The Effects of Virtual and Physical Elevation on Physiological Stress during Virtual Reality Height Exposure

Howe Yuan Zhu, Hsiang-Ting Chen, and Chin-Teng Lin

Abstract—Advances in virtual reality technology have greatly benefited the acrophobia research field. Virtual reality height exposure is a reliable method of inducing stress with low variance across ages and demographics. When creating a virtual height exposure environment, researchers have often used haptic feedback elements to improve the sense of realism of a virtual environment. While the quality of the rendered for the virtual environment increases over time, the physical environment is often simplified to a conservative passive haptic feedback platform. The impact of the increasing disparity between the virtual and physical environment on the induced stress levels is unclear. This paper presents an experiment that explored the effect of combining an elevated physical platform with different levels of virtual heights to induce stress. Eighteen participants experienced four different conditions of varying physical and virtual heights. The measurements included gait parameters, heart rate, heart rate variability, and electrodermal activity. The results show that the added physical elevation at a low virtual height shifts the participant's walking behaviour and increases the perception of danger. However, the virtual environment still plays an essential role in manipulating height exposure and inducing physiological stress. Another finding is that a person's behaviour always corresponds to the more significant perceived threat, whether from the physical or virtual environment.

Index Terms—Virtual Reality, Physiological Stress, Walking at Heights, Height Exposure

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1 INTRODUCTION

PHYSIOLOGICAL stress is a universal survival mechanism that is directly related to a human's natural fight, flight, or freeze response [1]. Stress at different levels will heavily influence a person's general quality of life, mental health, and life span [2]. At manageable levels, a person may observe positive benefits such as improved mental focus and heightened performance [3]. Its adverse effects can lead to mental health disorders, physical illnesses, and deterioration in cognitive ability when the stress levels are outside of the healthy range [4]. For this reason, researchers strive to explore and create different methods of inducing stress to better understand the impacts of stress on a person's mental health and how it affects their behavioural and physiological states [5]. The main struggle of traditional paradigms is the inability to coherently, realistically, and reliably induce varying levels of stress.

Height exposure is a reliable method of inducing physiological stress. Acrophobia-related stress exposure is known to produce a consistent stress response across various ages and demographics [2], [6]. Before the popularisation of virtual reality (VR) technology, the traditional approach was to use in vivo (real-world) height exposure methods to induce stress. The standard techniques for this form of exposure tend to be through either self-guided height exposure [7], controlled height exposure [8], or imaginal exposure [2]. The in vivo methods relied on modulating a person's physical height to produce height exposure. These methods were generally effective in inducing stress. However, the drawback of in vivo methods is the practicality and cost, which restricted researchers to smaller sample sizes and more straightforward methods of exposure such as a balcony or window [9], [10].

The introduction and improvement of VR technology address the drawback of in vivo methods by enabling controlled exposure to heights safely, and in a cost effective manner [11]. This new technology has caused a dramatic shift in height exposure research as researchers are moving away from in vivo exposure and towards virtual exposure methods [12]. Virtual exposure is a safer, more economical approach that provides a greater degree of control of the exposure. Previous studies [9], [10] that compared in vivo exposures to virtual exposures found that VR exposure produces a comparable amount of stress to that produced using in vivo methods. The virtual environment (VE) plays a vital role as a spatial medium for researchers to manipulate and control the levels of stimuli exposure that a person experiences when using a VR system [13].

Researchers tend to primarily focus on creating and improving VEs that are effective in inducing a controlled amount of physiological stress. This shift in focus causes less attention to be allocated to the improvement of the physical environment for height exposure. Meehan et al. [14] investigated the idea of using a modified physical environment with a VE during height exposure. The study introduced the usage of a walking platform or plank as a form of passive haptic feedback to improve the user's sensory congruence with the VE [14]. Many height-related VR studies [15], [16],

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[17] have accepted and adopted passive haptic feedback to enhance the correspondence between the real-world environment and the VE. The typical design attributes shared by various passive haptic feedback platforms are the benign or safe nature of the platform design with the visual display as the source of the stressful stimuli. The physical environment only has a supplementary role in improving the realism of the virtual environment and does not inherently provide a sense of height or danger.

This paper presents an experiment investigating the impact on a person's physiological stress when using a physically elevated walking platform with different levels of virtual height exposure. The measurements taken during this experiment included gait parameters, heart rate, heart rate variability, and electrodermal activity. The experiment was designed to examine the three hypotheses described below.

