Perception of Height in Virtual Reality — A Study of Climbing Stairs

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ABSTRACT

Most virtual environments that people locomote through with head-mounted displays are flat to match the physical environment that people are actively walking on. In this paper we simulated stair climbing, and evaluated how well people could assess the distance they had climbed after several minutes of the activity under various conditions. We varied factors such as the presence of virtual feet (shoes), whether the stairwell was open or enclosed, the presence or absence of passive haptic markers, and whether a subject was ascending or descending. In general, the distance climbed or descended was overestimated, consistent with prior work on the perception of height. We find that subjects have significantly better ability to estimate their error with the presence of virtual shoes than without, and when the environment was open. Having shoes also resulted in significantly higher ratings of presence. We also find a significant tendency for females to show higher ratings of simulator sickness.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Empirical studies in HCI**; • **Applied computing** → *Psychology*;

KEYWORDS

virtual reality, height perception, virtual environments, locomotion

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1 INTRODUCTION

This paper investigates height perception in virtual environments (VEs) in conjunction with walking locomotion. Most walking interfaces in VEs, particularly those presented through head-mounted displays (HMDs), support only horizontal motion. Additional motions are sometimes supported to allow climbing and up-down movement [Lai et al. 2015; Slater et al. 1994b]. Usually, though, when general motion has been required in a VE, some form of "flying" interface has been the preferred technique [Stoakley et al. 1995; Tan et al. 2001]. However, interesting landscapes in the real world are rarely flat, and VR thus misses an important dimension of the physical world. The presented work does not focus directly on the design of a locomotion interface's support of non-horizontal travel. Rather, we examine how people perceive height as they locomote through a virtual environment that has significant height changes in it. Our choice is a commonly encountered environment—stairs. We employ a variant of a walking locomotion interface that has been recently developed for stair locomotion [Nagao et al. 2017, 2018].

The interface of Nagao et al. [2017] inspired us to conduct this study after we encountered the infinite stairs demonstration at SIGGRAPH 2017's Emerging Technologies program. In this exhibit, an infinite stairway was presented using passive haptic slats, which were placed to coincide with the stair edges of a virtual spiral staircase that one could climb. Their followup paper, Nagao et al. [2018], described the design of their system and evaluated both the shape of the passive haptic markers as well as how well they worked in terms of subjects' sense of presence and sense of riser height. Our goals were to further evaluate such a system in a more general locomotive setting and to perform a deeper evaluation of subjects' height perception.

Height perception in immersive VEs has been studied in the context of Gibson's theory that perception is directly related to action. Lin et al. [2012] studied height perception in the context of a passability *affordance*, where people had to judge the height of a door from the ground and determine whether they could pass underneath it without stooping. There have been fewer studies on direct height perception in immersive virtual environments, although literature exists on the effect of *eye height* on perception in immersive VEs (e.g., Corujeira and Oakley [2013]; Leyrer et al. [2011]).

Thus, there is little work evaluating the perception of height when using a locomotion interface to traverse a sloped environment in an immersive VE. In this paper, we take basic walking and assess whether the passive haptic markers proposed by Nagao et al. [2018] aid or hinder it. We further examine whether the presence of virtual shoes, the visual cues provided by an open or enclosed environment, and the direction of slope make a difference. We assess the perception of height with subjects' estimates of how high they had climbed and other measures of vertical distance. And we assess their overall experience through measures of presence and simulator sickness. In this paper, we first review relevant literature to this experiment. Then, we describe our stair system, stair climbing method, and the conducted experimental procedure. In the final sections we present our results and conclude with a discussion of these results.

