The Virtual Pole: Exploring Human Responses to Fear of Heights in Immersive Virtual Environments

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Abstract

Measuring how effective immersive virtual environments (IVEs) are in reproducing sensations as in similar situations in the real world is an important task for many application fields. In this paper, we present an experimental setup which we call the *virtual pole*, in which we evaluated human responses to fear of heights. We conducted a set of experiments in which we analyzed correlations between subjective and physiological anxiety measures as well as the participant's view direction. Our results show that the view direction plays an important role in subjective and physiological anxiety in an IVE due to the limited field of view (FOV), and that the subjective and physiological anxiety measures monotonically increase with the increasing height. In addition, we also found that participants recollected the virtual content they saw at the top height more accurately compared to that at the medium height. We discuss the results and provide guidelines for simulations aimed at evoking fear of heights responses in IVEs.

Keywords: Virtual Reality, physiological measures, fear of heights

1 Introduction

Virtual reality (VR) display systems featuring stereoscopic display and head-coupled perspectives have great potential as an enabling technology for immersive experiences in domains from three-dimensional (3D) visualization to entertainment. While many 3D user interfaces have been developed with the aim to increase task performance, scene understanding or data comprehension [BKLP04], natural user interfaces are often designed with the goal to elicit the perceptual illusion of *presence* [Sla09] in users. A high sense of presence is characterized by users responding realistically in a virtual environment (VE) as if they were in a comparable situation in the real world, which can be seen as an operational definition of presence [SVS05]. Realistic responses include *behavior*, which is characterized by movements of the body, *subjective* responses including self-assessment of one's current physiological and psychological state, as well as *physiological* responses [SKMY09].

Slater [Sla09] further characterizes presence with two concepts: "place illusion" (PI) and "plausibility illusion" (Psi). PI is defined as the feeling of being in the virtual place despite the sure knowledge that one is not there. In contrast, the Psi is defined as the feeling that what is happening is real despite the knowledge that it is not. An essential component of PI is that events caused by the user lead to sensations dependent on the synchronous correlations between body movements and computer-generated sensory feedback. In contrast, an important aspect of Psi is that external events not caused by the user lead to both *exteroceptive* and *interoceptive* sensations, i. e., external stimuli and those produced within the organism, respectively.

In this paper, we focus on human responses to fear of heights in an immersive virtual environment (IVE). Therefore, we developed an experimental setup which we call the *virtual pole*. We were inspired by the virtual pit [SUS95], in which interoceptive sensations such as an increase in heart rate [MIWBJ02] are investigated in a virtual room with a pit. Factors manipulated in research using the virtual pit are predominantly related to PI, i.e., level of sensorimotor contingencies (SCs) the virtual reality system can afford, e.g., multimodal feedback, display resolution, frame rate. In contrast to the virtual pit, our virtual pole setup allows us to examine responses to different levels of height by changing the height of a platform in a plausible scenario, thus perhaps changes in responses, while keeping PI-related factors constant. We assessed participants' responses during an event in the environment that causes a change in the height of the platform on which the user is standing or seated with respect to the rest of the scene. We measure interoceptive sensations of anxiety responses due to fear of heights both with subjective self-assessments via questionnaires and with physiological measurements of heart rate and galvanic skin responses (GSR).

We conducted two experiments in iterative designs of the virtual pole setup to understand the correlations between the two physiological measures, head movements and self-reported anxiety. Based on results published in related work we focused on two main research questions:

Q_1 Is there a correlation between the view direction and anxiety responses to fear of heights in VR, i. e., is the visual sensation of height when looking down essential or does the knowledge of being high up suffice to evoke anxiety?

Q_2 Is there a measurable linear or nonlinear correlation between height and subjective or physiological responses?

The results of our experiments provide support for answers to the research questions. For Q_1, just like anxiety responses to fear of heights in the real world are limited when standing on a cliff until someone says "Don't look down," we found that pitching the head down in the VE was correlated with both increased subjective and physiological responses. We discuss implications and correlations with the field of view of head-mounted displays (HMDs).

For Q_2, we found linear correlations of height with subjective anxiety ratings as well as nonlinear correlations with the physiological measures. The results are interesting as they suggest that self-reported anxiety may be subject to experiment biases; considering the observed linear relation, it seems unlikely that an increase in height from 30 to 40 meters would actually induce the same effect on anxiety as the first moments when height is increased from 0 to 10 meters. In contrast, GSR measures showed a curved correlation with heights and lower anxiety increases for larger heights, which appears more plausible.

2 Related Work

Virtual reality has been applied to the psychological treatment of phobias, including fear of heights – also known as acrophobia, from the mid-90s, with aims at reducing heightened anxiety responses to a normal level by repeatedly exposing patients in a phobic situation in VE. Studies have shown the effectiveness of such virtual reality exposure therapies (VRETs) by comparing to a non-exposure group [RHK+95] and also comparing to the *in-vivo* treatment of the acrophobia [EKH+02]. A primary reason for the efficacy of VRETs is that VR display setups could provide observers with virtual experiences that can provoke realistic anxiety responses to phobic events, which occur despite the observer's knowledge that the events are not real [SUS95]. Researchers also often used such anxiety-inducing VEs in their studies of presence [HKM+95, MIWBJ02].

In this section, we provide an overview of subjective and physiological measures of presence by means of anxiety responses caused by fear of heights.