- *H1*: Different levels of virtual height will induce different levels of physiological stress.
- *H2*: The physically elevated platform will inherently induce physiological stress when the virtual height is low.
- *H3*: Visual stimuli (of virtual height) will dictate the stress level when the height between physical and virtual environments is incongruent.

Eighteen participants were recruited, and each experienced four different conditions of varying physical and virtual heights. These four conditions are described below and shown in Figure 1:

- *GG*: Both the physical (G) and virtual environment (G) are on the ground level (0.02 m).
- *PG*: The person is physically elevated (P, 0.65 m) while on the ground level in the VE (G, 0.02 m).
- *PP*: Both the physical (P) and virtual environment (P) are elevated (0.65 m).
- *PH*: The person is physically elevated (P, 0.65 m) while experiencing extreme heights in the VE (H, 150 m).

1.1 Contribution

This paper makes the following contributions:

- A novel experimental setup with a physically elevated platform that induces physiological stress through the manipulation of the physical height and virtual height.
- A rich multimodal dataset of participants under different levels of stress including gait parameters, questionnaires, electrodermal activity, heart rate, and heart rate variability.
- Insights into how incongruence of physical and virtual elevation can affect physiological stress levels when using a VR system.

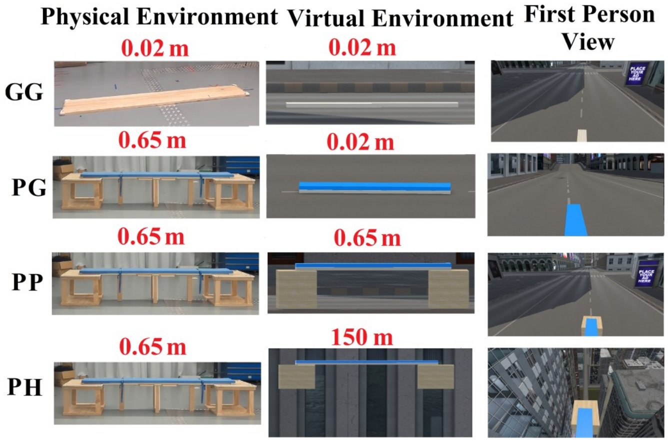

Fig. 1. The experimental conditions with condition labels, *GG*, *PG*, *PP*, and *PH* (G=ground, P=platform, H=Extreme height). First condition letter: the physical experiment setup; second condition letter: the virtual experiment setup.

2 Related Works

2.1 Physiological Stress and Fear

An essential part of stress-related research is selecting a reliable method that induces physiological stress in a controlled environment. The most common approach to inducing physiological stress is to target a person-specific fear [12], [13], [18]. Ledoux [19] aptly describes fear conditioning as one's involuntary ability to perceive a threat that automatically triggers a physiological response to danger. Later, Johnson et al. [20] established a strong causal link between the fear response and physiological stress response. The study found that the fear conditions trigger a physiological response, which in turn releases the hormones that are involved in the physiological stress response [20]. This consistency of behaviour during fear and physiological stress responses is the rationale for designing stress-inducing paradigms around specific fears and phobias.

There are two main criteria when selecting the appropriate phobia for a stress-inducing paradigm. First, exposure to phobia stimuli must be safe and controllable in an experimental environment [11], [12]. Second, a phobia must have a consistent and reliable physiological response within the targeted demographic [12]. The two widely accepted phobias used for stress paradigms are acrophobia (heights) [6], [11], [13], [15], and social phobias [21], [22]. Multiple studies [6], [21] have consistently linked the exposure of these phobias to an increase in physiological stress levels with a low variation between subject demographics. Before VR technology gained popularity, the first criterion proved to be a challenge for paradigms based on acrophobia. Without a VE, researchers either need to spend a large amount of resources and time exposing a small sample group to heights in vivo or opt for imaginal exposure [2]. This impracticality has led researchers to favour social phobia based paradigms for inducing stress [23], [24]. Brouwer and Hogervorst [23] mentioned that the reason for the desirability of social phobia paradigms is due to the paradigm's ability to induce stress in a reliable and efficient manner at a low cost.

On the other hand, the advancement and availability of VR technology provide researchers with the opportunity to create a more realistic, safe, cost-efficient, and controlled environment for extreme height exposure [15], [25]. Studies by Cleworth et al. [9] and Simeonov et al. [10] concluded that real-world and VR heights have comparable results when assessing threat perception and stress levels. VR based paradigms provide a naturalistic stimuli exposure, which is closer to real-world situations and environments. This realistic display is advantageous over imaginal exposure paradigms [8].