2 BACKGROUND

Locomotion interfaces for dealing with verticality while walking through a VE are uncommon, although work has been done for most methods, including walking on treadmills [Iwata et al. 2001], walking-in-place [Slater et al. 1994b], using gestures [Lai et al. 2015], and walking with both passive [Nagao et al. 2018] and active [Nordahl et al. 2012] haptics. These techniques work by coupling eye height manipulation with a motor action, either a walking locomotion or a gesture. The idea, common throughout much of the redirected walking literature [Razzaque 2005; Williams et al. 2007], is that the visual feedback of moving up (in this case) coupled with a motor action will result in a compelling virtual experience of moving up in the real world. Marchal et al. [2010] studied a similar phenomenon for walking over uneven terrain in immersive VEs. We are interested in methods of active locomotion in this paper, as a significant body of work shows that body-based self-motion improves spatial awareness and knowledge (e.g., Chance et al. [1998]; Ruddle et al. [2011]).

Few of the above papers have assessed how peoples' perception of height changes as they experience an interface. One exception is Nagao et al. [2018], which examined how people estimated a change of height in ranges of approximately 1m. For climbing stairs, this seemed to us to be insufficient. In immersive VEs, there is little literature on the estimation of heights. Lin et al. [2012] had participants perform active estimation of height from the ground up by having participants duck under a door; in a later study, Lin et al. [2015] had participants perform active estimation of height from above by judging whether they could step down from a ledge. Participants performed better at both estimations in the presence of a self-avatar.

There has been more study of height estimation in the real world. Several studies have reported overestimation of heights, especially when judging from above, e.g., Jackson and Cormack [2007]; Sinai et al. [1998]; Stefanucci and Proffitt [2009]. Jackson and Cormack [2007] provided evidence to support asymmetric distance perception not only between horizontal and vertical surfaces, but also within different height-perception scenarios. Namely, they found that subjects generally overestimated height and that viewing a height from the top of a ledge induced significantly greater overestimation than when viewing a height from the bottom. Stefanucci and Proffitt [2009] also investigated vertical distance estimation, confirming a perceptual bias in height perception when viewed from the top. They found evidence that fear of heights, or emotional arousal, influenced height perception. This was further evaluated and confirmed by Stefanucci and Storbeck [2009].

The measures typically used to assess distance estimates in these cases involve visual matching. For our experiment in stair climbing, subjects climb flights of stairs to heights well beyond the distances used in all prior studies that we are aware of, and visual matching does not seem like a reasonable method to estimate height. For the same reason, blind-walking, used in much of the horizontal distance estimation literature, e.g., [Thompson et al. 2004], would not work. We therefore employ verbal estimates, which have also been used effectively in horizontal distance estimation [Kelly et al. 2017; Kunz et al. 2009; Napieralski et al. 2011].

In terms of affordance-based judgments, Stefanucci and Geuss [2010] altered subjects' perceived heights by having them wear a helmet or shoes in an action-based judgment of height from the ground. Subjects generally used a larger margin of safety when their height was manipulated, supporting the idea that body-based cues scale height perception. Mark [1987] manipulated eye height to determine climbability of stairs, and Warren's classic paper operationalizing affordances was on determining the climbability of stairs [Warren 1984]. Our study is not affordance-based, in that neither actual eye height nor the virtual model of our stairs are manipulated in any way. In fact, our stairs are designed according to standard guidelines for stairs in the United States [International Code Council, Inc. 2012].

Various cues that might be important in determining the perceived height that people actively locomote through include the presence of the passive markers, as mentioned previously. Also, the presence of body cues in the form of virtual shoes might be important [Jun et al. 2015; Linkenauger et al. 2013]. The presence of visual cues from the surrounding environment in the form of either optic flow or distant horizon cues related to openness may also be relevant [Cutting and Vishton 1995; Klatzky et al. 2017]. And finally, the direction (whether descending or ascending) might be a factor. We assess these factors by testing the following hypotheses: (1) Based on the results of Nagao et al. [2018], we predict that passive haptic markers will provide improved height estimation and sense of presence. (2) Based on results of Jun et al. [2015] and others, we predict that adding a virtual representation of shoes will improve height estimation and presence. (3) We predict that the presence of landmarks in an open environment, as opposed to featural cues of an enclosed environment, will provide better information for improved height estimates.