2.1 Subjective Measures

Subjective measures provide an easy-to-use method to elucidate a user's perception of VR experiences. Measures in the fields of anxiety responses or presence in stressful VEs include an individual's subjective self-assessment of anxiety levels by using self-report questionnaires, subjective units of distress (SUDs) or breaks-in-presence (BIPs) [SBS03, SBV05, WJKW02, Wol73]. The most frequently used types of subjective measure are SUDs and questionnaires [She92]. Various questionnaires and scales have been introduced over the last years, such as the Slater-Usoh-Steed questionnaire [UCAS00], the igroup presence questionnaire [RS02] or the Witmer-Singer presence questionnaire [WS98].

Subjective measures are widely used to assess presence and anxiety responses. However, subjective responses have limitations, such as their inherent dependency on the memory of an event when post-test questionnaires are used. Further drawbacks of these subjective and qualitative measures include participants' inaccurate self-assessments, mediated answers, and biases from guessing the investigator's intention.

2.2 Physiological Measures

In contrast to subjective responses, the main argument for physiological measures is that they are regarded as quantifiable objective measures of presence and are difficult for users to bias voluntarily. While there is evidence for the human ability to train control over certain physiological responses with repeated trials and sensory feedback loops [NKLM11], it is not considered an exclusion criterion of these measures in the field of presence research.

Physiological measures of presence in VR have been investigated in different application fields. Meehan et al. [MIWBJ02] investigated reliability, validity, sensitivity, and objectivity of physiological measures. Among heart rate, skin conductance — GSR has also been referred as skin conductance or electrodermal activity —, and skin temperature, heart rate satisfied their requirements for a surrogate measure of presence in a virtual pit environment. Although further research on whether their results only apply to PI in a stressful VE is needed, their study provided insights into the feasibility of approaches to objectively measure a theoretical concept. Yuan and Steed [YS10] used GSR toward a threat in a VE to compare the inducement of body ownership in four conditions. The GSR measures for the conditions with virtual hands and arrows were significantly different and correlated with subjective questionnaire responses. Wiederhold et al. [WDW98] evaluated heart rate, respiration rate, peripheral skin temperature, and skin resistance levels and found differences between physiological responses of phobics and nonphobics during a virtual flight. Furthermore, Stoermer et al. [SMR+00] evaluated heart rate variability and found that it can be used as an instrument for monitoring anxiety.

Overall, since Lang's [Lan85] suggestion 30 years ago, anxiety levels are increasingly assessed using a combination of objective and subjective measures with physiological sensors and SUDs or subjective questionnaires. However, the interpretation of the often conflicting data from the different sources is still not well defined and we are missing a thorough understanding of how these methods correlate with each other, the stimuli and unwanted biases. In this paper we make a step towards a better understanding of heart rate and GSR measures, head movements and SUDs in a controlled virtual pole environment.

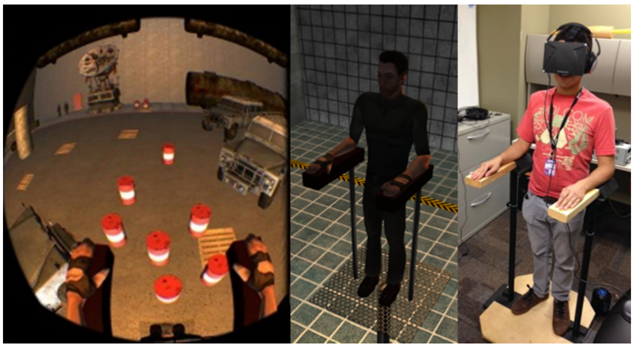

Figure 1: Screenshots and photo depicting the virtual pole setup used in Experiment 1.

3 Experiment 1

In this section we present the first experiment, which we conducted in the virtual pole setup to analyze view directions and subjective anxiety estimates caused by fear of heights in correlation with physiological responses of heart rate and GSR.

3.1 Participants

We recruited twenty-one undergraduate and graduate students within our university community as participants in this experiment (15 male, 6 female, mean age: 24.1, age range: 20 – 32 years). Participation was voluntary. The duration of the experiment was 30 minutes for each participant.

3.2 The Virtual Pole Setup

The virtual "pit" is a classic setup which has been used extensively to study fear of heights responses in VR [MIWBJ02, SKMY09]. Previous studies showed that users' physiological signals changed significantly when they were exposed to the virtual pit. However, we designed a virtual "pole" in our experiment due to our need for controllable multi-level stimuli as well as since we aimed to control and limit the user's movements in the VE (cf. Section 1). We designed different stimulus intensities via different heights similar to Breimhorst et al. [BSF$^+$11]. For these multi-level stimuli, the height in the simulation would have to be continuously changing during the experiment to preserve the Psi as discrete changes in heights would be implausible in real life. In this regard, a virtual "pole" serves as a more plausible VE than a virtual "pit."

We constructed the virtual pole for this experiment based on a square-shaped warehouse (width, depth, height: 40 m, 40 m, 40 m) with a high ceiling using the Unity3D game engine[1]. At the center of the space on the ground, we placed a virtual pole platform, on which an avatar was standing with both arms placed on the armrests (see Figure 1). We placed the avatar on the platform to give participants a basic sensation of body ownership in the VE. Armrests were employed to reduce motion artifacts in measuring physiological responses by allowing users to place both arms on armrests in the real world during the experiment [Suc07]. We constructed a platform in the real world that matched the virtual counterpart, with height adjustable armrests so that each participant standing on the platform could place their arms on the armrests comfortably. A strong bass shaker called a ButtKicker LFE[2] was mounted on the side of the physical platform to simulate mechanical vibration when the pole was moving. We used the Oculus Rift DK1[3] head-mounted display in this iteration of the virtual pole setup. Participants experienced the VE from the avatar's perspective (see Figure 1). Participants were instructed not to move around on the platform; with the DK1, translational motion parallax was not considered in this experiment. In order to facilitate a reasonable sense of depth in the experiment, we placed familiar-sized objects in the VE.