2.2 Sensory Realism and Presence

The level of immersion of a VR system has a direct effect on the sense of presence felt by the user [26]. Bowman and McMahan [11] identified the two key aspects that influence the effectiveness of a VE; the person's sense of presence and the level of immersion. Slater [26] defined immersion as the objective level of sensory fidelity provided by the VR system and presence as the subjective response of the human using the VR system. Conventionally, immersion is a function of the quality of the visual display, the existence of auditory noise, and haptic feedback; this is known as sensory realism [27].

2.2.1 Visual Realism

Visual realism is the visual display element of sensory realism. Visual realism refers to the level of visual accuracy to the real-world environment that is rendered on a VR system [11]. Slater et al. [27] demonstrated the importance of visual realism. Their study compared two different environmental rendering methods and produced different levels of visual realism (low vs. high-quality VE) and measured stress levels and the user's sense of presence [27]. The study found a significant increase in a user's sense of presence and a higher level of stress when experiencing a more realistic VE [27]. Hvass et al. [28] and Debattista et al. [29] also found similar results. To achieve a high level of visual realism, one must select a VR headset and graphics processor unit (GPU) with the appropriate hardware and software capabilities. With the wide range of head-mounted display (HMD) VR systems in the current market, it is essential to have clear guidelines of qualities required to achieve the benchmark visual performance [30]. Bowman and McMahan [11] and Lee et al. [31] outlined these qualities, which include the field of view , display resolution, tracking latency and accuracy, the realism of lighting, and frame rate; these qualities are crucial aspects that directly affect the level of immersion.

2.2.2 Auditory Stimuli

Auditory stimuli significantly contributed to creating a sensory realistic VE [32]. If a VE intends to simulate a real-world environment, then auditory stimulation is an indispensable component of the VR system [33]. Researchers such as Sanchez and Slater [12] stipulate that the lack of auditory representation negatively affects the realism and sensor perception of the presence of the VE. Hendrix and Barfield's [34] study established that the introduction of sound does positively affects the user's sense of presence. This result was supported by the Larsson et al. [35] study, which concluded that there is a significant difference in the presence rating between the absence and existence of auditory noise. Interestingly, the study found no significant difference between different types of auditory stimuli [35]. This finding suggests that the simple presence of an appropriate auditory stimulus is enough to increase the realism of the VE and improve the user's sense of presence.

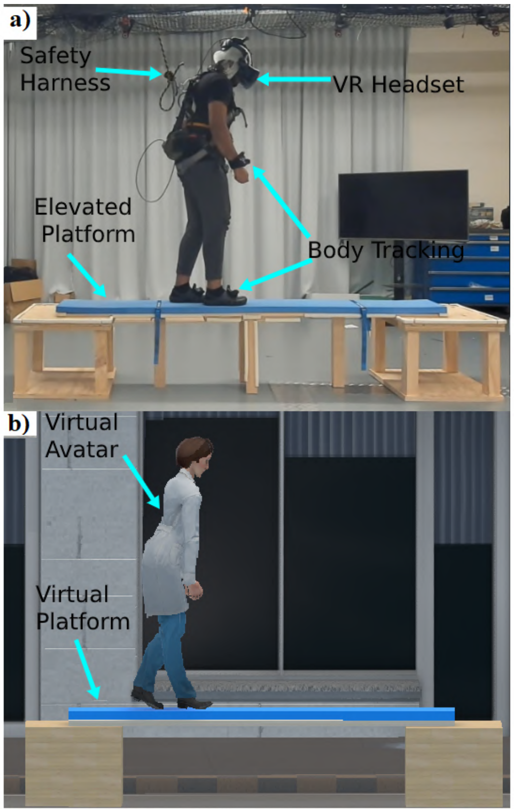

Fig. 2. a) The physical elevated platform, VR headset, body tracking, and safety equipment. b) The virtual environment used in this experiment with a virtual avatar that is driven by body tracking.

2.2.3 Haptic Feedback

Haptic feedback refers to the user's sense of touch and enables the user to interact with and gauge the environment through tactile sensing [36]. Haptic feedback enhances the user's sense of presence by allowing a user to hold unique objects or feel environmental features and surfaces [14], [37]. The findings of the Meehan et al. [14] study popularised the use of passive environmental haptic feedback VR height exposure studies. The study found that the incorporation of a floorboard (passive haptic feedback) that elevated the user by 1.5 inches (or 3.81 cm) induces a heightened physiological response from users [14]. The use of passive haptic feedback improved the sensory realism for locomotive based VE and proved to be exceptionally useful for virtual height based experiments. Additionally, the degree of sensory correspondence between the VE and the physical environment directly affects the user's physiological response to a stressful environment [14]. Both Asjad et al. [16] and Nagao et al. [38] demonstrated the effectiveness of passive haptic feedback in influencing a person's perception of height and presence in a VE.

