 4.349, p = 0.05, r = 0.42$).

Bridge Naturalness. Here, the visual height had a statistically significant main effect ($F(3) = 13.766, p < 0.001$). Contrasts revealed the significant differences in answers for the conditions with added visual heights. The bridges with lower amounts of added visual height ($\pm 20cm$) were perceived as "somewhat natural," while conditions with $\pm 40cm$ of added visual height were rated as "somewhat unnatural" if there was a pitch or vibrotactile stimulation. Our baseline condition was rated the highest ($MD = 2.29, SD = 1.05$) which is equivalent to answer "natural" in comparison to the rest of conditions that had the median of ratings slightly below 1 in case of $\pm$ 20 cm and around or below 0 for $\pm$ 40 cm of added visual height.

6.3.4 Cybersickness

As the numbers and strength of the reported symptoms were rather low, we computed the sum of the SSQ symptoms for each participant for pre - and post-exposure. Due to hot weather, a majority reported stronger sweating in the pre-test than post-test. We had to exclude the sweating symptom to avoid biasing the results. The paired samples T-test showed that on average participants experienced a slight increase in total cybersickness score ($M_{sumdiff} = 1.0, SD = 2.07$) which was statistically significant ($t(21) = 2.266, p = 0.034, r = 0.44$). That means that the SSQ post-exposure scores typically increased by 1 point for only one symptom.

6.3.5 Virtual and Real Bridges

According to participants' reports, they noticed a mean number of $M = 7.18, SD = 2.79$ different virtual bridges that differed in height, although there were only 5 visual heights in the VE. For the real bridges, the mean detected number was $M = 2.86, SD = 3.32$. Paired

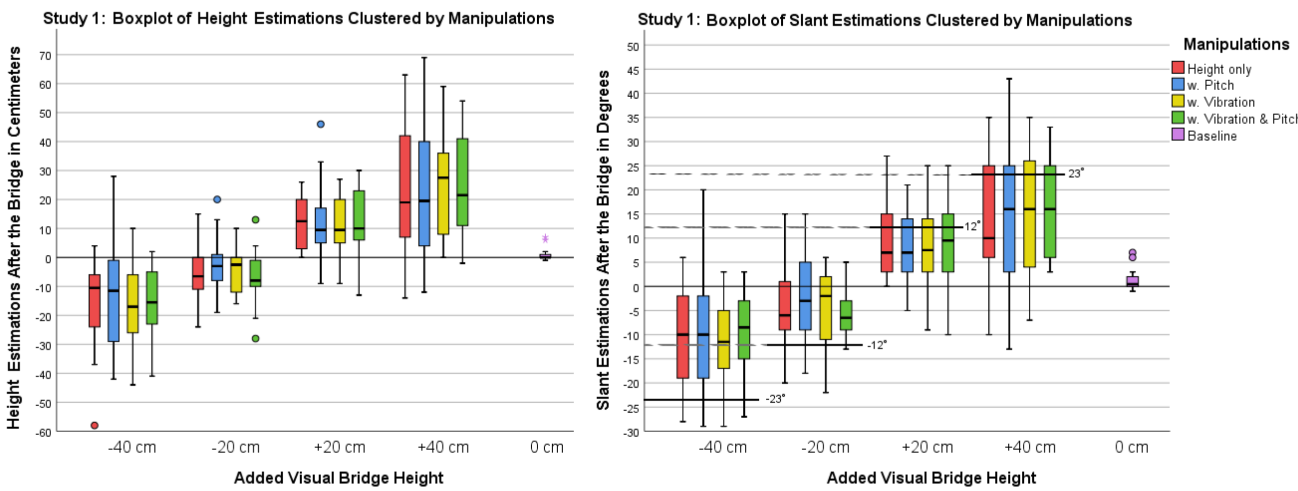

Figure 4: Study 1: Clustered boxplots for the heights (left) and slant (right) estimations for the flat physical bridge. Added visual height denotes the maximum additional height added to the virtual bridge model that replicated the real bridge. The estimations are done relative to the start of the bridge (12 cm off the ground). Slant graph includes the indication of the maximum slant of virtual bridges in accordance with the value of added visual height.

samples T-test also showed that the difference in numbers of virtual and real bridges is statistically significant with a large effect size ($t(21) = 8.116, p < 0.001, r = 0.87$).