3 SYSTEM

3.1 Virtual Stairs

An infinitely ascending staircase was built procedurally and embedded in two VEs. The stairs consisted of two flights with landings in a seamlessly repetitive pattern. The exact dimensions of the stair flights are based on measurements taken from the main stairwell of a building at Vanderbilt University. The rise and tread of each step are 15cm and 30cm, respectively. Each flight of stairs consists of 11 steps, including a landing as the end of each flight. Flights

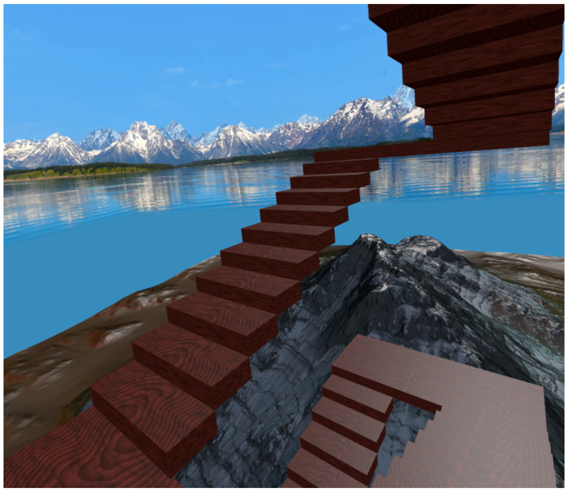

Figure 1: View of the open virtual environment.

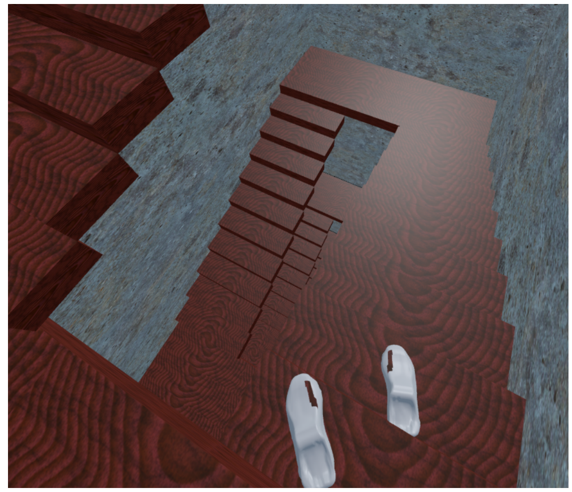

Figure 2: View of the closed virtual environment and the virtual shoes used.

alternate in direction and are connected by the landings, which measure 93.5cm x 2.64m x 15cm, thus completing a stair sequence. The staircase does not have railings.

We embed the staircase in two environments: an enclosed stairwell and an open stairwell. The open environment placed the stairwell amid an expanse of mountainous terrain (Figure 1). The enclosed stairwell environment consists of four concrete-textured walls that surround the outer perimeter of the stairs (Figure 2). Terrain assets and the 360° image of mountains were obtained from the Autumn Mountain asset from the Unity Assets Store.

3.2 Height Translation

The virtual environment is presented using a commodity level immersive virtual reality system, the HTC Vive, with 1080 x 1200 resolution per eye. In order to simulate a realistic motion similar to ascending or descending a stair, the positions of the feet are tracked. This is accomplished using two HTC Vive Trackers, which are attached to the tops of a pair of Crocs shoes that users of the system wear. Feet are tracked throughout the simulation, and the appearance of the virtual shoes can be turned on and off. When visible, the shoes appear as simple, white sneakers in the VE.

The algorithm we developed for simulating ascending or descending is scalable for any type of sloped ground and does not interfere with the native position and orientation tracking of the HTC Vive. The heights of users' viewpoints are manipulated as a function of the height of the virtual ground beneath them.