2.3 Virtual Reality Height Exposure

The experimental design of this paper is motivated by past studies in the areas of physiological stress and VR exposure therapy. Early studies, such as Hodges et al. [39], established the efficacy of using VR to simulate a heightened environment for acrophobia exposure and inducing stress. Later studies [14], [40] began to emphasise the importance of immersion and presence through the introduction of passive haptic feedback. Based on these past contributions, we believe an effective height exposure-based virtual environment should:

- include a VR display that provides a high-quality visual rendering of the VE [11], [13],
- have existing auditory stimuli [34], [35],
- provide a physical sense of elevation in the real world [14], and
- include an active play area with strong correspondence to the physical environment [27].

The Peterson et al. [15] study is a more recent example of a height exposure experiment that abides by the requirements listed above. The investigation conducted by Peterson et al. [15] aimed to investigate the effects of heightened beam-walking on physiological stress and cognitive loading. The experimental setup used a high-quality GPU (NVIDIA Titan X) for rendering, background noise for auditory stimulation, a 2.5 cm tall walking beam (virtual height 15 m), a virtual avatar (virtual embodiment), and an identical virtual beam. This setup successfully created a realistic VE that induced physiological stress. Another notable study involved the virtual work-at-height simulator developed by Loreto et al. [17]. The VR simulator proposed by the study used a real ladder (virtual height 11 m) as passive haptic feedback to simulate ladder climbing at heights [17]. A novel contribution of the experiment is the incorporation of vibrations in the ladder, which showed a significant impact on the perceived realism of the VE. Overall, the study concluded that using a fidelity experimental setup with real physical elevation can reliably induce stress [17]. This paper will build upon the two studies [15], [17] mentioned above by incorporating the concept of a heightened platform (65 cm physical and 150 m virtual, see Figure 2) and the walking height exposure.

3 EXPERIMENT DESIGN

3.1 Experiment Physical and Virtual Environment

3.1.1 Physical Space

This experiment investigated the effects of physical height during virtual height exposure. The elevated physical platform provided physical height to this experiment. The design of the platform followed two requirements. The first requirement was to safely elevate the participant and the second was to introduce a sense of fear from the awareness of physical height. The primary construction material for the platform was pinewood with reinforced joints. The corners and edges were lined with protective foam, and a rail fall arrest system was used to protect the participants from fall-related injuries (no participant fell off during the experiment). Based on the height of the rail, safety line, and harness system, the platform was set to 0.65 metres in height and rated to support up to 150 kg (exclusion criteria restricted this to 95 kg).

After meeting the first requirement of safety, the second concern was creating a sense of danger on the platform. Plates were placed on the bottom of the ends of the platform, causing small amounts of instability during walking. A surface foam layer was introduced to add further postural instability when walking on the elevated platform. These instability factors created difficulties during walking which aimed to increase the participant's anxiety levels when walking. The ground platform consisted of a separate board with matched dimensions to the elevated platform. This correspondence ensured consistent gait behaviour during the experiment. Both the elevated (0.65 m height) and ground (0.02 m height) platform had the same walking space dimensions of 2.4 m long and 0.3 m wide.

3.1.2 Virtual Space

As previously outlined, having a strong correspondence between the VE and the real world for the experimental setup improves the reliability of successfully inducing stress. The dimensions, orientation, and position of the physical plank were measured through the Optitrack motion capture system (12 flex13 cameras) and mapped in virtual space. The usage of motion capture ensured an accurate translation of motion between the physical and virtual space. HTC Vive controllers were used for active motion tracking to capture any offset movement and vibrations for the physical platform.

The VE was set in an urban environment because the buildings and the overall city provided the participants with a believable environment for the virtual height. The buildings also emphasised the sense of height through the scaling of the building; see Figure 2 for the physical and virtual setup. The visual display was rendered through the HTC Vive Pro VR HMD and used a VR-optimised configured PC (NVIDIA GTX1080 GPU, Core i7) to ensure a high-quality VE. The addition of the wireless adapter improved the safety and mobility of the participants.