6.4 Discussion

The use of the flat surface for uneven terrain simulation has its benefits and drawbacks. The positive factors are its practicality and lack of limitations for the type of terrain (elevation or indentation). However, our results show that both heights and slants were strongly underestimated in all conditions, suggesting that the persuasiveness of the simulations was not very high.

The height estimations for the virtual bridges were equal to a half of the simulated visual height if the virtual bridge was convex and even less for the concave bridges. The severe underestimations cannot be explained by a misunderstanding of the task by the participants. As in such a case, this should reflect in all estimations for the virtual bridges, including the flat baseline bridge, and shift them up uniformly by at least 10 cm. Consequently, an expected height estimation from the ground for the baseline would be 12 cm, but it follows the task instructions and is estimated to be 0 cm. Therefore, the fact that it did not happen suggests that the task was understood correctly.

The conditions with vibrotactile stimuli showed a tendency to bring the height estimations slightly closer to the desired effect for the large added visual heights (i.e., $\pm$ 40 cm), but not for the smaller values (see Fig. 4, left boxplot). That might be linked to a potential of vibrations to alter the proprioceptive, tactile, and vestibular cues and playing in favor of the visual input when the sensory conflict is resolved. Further research is necessary to draw a conclusion.

Similarly, the slant estimations were below the values that could have been expected based on the visuals. The estimations were closer to the expected values for the elevated convex bridges, and the additional stimuli seem to increase the estimated slant. For the hanging bridges, the underestimation was noticeably stronger and correlated with the height estimations. That might be explained by the more extensive experience with elevated bridges rather than hanging (concave) bridges in real life.

Unlike the real world research [34], in our setup, the height estimations did not depend on where they were made: on or off the bridge. Participants were able to distinguish the original bridge from the visually similar bridges with the small amounts of added visual height. It was rated as the most natural, and both estimations for it had the smallest variation. Moreover, almost half of the participants at the end of the experiment knew that there was only one physical bridge. We would expect an even higher level of detection if no prop is used for the simulation. This is based on a variety of existing replications of a ”virtual pit.” There feeling of leaving the floor and sensation of the board are very beneficial for the experience.

Altogether, our results suggest that simulations of smooth uneven surfaces might benefit from the use of non-flat physical surfaces. If the flat physical surface is used during the uneven terrain simulation, the minimum amplitude of the variation of the visual height should exceed 30cm and possibly employ vibrotactile stimulation.

7 User Study 2

Driven by the assumption that with a purposeful haptic and proprioceptive stimulation we can achieve better results than in study 1, we built a curved physical bridge. It has the same parameters as the bridge in study 1 (with a metal construction underneath), but the walkway is arched over the ground.

7.1 Design

Unlike study 1, the curved bridge allowed pitch manipulation for the ground truth and had a physical height. Thus, it also did not expose the manipulations and could be included in the experimental sequence. For the maximum height of the prop, we tried 20 and 30cm. As the former did not result in a well perceivable slant, we decided to use 30 cm height. For safety reasons, the shape of the bridge was made a bit more flat on the sides than in study 1. We adjusted the 3D model parameters to match the real bridge. That resulted in slightly different real and virtual slants than in study 1.

In this study, we maintained the 20 cm iterations of the added visual bridge height but excluded the hanging bridges due to the risk of tripping and falling. That resulted in the following set of added visual heights: -20 cm, 0cm (physical bridge height unmodified), +20 cm, and +40 cm. The binary variables (vibration and pitch) stayed the same. This configuration resulted in 16 different virtual bridges. The counter-balanced sequences were generated via a balanced Latin square. Measuring methods, technical setup, and procedure were identical to study 1. A partial view of the VE with visible bridges is shown in Fig. 6.