During the experiment, we measured participants' physiological responses and head motion. Galvanic skin response (GSR) was measured on the participant's right hand (electrodes were placed on the index and middle fingers) using the Shimmer GSR sensor[4]. Heart rate was measured on the participant's left hand (the sensor was placed on the index finger) using Thought Technology's blood volume pulse (BVP) sensor[5]. Along with the physiological responses we measured the participant's view direction using the inertial orientation sensor of the DK1 HMD.

[1]http://unity3d.com
[2]http://thebuttkicker.com
[3]http://www.oculus.com
[4]http://www.shimmersensing.com

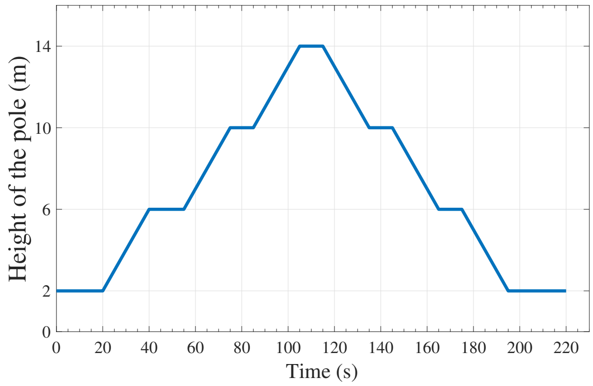

Figure 2: Illustration of the stimulus intensity levels with changes in height over time during Experiment 1.

3.3 Methods

We used a within-subjects design in which we exposed subjects to four heights ($2, 6, 10, 14$ m) in a plausible scenario in the virtual pole setup. When participants arrived, we briefed them about the experiment procedure. Then, we asked them to mark their self-judged susceptibility to fear of heights on a seven-point Likert scale (1: not at all, 7: very much). After that, they were guided to step on the platform. An experimenter adjusted the armrests and helped them to don the HMD as well as a noise canceling headphone. The experimenter attached sensors on the participant's fingers and asked them not to move their arms and fingers during the experiment. Once the simulation started, the height of the virtual pole was slowly increased up to 14 m in the VE, and slowly decreased back to the ground with rattling sounds (these sounds were amplified and used to vibrate the physical platform using the ButtKicker) at the speed of $20\,cm/s$. The pole performed short stops (10s) at heights of $6, 10, 14$ m (see Figure 2) while increasing as well as in reverse order while decreasing.

Twenty-five seconds after the pole landed, the simulation ended, and the experimenter helped the participants to take the devices off. Finally, participants were asked to rate their anxiety level from the fear of heights experienced in the simulation with a SUD on a seven-point Likert scale.

[5]http://thoughttechnology.com

3.4 Measures

3.4.1 Subjective Measures

Susceptibility to fear of heights: Participants rated their susceptibility to fear of heights on a seven-point Likert scale (1: not at all, 7: very much) before the simulation.

Anxiety level (from the simulation): Participants reported their anxiety level from their fear of heights in the experiment with a SUD comprised of a seven-point Likert scale at the end of the experiment.

3.4.2 Objective measures

Look-down time: We measured a participant's head pitch angle using the inertial orientation sensor of the HMD. From the pitch angle we calculated how much the participant looked down, i. e. looked toward the floor, during the experiment. We performed pretests and determined a threshold of 35 degrees as the angle at which the virtual floor was sufficiently visible with this HMD at the height of 14 m.

Head motion: From the head tracking data, we calculated the Euclidean distance between consecutive head pose data, and summed the Euclidean distances per each participant to determine the overall head motion magnitude.

Skin conductance (SC): We measured the participant's skin conductance using the Shimmer GSR sensor. A moving average filter (with 1 second window size) was applied to the measured data.

Pseudo phasic SC (PPSC): In line with the literature, we calculated the differences between two consecutive SC, i. e. $SC(t) - SC(t-1)$, and took the positive values only (negative values were set to zero).

Heart rate (HR): From the BVP data, we first detected peaks, and calculated interbeat intervals (IBIs) from the detected peaks. We averaged ten consecutive IBIs to calculate HR.

Heart rate variance: We calculated the variance of HR during the simulation per participant.

3.5 Results

We computed the Pearson product-moment correlation coefficient to assess the relationship between aggregated variables. We found positive correlations between anxiety level and look-down time [$r = 0.56, p < 0.05$], pseudo phasic SC (summed per participant) [$M = 3.86, SD = 1.4$] and look-down time [$M = 66.72, SD = 46.63$] [$r = 0.47, p < 0.05$]. Also, we found a positive correlation between head motion [$M = 123.33, SD = 68.99$] and normalized heart rate variance [$M = 0.05, SD = 0.01$] [$r = 0.47, p < 0.05$].

To calculate correlation coefficients in the time-series data, we divided the time-series data into twenty-two subsections and calculated Pearson product-moment correlation coefficients. We found a positive correlation between the height in the virtual world and normalized SC [$r = 0.44, p < 0.05$].