3.1.3 Peripheral additions

The incorporation of a virtual avatar provided the participants with a medium for virtual embodiment. The avatar used inverse kinematics (FinalIK by RootMotion [41]) and a six-point body tracking system (one HMD, one waist tracker, two hand trackers, and two feet trackers) with HTC Vive trackers. HTC Vive trackers were chosen for their accuracy and low latency [42]. The incorporated avatar improved the participant's spatial awareness of elevation and their sense of presence in the VE. The ambient urban environment noise played in the background served as the auditory stimuli to enhance the realism of the VE.

3.2 Experiment Design and Protocol

This experiment tested four conditions; each condition consisted of a combination of the physical (ground and elevated platform) and virtual (ground, elevated platform, and extreme height) independent variables. (See Figure 1 for the condition of this experiment; the conditions are *GG*, *PG*, *PP*, and *PH*). Every participant experienced the same four conditions in a randomised sequence. Due to timing constraints of the physical setup, the physical ground platform (*GG*) was randomised separately to the elevated platform (*PG*, *PP*, and *PH*). Each condition of the experiment consisted of 5 trials (1 walking baseline and 4 trials with a cognitive task).

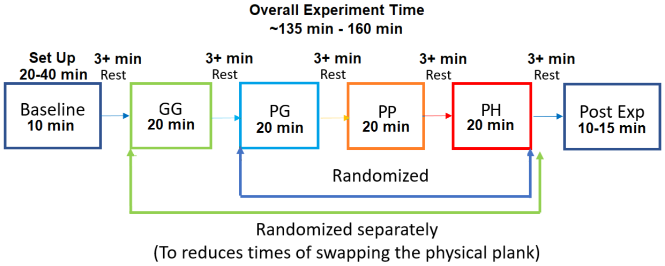

Fig. 3. The timeline of the experiment with the approximate timing for each section (Times vary between participants).

One trial constituted the trip from the starting position to the end, and the return walks back to the start. During the walk, participants received instruction to walk in their natural gait. During the non-baseline walk, the participant performed a cognitive task (Oddball paradigm) on the return trip in the middle of the platform. The oddball task consisted of a serialised sequence of images consisting of green (non-target) and blue (target) circles at a 1:4 target to non-target ratio. Using a remote, the participants reacted to the target stimuli. This task would prolong the height exposure for each trial. The participant performed a sitting and standing task during the baseline period while their physiological and behavioural data were recorded. The same standing task was performed during the post-experiment period, along with a post-experiment questionnaire.

The participants had 3 minutes (minimum) resting periods between each condition; the participants could extend this time based on need. The overall experiment took 2-3 hours to complete with the approximate timings for each section outlined in Figure 3. Each condition lasted for around 20 minutes due to the cognitive task extending each of walking trial time by 2-3 minutes (1 baseline and 4 walking trials per condition).

The participants were encouraged to wear the VR HMD throughout the experiment continuously. This instruction provided a continual sense of presence in the virtual environment along with the virtual avatar. The participants stepped onto the physical platform while in a VR calibration scene. After the participant securely stepped onto the platform, they moved the VE based on the experimental condition. During rest breaks, participants were encouraged to close their eyes to prevent eye strain and provided the option to remove the VR HMD if they felt severe discomfort.

3.3 Participants

This human research experiment had the approval of the local institute's research ethics committee. All participants provided written informed consent and were compensated for their participation (regardless of outcome or termination). We recruited 20 adults (5 females and 15 males) with ages ranging from 21 to 35. The mean age was 26, and the population variance was 4.70. The key inclusion criterion was the participant's age range (18-35 years). The key exclusion criteria were:

- an inability to understand the experimental instructions (language and cognitive ability),
- existing medical conditions, such as
    - neurological and cardiovascular disorder,
    - diagnosed mental health issues (depression, anxiety, or chronic stress),
    - sensory (visual, vestibular, or auditory) dysfunction, and
    - gait (unable to perform unassisted walking) disorders.
- weight more than 95 kg (participant safety).

Data analysis only included the dataset of 18 participants because of the removal of two datasets. One of the discarded datasets (male) was due to incomplete data from hardware failure. The other participant (male) felt overwhelmed by the height exposure and did not complete one condition (150 m virtual height).

4 MEASUREMENTS AND ANALYSIS

4.1 Physiological Measurements

The primary function of the physiological and behaviour measurement was to measure the participant's physiological stress levels. Heart rate (HR), heart rate variability (HRV), and electrodermal activity (EDA) were the primary physiological measures. The HR and EDA devices continuously recorded data throughout the whole experiment (standing baseline and conditions).