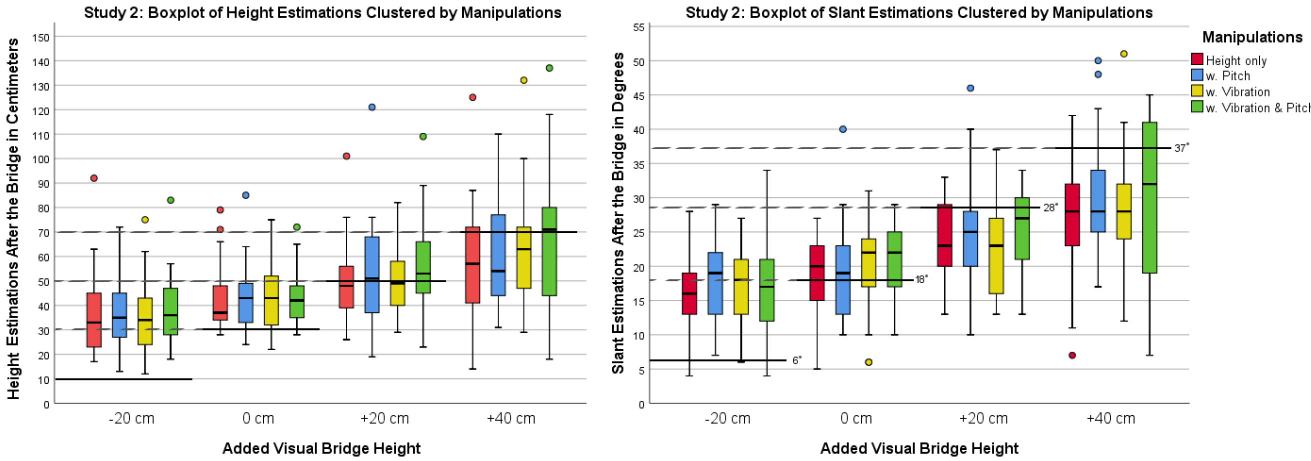

Figure 5: Study 2: Clustered boxplots for the height (left) and slant (right) estimations. Height estimations have additional indication of visual heights of the bridges in the VE. Slant graph includes the indication of the maximum slants of the 3D models for each level of added visual height.

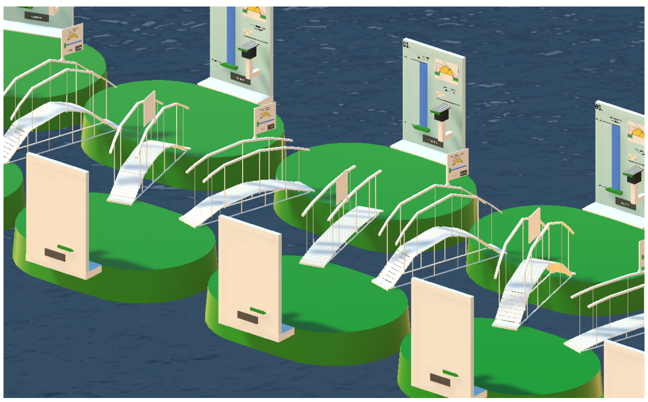

Figure 6: Birds view of the VE used in Study 2 with one curved physical bridge. The whole scene contains 16 virtual bridges, with visual heights of 10/30/50/70 cm. Note, that during the study the participants saw only one bridge at a time and there were no visible bridge during the task performance.

7.2 Population

Participants were recruited in the same way and under the same conditions as for study 1. 21 persons participated in study 2: 11 females and 10 males, aged 23-63 years old with a mean of 34.43 (SD = 12.24). No one of them participated in study 1.

VR Experience: 11 participants (52.4%) indicated that they had no prior experience with VR. The rest declared to have some experience, and only one participant reported that he is a VR expert.

7.3 Results

Results are reported using the same methods and data encoding as in study 1. The total time of the experiment was approximately 1 hour.

7.3.1 Height Perception

A boxplot with the height estimation results clustered according to the multi-sensory simulations used is shown in Fig. 5 on the left. The sphericity test determined the assumption was violated for the height estimations ($\chi^2(5) = 31.083, p < 0.001, \varepsilon = 0.5$). There was a significant main effect of added visual height on height judgment made after experiencing the bridge ($F(1.5) = 24.693, p < 0.001$). Contrasts showed that the height estimations differed significantly between different added visual heights ($p < 0.008$):

- -20 and 0cm ($F(1) = 12.94, r = 0.62, M_d = 5.99cm$),
- 0 and 20cm ($F(1) = 22.62, r = 0.73, M_d = 9.18cm$),
- 20 and 40cm ($F(1) = 8.8, r = 0.55, M_d = 9.21cm$).