No correlation was found between susceptibility to fear of heights [$M = 5.74, SD = 1.1$] and anxiety level [$r = 0.31, p = 0.19$]. In general, participants reported a moderate level of anxiety in the experiment [$M = 3.5, SD = 1.21$].

Additionally, we asked the participants to choose the most fearful moment during the simulation. We expected them to choose the highest point, but only three chose the highest point as the most fearful moment. Rest of the participants chose either at the very beginning when the platform started moving or the period while the platform was rising.

3.6 Discussion

Overall, the results show the potential for measuring anxiety from heights in a VE by monitoring physiological responses. Especially the positive correlation between normalized SC and height is promising as we believe the height would be strongly correlated with anxiety level.

The correlation between anxiety and look-down time is interesting as it might be due to the limited vertical field of view (FOV) of the HMD. The vertical FOV of human eyes ranges around 135°, whereas the Oculus Rift DK1 offers 110°, or 55° when only considering the inferior FOV. This difference might be critical when considering fear of heights related to depth perception from peripheral vision.

During the experiment, we restricted the participant's hand movements in order to reduce motion artifacts in physiological responses. However, the correlation between head motion and heart rate variance shows that motion in any body part might affect heart rate related variables. This is problematic especially in HMD-based VR systems, as head rotations are a minimum requirement for users to get a reasonable spatial impression of the 3D environment.

The maximum height of the pole was 14 m in this experiment, which we considered would be sufficient to induce a strong anxiety response in the real world for most persons. However, we only observed moderate anxiety levels in this experiment, which might be caused by a variety of factors related to the sense of presence or the well-known distance underestimation problem with HMDs [LK03, RVH13]. This observation lead us to consider higher poles in the second iteration of the virtual pole setup presented in the following section.

4 Experiment 2

Considering the results of Experiment 1, we modified our virtual pole setup to induce more discernible responses from users. In particular, we increased the maximum height (from $14m$ to $40m$) and the speed of the pole (from $20cm/s$ to $1m/s$), and we added a stool without armrests to our physical pole setup. Moreover, we adopted the *Think Aloud* method [LR93] to measure the participant's subjective anxiety responses at different heights during the experiment.

4.1 Participants

We recruited thirteen undergraduate and graduate students within our university community as participants (6 female, 7 male, mean age: 22.8, age range: 20 – 27 years). All participants had normal vision and hearing and we made sure that they were not sweating excessively. Four participants were familiar with the concept of VR, and three of them had used an HMD before. All participants received $10 as compensation for their participation. The average duration of the experiment was about 40 minutes.

4.2 The Virtual Pole Setup

We used the VE as detailed in Section 3.2 with a few modifications (width, depth, height: 40 m, 40 m, 80 m). We increased the ceiling of the VE so that the virtual pole could be lifted up to 40 m. At the center of the floor in the VE, we placed a stool on the pole and positioned an avatar sitting on the stool with both hands touching each side of the stool seat (see Figure3). Participants were asked to hold the same pose during the experiment to reduce motion artifacts in measuring physiological responses. In the physical space, we used a stool with the same shape with the ButtKicker attached to one leg of the stool. The ButtKicker simulated mechanical vibrations when the pole was moving in the VE. We used the Oculus Rift DK2 HMD in this experiment to introduce motion parallax. The user's head position and orientation tracked by the DK2 tracking system were applied to control the avatar's upper body pose using inverse kinematics. On the front side of the floor, we placed a small hemispherical marker that changed color during the simulation. Head tracking and physiological data were sent to the simulation software and logged at 20 Hz.

4.3 Methods

During the exposure to the virtual pole simulation, we measured participants' physiological responses and head motion as described in Experiment 1. Furthermore, we asked participants to report the color of the hemisphere on the ground and their self-judged anxiety level in 10-point Likert-scale each time a bell sound rang. We used 10-point scale as it would be more intuitive compared to 7-point scales for participants considering the study scenario, where they needed to respond in a short time. During the simulation, the bell sounds rang at 17 designated moments (see Figure 4). This task was designed to ensure that all participants looked down to perceive the height, and to measure their anxiety level and physiological responses at the different heights. Each time the bell rang, the color of the hemisphere changed to one of the five colors (white, yellow, red, blue, and black). Later in a post-questionnaire, participants were asked to recall/fill-out the colors they saw during the simulation into a table (see Figure 5).

When participants arrived, we asked them to read through the informed consent, and fill out a pre-questionnaire. The pre-questionnaire included a demographic questionnaire as well as a height anxiety/avoidance questionnaire [Coh77, Mee01]. Then, we guided them to the experimental space and explained that their task was to look around the VE and report their anxiety level and the color of the sphere on the ground whenever they heard a bell sound. We did not inform the color recall task to the participants, in order to prevent deliberately memorizing the colors. We played the bell sound once for them to hear while explaining the task. After the instruction, participants donned the physiological sensors (the Mio Alpha 2 [6] heart rate monitor and the shimmer GSR sensor). An experimenter asked them to assume a seated pose as shown in Figure 3 and helped them to don the