4.1.1 Heart Rate and Heart Rate Variability

HR and HRV are reliable indicators of changes in cardiovascular and autonomic activity [43]. There is a strong correlation between physiological stress and HR. The participants wore a wearable Zephyr^{TM} bioharness device to measure and calculate their HR and HRV. The device is lightweight (85 g) and can accurately measure HR through electrocardiography (ECG, sampled at 250 Hz) [44]. The bioharness and HR/HRV analysis are ideal for ambulatory (in various conditions) experimental data. From the ECG data, the HR (BPM) calculations (provided by Zephyr) involved using the RR interval time [45]. The HRV calculation involves a 300-sample (5 minutes) rolling average of the standard deviation of the NN interval time [45]. HR data points outside the normal human BPM range ($30 < BPM < 120$) or calculated with low ECG signal to noise ratio ($noise > 20\%$) were filtered out. The HR data were normalised to account for the variance in cardiovascular behaviour. The data went through feature scaling (min-max) normalisation, which included the stationary standing data (for minimum scale value). HRV data points outside of the standard human scores ($20\ ms < HRV < 110\ ms$) and low ECG signal to noise ratio were filtered out.

4.1.2 Electrodermal Activity

EDA is another reliable indicator of physiological stress [46]. The Empatica E4 wristband was used to measure EDA. The wristband allowed a portable and non-intrusive method of recording EDA (sampled at 4 Hz) while maintaining an acceptable level of data quality [47]. The EDA (μs) data collected by the dry electrodes of the wristband measured the participant's skin conductance response. An increase

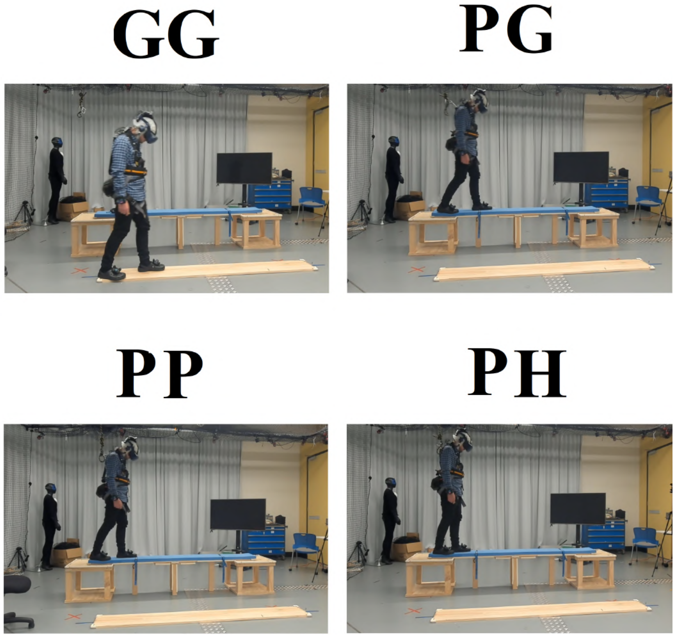

Fig. 4. A comparison of the participant's first step gait behaviour during walking.

in EDA indicated a heightened autonomic nervous system response and a potential increase in physiological stress [46]. The data points were separated by condition, filtered by the removal of values outside of the human skin conductance range ($0<\mu s<20$) and outliers (2 standard deviations from the mean). The EDA data were normalised to account for the variance in individual skin conditions. Similar to the HR data, the EDA data went through feature scaling (min-max) normalisation with the stationary standing data for the minimum scale value.

4.2 Behavioural Measurements

The six-point motion tracking system provided data to calculate the participant's behavioural gait parameters. Each tracker recorded the global position vector (x, y, z), orientation vector (Quaternion), and time stamping. It is expected for the height exposure to cause a significant change in gait behaviour, specifically a reduction in step length and an increase in cadence Figure 4. The gait parameters only included the forward (continuous) walking component of each trial. The exclusion of the return trip was due to a pause in walking to complete the cognitive task. The calculation excluded the first and last step of each trial as the participants were entering and exiting the walk space.

The three main parameters presented are the step length, step count per trial, and trial completion time. The gait parameter calculation involved replaying the tracker data (with inverse kinematics) and the Unity game engine collider system. The analysis included filtering outlier values (2 standard deviations from the mean) and averaging the data across the 18 participants.