The height of the ground is determined by downward ray casts, which extend from the bottom of each foot in the virtual environment. The origin of a ray is placed near the front of the shoe so that the moment the front third of the shoe is placed over a new surface, the downward ray will register a point of collision. This point of collision corresponds to a point on the surface directly beneath the shoe. From this position, we extract the height of the ground beneath the user. This process occurs at every frame, and the initial ground height is determined by a ray cast from the left foot upon startup.

The threshold for step detection is determined by a difference in value greater than some $\epsilon > 0$ between the height of the current detected ground surface, h_{cur}, and the height of the surface beneath the user's lower foot, h_{new}. The lower foot was chosen to dictate change of height, because it elicited visually natural movement from the camera for both climbing up and climbing down. In practice, this results in the trailing foot initiating upward movement when climbing up and the leading foot initiating downward movement when climbing down. An ϵ of 1cm was found to work well in practice to prevent tracking noise and small foot movements from unnaturally perturbing eye height. Thus, the expression for threshold detection is

$$|h_{cur} - h_{new}| > \epsilon \tag{1}$$

If the conditions of Equation 1 are met, then the current detected ground surface height, h_{cur}, is updated by h_{new} in a weighted fashion according to

$$h_{cur} = (1 - \alpha)h_{cur} + \alpha h_{new} \tag{2}$$

where we found that a value of $\alpha = 0.05$ worked well in practice. Next, the updated ground height is added to the actual height of the user's viewpoint, H_{Real}, to displace the user's height vertically in the virtual environment (a quantity denoted by H_{VE})

$$H_{VE} = H_{Real} + h_{cur} \tag{3}$$

This method ensures that the eyeheight rises more smoothly than the foot, yet has the abrupt rise typical of stepping on a stair. For the experiment described in Section 4, ground detection was modified so that only the stair steps were used to manipulate a user's height. This prevented users from virtually falling off of the stairs should they move both feet off of the steps.

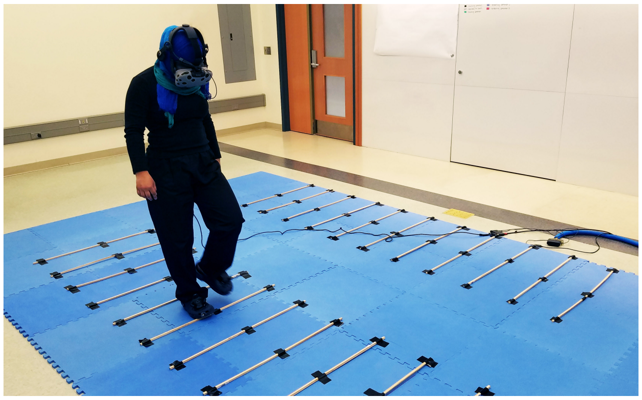

Figure 3: A participant climbs the virtual stairwell with passive haptic feedback.

3.3 Passive Haptics

Nagao et al. [2017, 2018] employed passive haptics in their staircase system to enhance the sense of ascending and descending. We wanted to emulate this, so our system uses wooden slats at the edge of each step on the infinite stair. Wooden slats in the shape of rectangular prisms were selected after a series of preliminary trials in which different materials were tested on pilot subjects to determine which slat type induced the most natural sensation of stepping on a stair ledge, although we did not conduct formal testing as in Nagao et al. [2018]. Metallic, plastic, and wooden materials were informally evaluated in rectangular and triangular prism shapes. For the final environment, 96cm x 0.95cm x 0.95cm long rectangular slats were cut and aligned along the protruding edge of each step on the virtual staircase. An image of a participant walking across the wooden slats can be seen in Figure 3.

4 EXPERIMENT

4.1 Participants

Forty-eight participants from Vanderbilt University, between the ages of 18 and 30 participated in the experiment. Of these, 24 were male and 24 were female. All participants were kept naive as to the purpose of the research until after the experiment was completed. They were financially compensated for an hour of their time with $10 USD. The current research was approved by the Institutional Review Board, and written consent was obtained from all subjects prior to participation.