7.3.2 Slant Perception

A boxplot with the slant estimation results clustered according to the multi-sensory simulations used is shown in Fig. 5. The Maulchly's test showed that the sphericity assumption for the slant estimations was violated for the visual height variable ($\chi^2(5) = 22.859, p < 0.001, \varepsilon = 0.605$). There was a significant main effect of visual height on slant estimations ($F(1.818) = 31.512, p < 0.001$) and slant adjustment ($F(1) = 7.056, p = 0.015$). Contrasts showed that the slant estimations differed significantly between different visual heights in favor of the higher ones:

- -20 and 0cm ($F(1) = 11.317, p = 0.003, r = 0.6, M_d = 2.62°$),
- 0 and 20cm ($F(1) = 22.78, p < 0.001, r = 0.73, M_d = 4.18°$),
- 20 and 40cm ($F(1) = 11.478, p = 0.003, r = 0.6, M_d = 4.99°$).

7.3.3 Questions

Bridge Post-exposure Physical State Self-reports. There were the following effects on the participants' state self-report values: statistically significant main effects of added visual height that violated the sphericity assumption ($\chi^2(5) = 17.803, p = 0.003, \varepsilon = 0.665, F(1.995) = 13.668, p < 0.001$), and interaction of added visual height and pitch manipulation ($F(3) = 4.329, p = 0.008$). Pitch manipulation alone resulted in a trend for significance ($F(1) = 4.068, p = 0.058$), although its presence decreased the mean rating by 0.2. Contrasts revealed the significant differences for the following levels of added visual height: -20 and 0 cm ($F(1) = 6.99, p = 0.016, r = 0.51$), as well as 20 and 40 cm ($F(1) = 21.066, p < 0.001, r = 0.72$).

Bridge Preference. Unlike study 1, for the preferences for the bridges we found the following statistically significant effects: added visual height ($F(3) = 21.461, p < 0.001, r = 0.73$), camera pitch ($F(1) = 8.741, p = 0.008, r = 0.56$), and their interaction ($F(3) = 4.585, p = 0.006, r = 0.44$). In addition, there was a trend for significance for the interaction of added visual height and vibration ($F(3) = 2.741, p = 0.052, r = 0.35$).

Bridge Naturalness. For the naturalness, the statistically significant main effects were found for the added visual height ($F(3) = 30.659, p < 0.001, r = 0.79$), pitch manipulation ($F(1) = 6.314, p =$

$0.021, r = 0.5$), interaction of added visual height and vibration ($F(3) = 3.946, p = 0.013, r = 0.41$), and only a trend for the added height and pitch interaction ($F(3) = 2.575, p = 0.063, r = 0.34$).

The naturalness rating differed significantly for all the visual heights ($p < 0.004$). The bridges without height manipulation were rated as the most natural $M_{0cm} = 1.585$, and the bridges with added visual height were rated as "somewhat unnatural." Added vibration made a difference for the added visual heights -20 and 0 cm ($F(1) = 7.431, p = 0.013, r = 0.53$), as well as 0 and 20 cm ($F(1) = 6.228, p = 0.022, r = 0.5$), increasing the scores for the cases with height manipulation.

7.3.4 Virtual and Real Bridges

According to participants' reports, they noticed $M = 5.33, SD = 2.37$ different heights of virtual bridges, which is correct. As for the real bridges, participants reported 4 ($M = 3.9, SD = 4.31$) real bridges on average.

7.3.5 Cybersickness

As the cybersickness symptoms were barely present, we used the same approach as in study 1: sum up all the symptoms, excluding sweating. The mean total change in state among the participants was only slightly higher than in study 1 ($M_{sumdiff} = 1.9, SD = 2.23$), and was statistically significant ($t(20) = 3.907, p = 0.034, r = 0.66$). That means that the SSQ post-exposure scores typically increased by 1 point for two symptoms or by 2 points for one symptom.

7.4 Discussion

We observed major height overestimation for the bridges without height manipulation and negative added visual height. The underestimation was observed only for a large added visual height. However, the underestimation seems to be countered with a combination of pitch and vibrotactile manipulations, bringing the estimations in accordance with the visual stimuli.

Similarly to height, slant estimations for the virtual bridges with added visual height equal to 0cm and -20cm resulted in overestimation. For the bridges higher than the physical one, the slant was underestimated. Except for the case with negative added height, a combination of pitch and vibrotactile stimulation noticeably improved the estimations, bringing them closer to the values suggested by the visualization.