4.3 Questionnaires

The participants provided questionnaire responses at various points during the experiment. Before the experiment, the participants filled out a questionnaire to provide insight into their level of acrophobia and their prior experience with heights, video games, and VR. At the end of each trial (5 trials per condition), the participant provided a Self-Assessment Manikin (SAM) rating (1-9) concerning their current arousal level [48], [49]. The participants were shown the SAM questionnaire figures before the experimental conditions. Participants were verbally (without the figures) asked for their SAM responses during the conditions. The SAM analysis involved separating the data by condition and averaging across 18 participants. The SAM results were also used to evaluate the condition order effect.

TABLE 1
Scaled DASS normative scores based on previous studies.

	Stress			**Anxiety**		
DASS	**Scaled**	**21**	**42**	**Scaled**	**21**	**42**
Normal	0-4	0-7	0-14	0-1	0-3	0-7
Mild	5-6	8-9	15-18	2-3	4-5	8-9
Moderate	7-8	10-12	19-25	4-5	6-7	10-14
Severe	8-9	13-16	26-33	6-7	8-9	15-19
Extremely Severe	10+	17+	34+	8+	10+	20+

During each resting period between experimental conditions, the participant provided a height estimate of the perceived height (in metres) and answered a modified Depression Anxiety Stress Scale (DASS) questionnaire [50]. The DASS questions involved the participants answering a series of questions (rating 0-3) to gauge their level of anxiety (sense of uncertainty) and stress (heightened arousal and emotional response). Due to experiment duration, the questionnaire was modified to remove the depression component, which shortened the questionnaire to eight questions (originally twenty-one, four questions for anxiety and four for stress). The DASS analysis separated the data by condition and component (anxiety and stress), then averaged across 18 participants. The DASS scores were compared to the normative scores based on the previous DASS-42 [50] and DASS-21 [51] studies. The score ranges were scaled to a four-question category range (DASS-42 has fourteen, and DASS-21 has seven per category). The scaled normative scores can be found observed in Table 1.

During the post-experiment phase (end of the experiment), the participants provided a retrospective ranking questionnaire (user ranking) responses for each condition. The participants provided a ranking for the four conditions based on stress level (1st, the most stressful, to 4th, the least stressful).

4.4 Statistical Analysis

A one-sample Kolmogorov-Smirnov test was applied to determine the normality of each metric. The results were confirmed visually through a cumulative distribution function (empirical vs normal) plot. The test found the HR, HRV, EDA, and DASS scores to be normally (Gaussian) distributed; hence the one-way ANOVA was applied to determine the statistical significance between the four conditions. The test found the gait parameters and SAM ratings to be of non-normal distribution; therefore, the appropriate test was the Wilcoxon signed-rank test. The statistical tests compared the four conditions in a pairwise manner with a significance

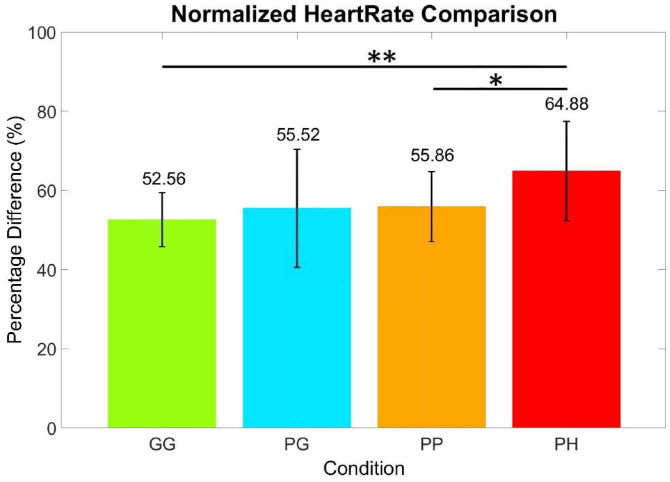

Fig. 5. A bar plot of the normalised HR values averaged across all the participants.

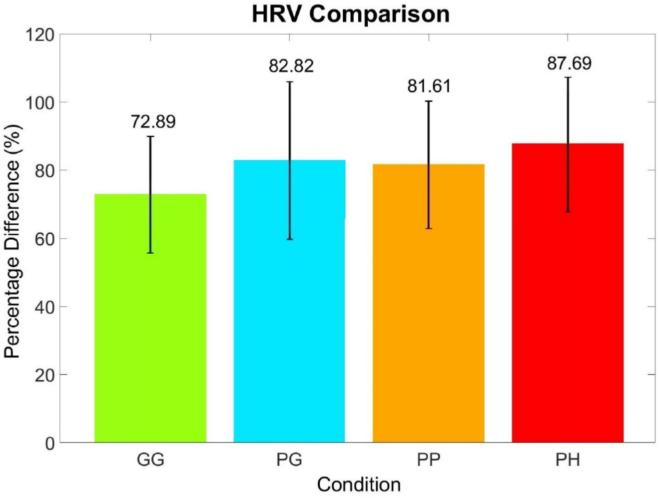

Fig. 6. A bar plot of the HRV value averaged across all the participants.

level ((α) of 0.05 determining statistical significance. In all figures, *p<0.05, **p<0.01, and ***p<0.001.