4.2 Design

The experiment used a between-subjects design. The participants were divided into two gender-balanced groups with 12 females and 12 males per group. One group climbed the stairs with passive haptic markers in place on the floor, as shown in Figure 3, and the other group climbed without the passive haptic markers. Within each haptic condition, all participants were exposed to four combinations of environmental and avatar sub-conditions: an open stairwell with virtual shoes, an open stairwell with no shoes, an enclosed stairwell with virtual shoes, and an enclosed stairwell with no shoes. The order of trials was blocked with respect to environmental condition (open or enclosed environment) and the presence of virtual shoes was counterbalanced across subjects but consistent between environmental conditions for each subject.

Within each of these trials, participants climbed the staircase for six minutes in total, with three minutes of ascending the staircase and three minutes descending during each trial. The number of steps in a flight of stairs was not manipulated in this experiment, i.e., it was held constant over all trials due to the setup of the haptic slats. Each subject either ascended first for all trials or down first for all trials, and this order was balanced across all subjects and both genders. All participants started from an elevation relative to the ground, so that they could go down or up first without problem.

4.3 Procedure

After obtaining written consent, subjects were asked to fill out a series of questionnaires to determine demographic information, prior experience with video games, prior experience with virtual reality, fear of heights, fear of closed spaces, and pre-simulator sickness (SSQ) [Kennedy et al. 1993]. Responses were evaluated on a seven point Likert scale. Then, the experimenter explained the task and protocol to each subject.

Participants were informed that for the experiment, they would be ascending and descending stairs in a virtual environment. In addition, participants in the haptic feedback group were told that the wooden slats on the floor represented the edge of the virtual stairs. All participants were then given the head-mounted display, earphones, and tracked shoes. The earphones played white noise to mask sounds from the real environment during the experiment. Before entering the simulation, subjects were informed that they could stop the experiment at any time should they feel unsafe or nauseous.

While climbing the stairs, subjects were instructed to count aloud by multiples of 7 from 0 to 98 repeatedly until the end of the trial. This action prevented subjects from counting flights as they climbed. They continued to climb the stairs until they heard a sound in the headphones, which indicated the end of the trial. As mentioned previously, the duration of each trial was three minutes; subjects were not informed of the duration of each trial, nor were they told it was the same across all trials. Upon hearing the auditory cue, they were instructed to finish climbing the current flight of stairs, remove their headphones, and await further instruction.

At this point participants were asked to verbally estimate the number of flights climbed. Then they resumed climbing, but in the opposite direction. Hence, if they climbed up during the first half of the trial, then they would climb down during the second half of the trial, and vice versa. After completing the entire six minute trial, subjects filled out a modified SUS presence questionnaire [Slater et al. 1994b] and recorded their flight estimations for each climbing direction. They were also asked to report what they believed was the height of each flight of stairs and the height of the stair risers in feet or meters. Additional questions about the realism of the sensation of climbing when moving up versus moving down were also integrated into the questionnaire.

As the experiment blocked for environmental condition, subjects repeated this same procedure twice for both the open and closed stairwell environments. Within each condition, they were introduced to the shoe and no shoe conditions in the same order. After completing each environmental block of the experiment, subjects filled out an additional post-environment SSQ questionnaire. In total, subjects were in the HMD for approximately 24 minutes, with short breaks every six minutes and a longer break after 12 minutes while they answered questions. At the end of the experiment, participants were paid and allowed to experience other games in an Oculus Rift.