[6] http://www.mioglobal.com

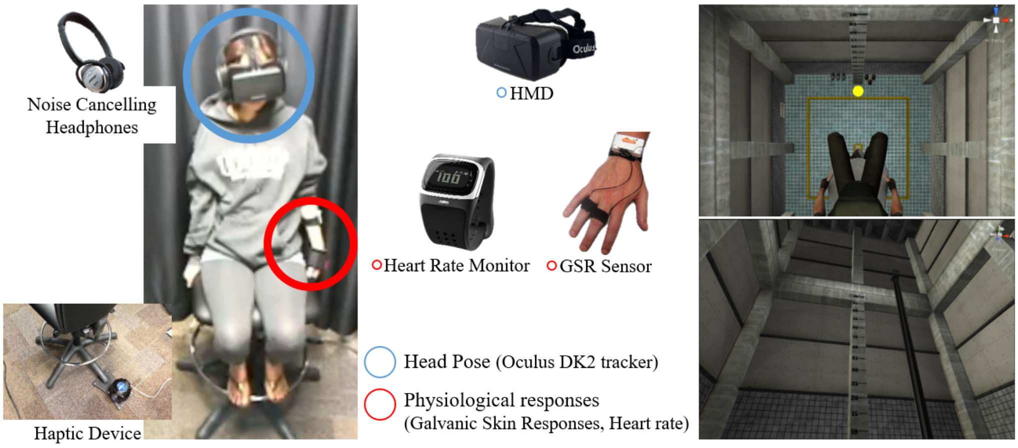

Figure 3: Virtual pole setup used in Experiment 2. A stool without armrests was used to increase instability. A haptic device was attached to a leg of the stool to simulate mechanical vibrations. Participants were exposed to the IVE (images on the right) using the Oculus DK2 HMD and a noise cancelling headphone. During the simulation, their physiological responses and head motion were recorded.

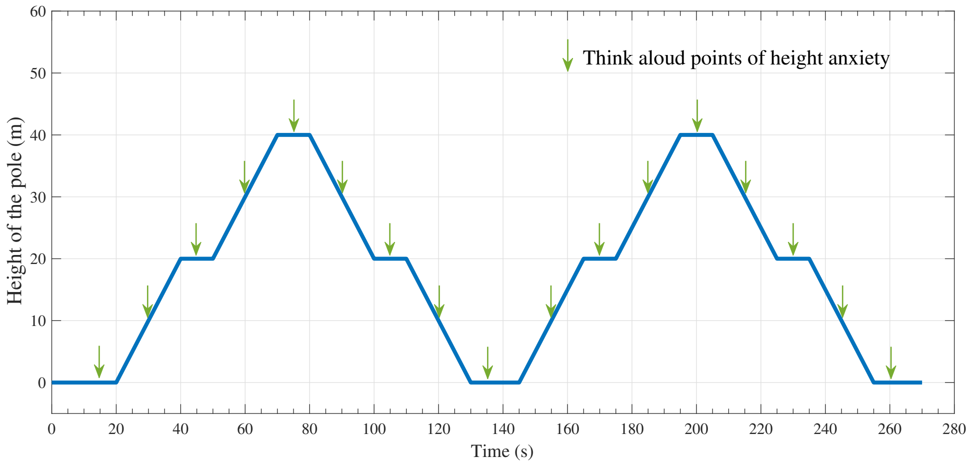

Figure 4: Illustration of the stimulus intensity levels with changes in height over time during Experiment 2. We recorded subjective self-judged anxiety levels at 17 points during the experiment.

HMD and headphones. Once the simulation started, the height of the virtual pole was increased up to 40 m in the VE and decreased back to the ground with rattling sounds at the speed of $1\,m/s$. The pole stopped (duration: 10 seconds) at 20, 40 m (see Figure 4) while increasing/decreasing. In this experiment, the pole moved up and down two times. When the simulation ended, the experimenter helped participants to take the devices off. Finally, participants were asked to fill out a post-questionnaire.

4.4 Measures

We used the following revised measures in this iterative design of the experimental setup.

4.4.1 Subjective Measures

Susceptibility to fear of heights: We measured participants' susceptibility to fear of heights using a height anxiety/avoidance questionnaire [Coh77, Mee01] as part of the pre-questionnaire in the experiment. Participants answered each question on 10-point Likert-scale (1: not at all anxious, 10: extremely anxious), and the scores for all questions were summed.

Anxiety level in situ: Participants reported their anxiety level on 10-point Likert-scale at 17 reporting points via the Think Aloud method (see Figure 4). An experimenter recorded the reported scores in a table during the experiment.

0m■	10m▲	20m ■	30m▲	40m■	30m▼	20m■	10m▼	0m■
	10m▲	20m■	30m▲	40m■	30m▼	20m■	10m▼	0m■

(■ staying ▲moving up ▼ moving down)

Figure 5: Table for the memory test in Experiment 2. Participants were asked to fill out the name of the color they saw during the simulation onto a section related to the height. The table shows the overall scenario of the pole motion.

4.4.2 Objective Measures

Look-down angle: During the experiment, we measured participants' head pitch angle using the Oculus Rift DK2 tracking system.

Memory: We checked whether participants remembered the correct color of the spheres. When they recalled the color correctly, we marked it as 1, otherwise 0.

We used **Skin conductance (SC)** and **Pseudo phasic SC (PPSC)** as described in 3.4. Also, we derived following measures using Ledalab[7], a Matlab-based software that decomposes SC data into phasic skin conductance responses (SCRs) and tonic activities (we used a response window as 1 to 4 sec after the Think Aloud points) [BK10].

AmpSum: Sum of SCR-amplitudes of significant SCRs (amplitude $>$ 0.01uS) within response window (reconvolved from corresponding phasic driver-peaks).