The state self-reports suggest that participants could feel if the added pitch did not correspond to the physical bridge, even though the added camera pitch was equal to a half of the visual slant. At the same time, the vibrotactile stimulation had no such negative effect and somewhat improved the preference and naturalness scores for the virtual bridges higher than the physical one, but only when used without the pitch manipulation. For the virtual bridges without added height, conditions with vibrations were somewhat less appreciated and natural.

Our results suggest that uneven virtual surfaces can be simulated using the slightly curved real props. However, the prop surface orientation should not conflict with the presented visuals. I.e., the visual height might be added only in the direction matching the bend of the real surface. Moreover, a combination of pitch and vibrotactile stimulation can be used to create a more convincing illusion of uneven virtual surfaces that otherwise clearly exceed the height of the real prop. However, the post-exposure answers suggest that the amount of the added pitch to the virtual camera should be slightly lower than 50% of the slant of the virtual bridge that we used. Further research is needed to check if the same would apply to the concave surfaces.

8 General Discussion and Conclusion

Smooth transitions between different heights are often seen in the real world, but often missing in VR. In this paper, we address the issue of the multi-sensory simulations of smooth uneven surfaces in VR and how they are perceived. In the scope of this project, we conducted two user studies: one with a flat physical bridge and another with a convex bridge.

Our findings suggest that simulation works best with a virtual surface that reflects the real surface or raises above it. The use of a flat real surface allows the simulation of a concave surface as well, but our observations suggest that the illusion of depth is less convincing than height. Also, the flat surface eventually will be detected by the users due to discrepancy of visuals with the proprioceptive cues. This limits the amount of visual manipulation that might be applied and still be safe. For the surfaces with the added visual height in range $\pm$20cm, the height manipulation alone is sufficient. For the stronger height manipulations, the use of vibration seems to contribute to the height perception (see Fig. 4. Regardless of stimuli, the perceived slant tends to be greatly underestimated.

The attempts to simulate height and slant smaller than those of the convex physical bridge were not very successful. Haptic and proprioceptive cues seemed to overrule the visuals as faulty information. This observation is consistent with the prior research by Ernst et al., where haptic feedback was reinforcing the visual slant perception if they were consistent and overruled it if they were not [11].

It is worth to mention our anecdotal attempts to walk over a virtual bridge that was hanging down well below the floor level while using the convex physical bridge. Albeit completed, the walk-through resulted in a state of strong disorientation, similar to the one experienced during a roller coaster ride. We find it interesting, as the roller coaster involves purposeful overstimulation of vestibular apparatus linked with correct visual feedback. At the same time, our attempts were purposefully set up for a sensory conflict between the vision and proprioceptive and haptic sensations. Yet, the resulting experiences were quite comparable.

The usage of the curved (convex) surfaces might be indeed beneficial for the simulations of uneven surfaces such as hills or bridges. Our participants systematically overestimated the height of the virtual bridges without height manipulation. They correctly estimated the height of the virtual bridge 20 cm (66%) higher than the physical prop with height adjustment alone. An additional 40 cm (133%) to the prop's height was perceived for the case where all three types of manipulation were used. That did not occur in study 1, therefore confirming our hypothesis H1. We assume that the usage of concave physical and virtual surfaces for depth simulations will produce similar results. However, further research is needed to confirm that.

In both studies, the conditions with pitch manipulation had increased variance of the perceived height and slant in comparison to the conditions without it. This manipulation also had a consistently negative impact on participants' state self-reports, preferences, and naturalness, even though we scaled it down to 50% of the calculated value. Thus, we could not confirm our hypothesis H2. We theorize that the pitch manipulation possibly should not be dependent on a surface shape as in our implementation, but rather use a fixed value. However, further research is needed to verify this assumption.

Vibrotactile stimulation improved the height and together with pitch manipulation also the slant estimations for conditions with large added height. It also seemed to improve the naturalness and preference scores for the bridges with high amounts of added height in study 2. At the same time, it was not effective for small values of height manipulations ($\pm$20cm). Therefore, the hypothesis H3 is confirmed only partially.

Ultimately, our results suggest that usage of the curved physical props in combination with redirection and multi-sensory stimulation is a viable approach towards a realistic VR simulation with a non-flat walking surface.

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