5 RESULTS

5.1 Height Perception

After each experimental trial, subjects reported how many flights of stairs they climbed in each direction as well as their perceived height of each flight of stairs and the height of a single step—the stair riser. Over all conditions, subjects climbed or descended an average of 14 flights of stairs during each trial (SD=7.64). Estimates were reported in either metric or imperial units of measure. All units were later converted to the metric system for analysis. Our primary measure was the absolute error in the difference between the estimated distance climbed and the actual distance climbed in terms of flights of stairs. This is the natural measure since subjects can either overestimate or underestimate the number of flights they climbed. We analyzed this quantity across the four independent variables: presence of passive haptic feedback (slats or no slats), type of environment (open or enclosed), presence of virtual shoes (virtuals shoes or no shoes), and climbing direction (up or down). The only between-subjects variable was the presence of passive haptic feedback, which resulted in a full factorial mixed model design.

A mixed model ANOVA showed a significant effect of virtual shoes, $F(1, 46) = 4.517$, $p = 0.039$, $\eta_p^2 = .089$, and environment, $F(1, 46) = 4.570$, $p = 0.038$, $\eta_p^2 = .09$. When subjects had virtual shoes they had significantly lower error (M=3.24, SD=2.97) than when not wearing shoes (M=3.94, SD=3.96); subjects in the open environment had significantly lower errors (M=3.20, SD=3.43) than in the enclosed environment (M=3.98, SD=3.56). The η_p^2 values suggest that effect sizes for both effects are moderate. No other conditions or interactions were significant. Additional repeated measures ANOVAs with the presence of shoes, environment, and haptic feedback showed no main effects or interactions on either estimated riser height or estimated height of a flight of stairs. Figure 4 shows the absolute error in flight estimation among these conditions: open vs. enclosed environment and shoes vs. no shoes.

We also calculated the mean errors for the task, which gives an indication of the bias present in each condition, that is, whether subjects overestimated or underestimated how much they actually climbed, and by how much. Overall, subjects overestimated how many flights they had climbed by 7.25%. This result is broken down for each of the eight experimental conditions are shown in Table 1. Considering all trials, 27% of the trials were underestimates, 12.5% were perfect estimates, and more than 60% were overestimates. We performed independent single sample t-tests on these conditions to determine if any of them had estimation errors significantly different from 0. Only the condition in which subjects had shoes ($\bar{x} = 1.677, SD = 4.067, t = 2.85, p < .01$) was significantly different from 0. Cohen's effect size value ($d = 0.41$) suggests a moderate effect of this bias.

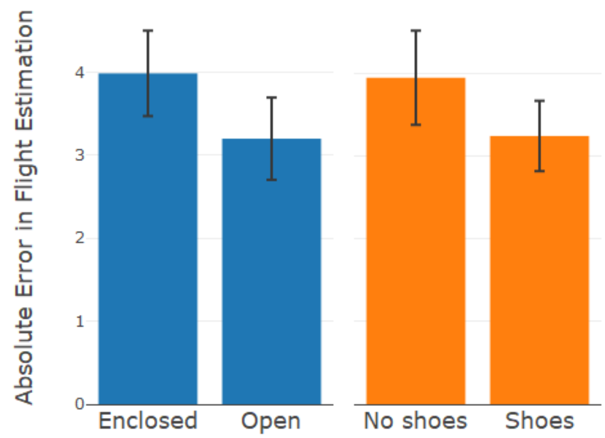

Figure 4: Absolute error (and the standard error of the mean) in flight estimation associated with the presence of an shoes and the environment.

Table 1: Mean error, mean percentage error, and standard deviation for the two states in each of the four conditions of the experiment.