ISCR: Sum of phasic driver within response window.

PhasicMax: Maximum value of phasic activity within response window.

Tonic: Mean tonic activity within response window (of decomposed tonic component).

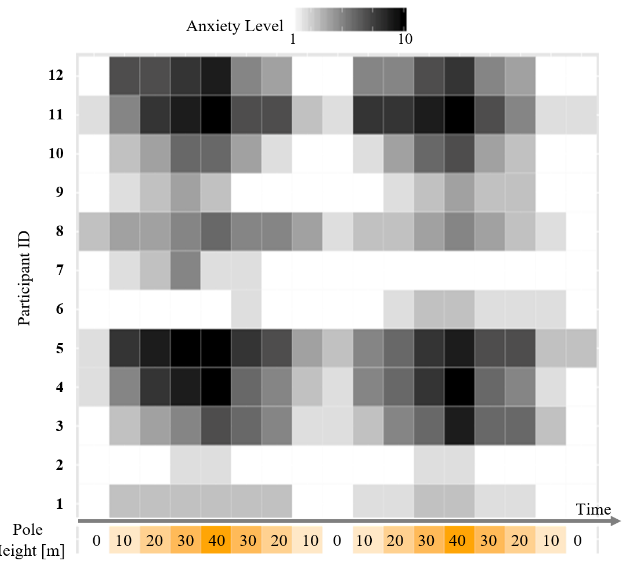

Figure 6: Self-reported individual anxiety levels in Experiment 2. Self-reported anxiety levels are depicted as grayscale heatmap. Each row represents a participant, and each column represents the Think-aloud points (see Figure 4).

Sbj.	v1	v2	v3	v4	v5	v6
12	0.76	0.00	0.00	0.00	0.00	0.76
11	0.00	0.71	0.58	0.68	0.66	0.00
10	0.59	0.00	0.00	0.00	0.00	0.71
9	0.00	0.00	0.00	0.00	0.00	0.50
8	0.65	0.64	0.76	0.76	0.76	0.54
7	0.00	0.00	0.56	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.51	0.00
5	0.59	0.00	0.00	0.00	0.00	0.57
4	0.62	0.00	0.00	0.00	0.00	0.00
3	0.00	0.56	0.58	0.57	0.51	0.00
2	0.51	0.00	0.00	0.00	0.00	0.58
1	0.00	0.00	0.00	0.00	0.00	0.00

Height

Sbj.	v1	v2	v3	v4	v5	v6
12	0.58	0.00	0.00	0.00	0.00	0.51
11	0.00	0.78	0.63	0.70	0.64	0.00
10	0.80	0.00	0.63	0.60	0.58	0.82
9	0.49	0.00	0.00	0.00	0.00	0.52
8	0.50	0.58	0.68	0.67	0.78	0.00
7	0.65	0.00	0.00	0.00	0.59	0.60
6	0.00	0.00	0.00	0.00	0.00	0.00
5	0.58	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00
3	0.48	0.60	0.61	0.63	0.57	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00

Anxiety level

Figure 7: Correlation results for each participant in Experiment 2. "0.00" means there was no statistically significant correlation. (v1: SC, v2: PPSC, v3: AmpSum, v4: ISCR, v5: PhasicMax, v6: Tonic)

4.5 Results

The data from one female participant had to be omitted from the analysis due to a data recording error. We did not analyze heart rate data because Bluetooth communication for the heart rate monitor failed occasionally. We observed noticeable interpersonal differences in physiological responses and decided to perform the analysis both on a per-participant basis and using the pooled data.

4.5.1 Individual Analysis Results

SC and PPSC were averaged within response windows of 1 to 4 sec after the Think Aloud points, i. e. we generated 17 values per each measure, to analyze them with the other measures. The individual results for self-reported anxiety levels are shown in Figure 6. We used Pearson product-moment correlation coefficients to assess the relationship between measures and height/anxiety level per each participant. The results are listed in Figure 7. We are reporting the number of participants with a statistically significant correlation [$p < 0.05$] and averaged correlation coefficients here.

We found significant correlations between height and anxiety level in eleven participants [$r = 0.81, SD = 0.12$]. Among them, six participants showed a strong positive correlation [$r > 0.8$]. There was a positive correlation between height and SC in six participants [$r = 0.62, SD = 0.08$]. SC was positively correlated with anxiety level in seven participants [$r = 0.58, SD = 0.11$]. There was a positive correlation between height and PPSC in three participants [$r = 0.63, SD = 0.08$]. Also, we found a positive correlation in three participants between PPSC and anxiety level [$r = 0.65, SD = 0.11$]. There was a positive correlation between height and AmpSum in four participants [$r = 0.62, SD = 0.1$]. Four participants AmpSum data were positively correlated with anxiety level [$r = 0.64, SD = 0.03$]. There was a positive correlation between height and ISCR in three participants [$r = 0.67, SD = 0.09$]. Between ISCR and anxiety level, four participants showed a positive correlation [$r = 0.65, SD = 0.03$]. There was a positive correlation between height and PhasicMax in four participants [$r = 0.61, SD = 0.12$]. PhasicMax was positively correlated with anxiety level in five participants [$r = 0.63, SD = 0.09$]. There was a positive correlation between height and Tonic in six participants [$r = 0.61, SD = 0.1$]. We found a positive correlation between anxiety level and Tonic in four participants [$r = 0.61, SD = 0.14$].

4.5.2 Collective Analysis Results

For modeling the relationship between height and measures, we divided the height into four sections; 0 to 10 m, 10 to 20 m, 20 to 30 m, 30 to 40 m. Each measure was normalized per participant, and averaged per each section. For the color recall score, we used the ratio of the correct answer to compensate the difference in total number to recall per each section. In other words, we formulated the data based on height such that each participant had four values per each measure. The pooled results for the different subjective and physiological measures are shown in Figure 8.

For the sake of convenience, we defined pairs of two sections as follows: pair1 (section 1 vs. 2), pair2 (section 1 vs. 3), pair3 (section 1 vs. 4), pair4 (section 2 vs. 3), pair5 (section 2 vs. 4), pair6 (section 3 vs. 4).

A non-parametric Friedman test of differences among repeated measures (sections) was conducted for each measure. We compensated for multiple comparisons using Bonferroni correction for the post-hoc comparisons.

For the anxiety level [$\chi^2 = 35.72, p < 0.001$], we found significant differences in pair2, 3, 5 [$p < 0.01, p < 0.001, p < 0.001$ respectively]. For the SC [$\chi^2 = 34.90, p < 0.001$], there were statistically significant differences in pair2, 3, 5 [$p < 0.001, p < 0.001, p < 0.01$, respectively]. For the PPSS [$\chi^2 = 7.1, p = 0.069$], there was no significant difference in all pairs. For the AmpSum [$\chi^2 = 23.5, p < 0.001$], pair2, 3 [$p < 0.01, p < 0.001$, respectively] were significantly different. For the ISCR [$\chi^2 = 18.1, p < 0.001$], we found statistically significant difference in pair2, 3 [$p < 0.01, p < 0.001$, respectively]. For the PhaicMax [$\chi^2 = 18.7, p < 0.001$], there were significant differences in pair2, 3 [$p < 0.001, p < 0.01$, respectively]. For the Tonic [$\chi^2 = 34.9, p < 0.001$], we found significant differences in pair2, 3, 5 [$p < 0.001, p < 0.001, p < 0.01$, respectively]. Finally, for the memory test [$\chi^2 = 10.86, p < 0.05$], we found a significant difference in pair5 [$p < 0.05$].

4.6 Discussion

Overall, the results show that there are positive correlations between height/anxiety and physiological measures.

From both the individual analysis and the collective analysis, we found an uncanny correlation between subjective responses (i. e., the self-reported anxiety levels) and the height of the platform in the VE (see Figure 8 top left). Most participants judged anxiety to increase with a linear relation from a height of 0 m to the top height of 40 m. In other words, the difference in height between 0 and 10 m was judged as just as anxiety-provoking as the difference between 30 and 40 m. Furthermore, participants, who rated the same or higher number for 30 m in the first lifting,

[7] http://www.ledalab.de

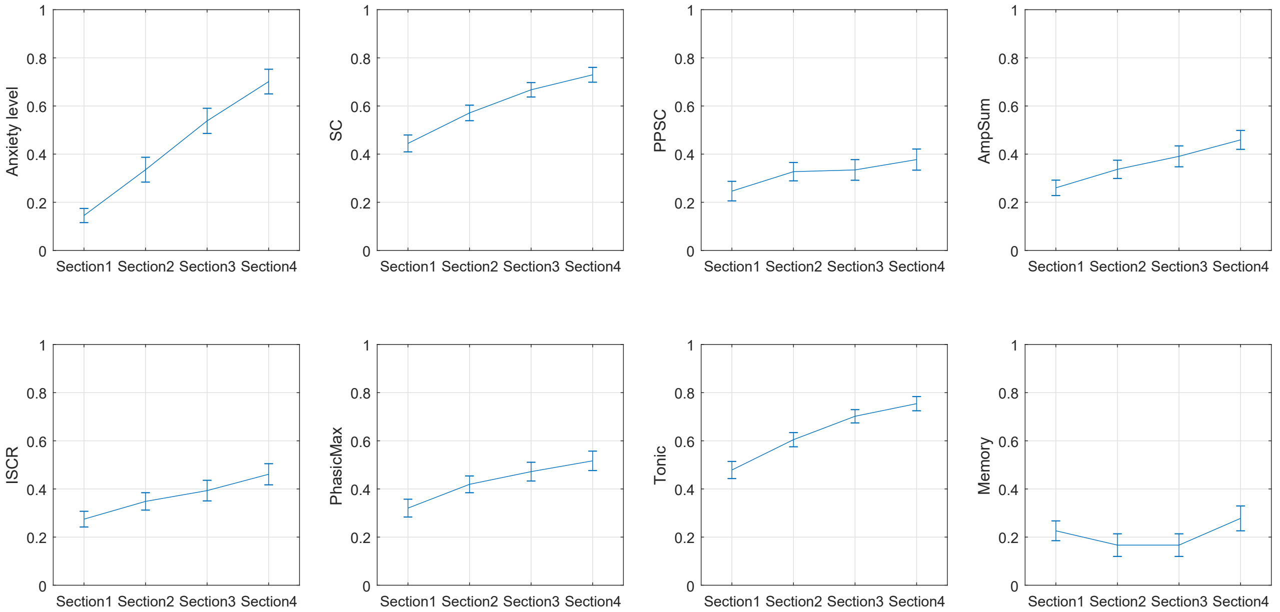

Figure 8: Responses in Experiment 2 from top left to bottom right: subjective self-reported anxiety level, SC, PPSC, AmpSum, ISCR, PhasicMax, Tonic and Memory. All measures are normalized as described in Section 4.5.

transferred the score to the second lifting and rated the highest score for the top as if they knew that there would be no more lifting. One possible explanation of these results is an experiment bias. Participants might have guessed the conditions of the experiment and rated anxiety as higher because they noticed that the height was increased, not because they actually felt more fear.