Condition	Mean Error	Mean % Error	SD
Shoes	1.68	10.3%	4.07
No Shoes	0.60	4.2%	5.57
Haptic	1.53	9.5%	3.97
No Haptic	0.75	5.0%	5.62
Open	0.95	7.3%	4.60
Enclosed	1.33	7.2%	5.18
Up	1.11	7.1%	4.96
Down	1.12	7.4%	4.85

5.2 Presence

After each trial in the experiment, subjects were asked to fill out a modified SUS questionnaire. The responses were transformed into a binary value [Peck et al. 2009; Slater and Usoh 1993; Slater et al. 1994a] in which responses of 5, 6, and 7 were considered high presence; all other values were considered low presence. The results of this transformation are summarized in Table 2. This table shows the total number of high responses for each condition over all subjects, consistent with the methods of Peck et al. [2009] and others, and the mean of these responses over all possibles responses. A pairwise logistic regression between methods was performed. We found a statistically significant difference between the shoe conditions in which a stronger sense of presence was elicited when shoes were present ($\chi^2(1) = 9.77, p < 0.01$). There was no statistical difference between the passive haptics—wooden slats—conditions. Similarly, there was no effect of environment.

5.3 Simulator Sickness

Subjects received three simulator sickness questionnaires (SSQs), one prior to the experiment and one following each of the the two blocked environmental conditions. This resulted in two SSQ difference scores that indicated the simulator sickness caused by each environment [Kennedy et al. 1993]. While sex showed no effect on either environment individually, the environment that was presented second induced a significantly higher increase in simulator sickness for women, $F(1, 44) = 4.529$, $p = 0.039$. Figure 5 shows the difference in SSQ scores by sex following the second environment.

Table 2: High responses and mean high responses for the presence questionnaire.

	High Responses	Mean High
Avatar	322	0.5590
No Avatar	269	0.4670
Slats	309	0.5365
No Slats	282	0.4896
Open	292	0.5069
Enclosed	299	0.5191

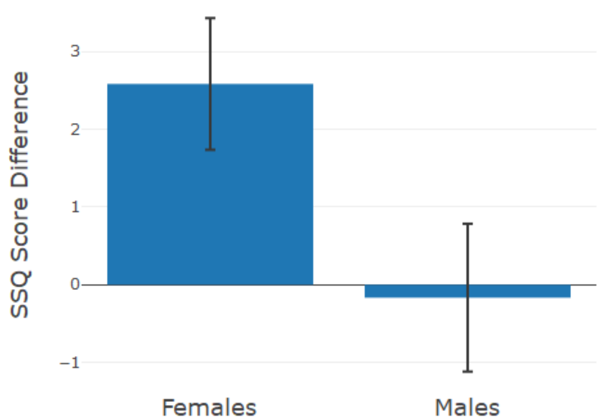

Figure 5: Simulator Sickness scores in the second experienced environment seperated by sex.

6 DISCUSSION

In this paper we assessed the ability of people to estimate how high they had ascended or descended while locomoting over a virtual staircase. We varied the factors of their virtual experience, including or excluding passive haptics, virtual shoes, and an enclosed or open environments. We also examined whether they were better at doing this while they were ascending the staircase or descending the staircase. Although not (usually) statistically significant, our findings generally support prior work in the real world that shows overestimation of heights [Jackson and Cormack 2007; Sinai et al. 1998; Stefanucci and Geuss 2010; Stefanucci and Proffitt 2009]. However, this work was done in a virtual environment, involved active locomotion, and generally involved heights greater than those encountered in the real world work. We note from Table 1 that, first of all, subjects could perform this task, and, second, their errors are in line with the types of errors that are reported when verbal reports are used with horizontal distance estimates [Kelly et al. 2017; Kunz et al. 2009].

Perhaps the most surprising result was the absence of an effect of the passive haptic markers, as we had hypothesized, either in height estimation or in measures of presence. Nagao et al. [2018] report both, so this failure to replicate their result is interesting. The style of our haptic markers was different from the ones used in their work, but not, we thought, significantly different, and it would be disappointing if the effect of the stairs were highly dependent on the shape and dimensions of such markers. The experimental methods that they used for height estimation were substantively different from ours, but we found no difference in people's ability to estimate riser height or the height of a single flight of stairs in our experiment, which brackets their distances of approximately 1 m. It may be important that our method of changing the eye height as a function of stepping is different from that of Nagao et al. [2018]. Our experience is that this method is critical to the proper functioning of the system, and perhaps more work investigating its robustness is needed, or how it interacts with various other cues. We note that video of subjects walking in the system of Nagao et al. [2018] typically show them in a different gait than in our system.

The strong effect of the presence of shoes in aiding height estimation is consistent with prior work on the relevance of body cues to size estimates [Jun et al. 2015; Linkenauger et al. 2013; van der Hoort et al. 2011] or more generally to the relevance of a self-avatar to judgments of distance in VEs [McManus et al. 2011; Mohler et al. 2010]. One possible interpretation for this finding is that the shoes provide a cue that give a perceptual estimate of height in the VE, namely eye height, that subjects then find useful in scaling how high they have ascended or descended. Another possible interpretation of the results is that the shoes increase the presence of the virtual environment, which leads to an increase in emotional arousal in the environment, leading to the bias in overestimation observed in the shoe condition. This emotional arousal causes subjects to pay more attention to how high they have ascended or descended. Resolving these interpretations is the subject of future work. It would be interesting to test whether the addition of a full self-avatar refines height estimation further. Note that the finding that subjects had a higher sense of presence when shoes were present is consistent with the literature on body ownership [Kilteni et al. 2012; Kokkinara et al. 2015].

Our hypothesis that estimates of how high people ascended or descended would be better in the open environment than in the closed environment was validated. Our theoretical basis for this hypothesis was that people would have more visual cues to establish how much they had ascended or descended in the open environment since cues that operate in regions further from the viewer will be active in the open environment [Cutting and Vishton 1995]. However, there was some basis to suppose that the opposite might be true. It is possible that ascending or descending the staircase in the open environment could have been perceived as a risky action, and there is evidence that risk, particularly fear of heights, causes one to overestimate distances and gaps [Geuss et al. 2016; Stefanucci and Proffitt 2009]. Similar results have been found for presence, as well [Phillips et al. 2012; Slater et al. 2009]. Our finding was that the open environment provided better height estimation, regardless of direction, but we found no effect on presence. It is interesting to note that subjects did not combine having shoes and being in the open environment to improve their height estimates even further than alone. This type of plateauing has been seen before in performance estimates in affordance judgments in VEs by Lin et al. [2015] who found that subjects were not able to combine action and self-avatars to improve their affordance judgments for stepping down from a ledge.

We found an interesting result for simulator sickness, although it is somewhat difficult to interpret. First, no subject complained of simulator sickness or withdrew from the experiment because of simulator sickness. Nevertheless, we found a sex-based effect in the second half of the experiment, where women showed significantly higher SSQ scores in the second half of the experiment than men. There is evidence that women are more susceptible to simulator sickness than men, e.g., [Graeber and Stanney 2002; Munafo et al. 2017], and our finding is broadly in line with this. However, as it was not dependent on any condition, and only appeared in the second half of the experiment, it is difficult to interpret as anything other than exposure to virtual environment. It is also difficult to assess what the severity of the symptoms were, since no one verbally complained.

7 CONCLUSION

In this paper we looked at the task of gauging how high a person has has ascended or descended on a virtual stairway while locomoting in the real world. We believe that this is the first work that has looked at how well people can judge how much they have ascended or descended in a virtual environment, and what factors influence those decisions. In our system, subjects had average errors typically less than 10%, which we consider reasonable when compared to errors in horizontal distance estimates with modern commodity level hardware [Kelly et al. 2017]. The factors that influenced height estimates were the presence of a virtual shoe, and the openness of the environment. We did not find that passive haptics aided our system in any way. Future work should investigate how fuller self-avatar representations affect the situation. Furthermore, it would be interesting to investigate the robustness of this type of locomotive system and perceptual findings to more general types of terrain. Interesting virtual worlds of the future will not be flat, and work should be done to understand both how to move naturally in them, and what perceptual mechanisms such locomotive systems afford.

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