In contrast, the physiological responses do not show such an effect. Our Friedman test and post-hoc comparison results support the notion that multi-level height could induce multi-level physiological anxiety responses. The normalized SC and normalized Tonic responses were statistically different in pair2, 3, and 5, and showed a monotonic increase as the height increased. However, unlike the self-reported anxiety levels, the physiological responses were characterized by a gentle curve, i. e., the effects on anxiety were not equal for all height differences, which we believe to be more reliable than a straight line correlation. Overall, we only found a positive correlation between self-reported anxiety and physiological responses for a small number of participants.

Measures related to the phasic activity of SC showed a statistically significant difference in pair2, 3, but not in pair5. This might be explained by a decrease in accuracy of human depth perception over distance and an underestimation of distances in VR [LK03, RVH13]. The gentle curve in measures related to tonic activity could be an effect of this reduced phasic activity.

From the individual analysis, we observed a trend that either phasic or tonic related measures showed a correlation with height. Our video recordings showed that participants with a correlation between height and phasic related measures only (i. e., without a correlation between height and tonic related measures) tended to look down only when they heard the bell sound, and turned the head back to look straight ahead. Informal comments and observations suggest that this might be a height avoidance behavior for them to control their anxiety. These participants indicated a high susceptibility to fear of heights.

In general, people tend to recall the first and last items in a series of items best, and the middle worst [Fre94]. However, the memory recall task show that participants remembered the color of the sphere more accurately at the highest pole position. This result is interesting as the highest positions were neither the beginning nor the end of the simulation. This might be a result of the amygdala activation, which is known to involve memory modulation and fear/anxiety. We believe that the height increases in the pole simulation activated the amygdala, i. e., fear/anxiety was induced, and the activation resulted in an increase in SC related measures and the retainment of the color they saw at the moment. However, this result has to be confirmed in a future iteration of the virtual pole setup including brain imaging technology.

5 General Discussion

Regarding our research question Q_1, we found correlations of anxiety measures in our experiments with the participant's head pitch angle. They also correlated with height, but strong anxiety levels were mainly visible when they were high up and looked down, especially in phasic skin conductance responses. This is an interesting observation and important for practitioners as it suggests that due to the smaller vertical field of view of current-state HMDs this might induce differences between anxiety responses in VR and corresponding situations in the real world.

Regarding Q_2, we found that GSR is a useful measure of anxiety and thus for presence in stressful VEs, whereas the subjective responses in our experiments raised doubts about potential experiment biases. We used different measures (features) of GSR in our experiments, and reported the correlations between anxiety/height and each measure. Our results have shown that overall tonic activity of GSR is closely related with height/anxiety, but the best fit measures varied individually. Some measures from the decomposition analysis were computationally more expensive, but did not show considerable improvement over simple filtering method.

Overall, based on our observations and findings in this experiment, we suggest the following implications and guidelines for future fear of height simulations:

- When using fear of heights in an HMD-based VE, the user may not perceive the actual height due to the limited vertical FOV of the HMD, resulting in unintended anxiety levels and relevant physiological responses. Therefore, either a wide vertical FOV HMD or a task that redirects users' gaze to perceive the height should be considered.

- Heart rate measures from the user's hand are sensitive to the user's body movements, and they are even affected by the user's head movements. When using a heart rate sensor in a VR simulation that requires gestures by the user, an algorithm to remove the artifacts from the heart rate must be used.

- The slowly changing tonic activity in GSR is closely correlated with anxiety/fear. Phasic activity is more correlated with the user's looking down behavior. A simple filtering of raw GSR data could work just fine when measuring anxiety/fear. The best correlated measures are found for individual per-user analyses.

6 Conclusions and Future Work

In this paper we presented two experiments that investigated human responses to fear of heights in immersive virtual environments. For that, we iteratively designed the virtual pole simulations, in which users stand/sit on a platform placed on a pole, and the pole moved up and down following plausible scenarios.

Our experiments revealed that users' self-reported anxiety level is linearly correlated with the height of the pole, while physiological responses do not have such linear correlations. In this study, we compared different physiological measures, and investigated their relationships with self-reported anxiety and height. Our results show large interpersonal differences for the measures, leading to the need for adaptive methods in using physiological measures. We also found a critical component for the fear of heights in VR. That is, due to the limited vertical field of view of current-state HMDs, users have to tilt their head down more than they would have to in the real world to feel anxiety from the height. This also leads to a correlation between looking down behavior and physiological responses.

Future work may focus on the following issues. First, we observed interpersonal differences and motion artifacts in the physiological data, which required post-processing of data to be analyzed [BK10]. However, training/therapy scenarios often need timely or real-time feedback. Therefore, methods to detect artifacts and to process data in real time need further investigation. Second, we used GSR and HR here with the aim of measuring involuntary and uncontrollable human responses in VEs. Those physiological responses are primarily under the autonomic nervous system's influence [Fai10], but the observed movement of the body also affected the signals to some extent. In this regard, research on correlations between bodily actions and changes in each physiological signal as well as brain activity, e. g., related to an activation of the amygdala, should be considered.

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