5 RESULTS

5.1 Heart Rate

Figure 5 illustrates the average (standard deviation bars) HR values (*GG* M=52.56% and SD=6.92, *PG* M=55.52% and SD=14.910, *PP* M=55.86% and SD=8.87, and *PH* M=64.88% and SD=12.53) across the 18 participants. The HR response during the *PH* condition was significantly different from that of the *GG* (F(1,30)=11.86, p=0.0017, and partial η^2=0.28), and *PP* (F(1,30)=5.53, p=0.0255, and partial η^2=0.16) conditions. This distinction indicates an increased physiological response when the participant was physically elevated (0.65 m) and exposed to an extreme virtual height (150 m). The HR data did not show significant difference when comparing *GG* condition to the *PG* and *PP* conditions. There was also no significant difference when comparing *PG* to *PP* and *PH* conditions.

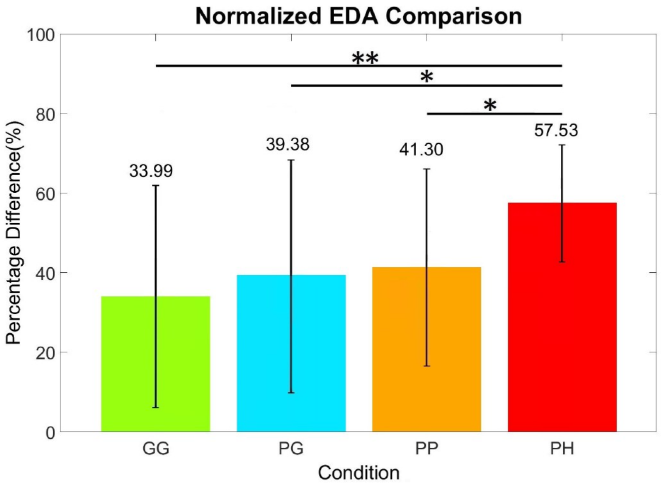

Fig. 7. A bar plot of the normalised EDA value averaged across all the participants.

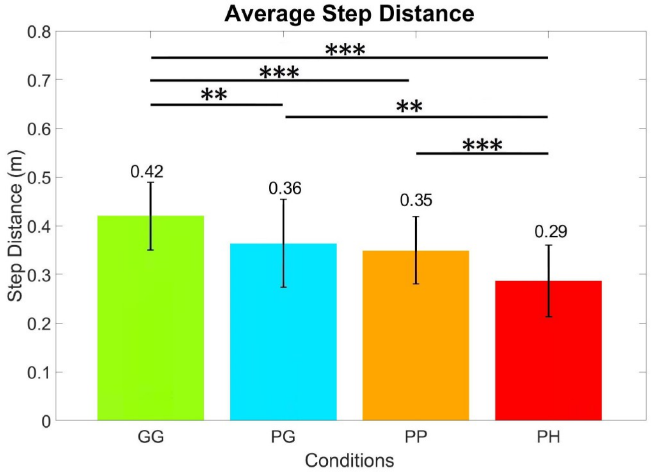

Fig. 8. Bar Plot of the Average Step Length.

5.2 Heart Rate Variability

Figure 6 presents the HRV values (*GG* M=72.89% and SD=16.74, *PG* M=82.82% and SD=22.98, *PP* M=81.61% and SD=18.52, and *PH* M=87.69% and SD=19.48) of the participants during the experiment. We did not find a significant difference in HRV data among the experimental conditions (F(1,30)<2.3, p>0.13, and partial η^2 <0.07).

5.3 Electrodermal Activity

Figure 7 presents the average (standard deviation bars) EDA results (*GG* M=33.99% and SD=27.66, *PG* M=39.38% and SD=28.87, *PP* M=41.30% and SD=23.79, and *PH* M=57.53% and SD=14.74) of the participants. There was a significant difference when comparing *PH* to *PP* (F(1,30)=5.04, p=0.0322, and partial η^2=0.14), *PG* (F(1,30)=4.98, p=0.0332, and partial η^2=0.14), and *GG* conditions (F(1,30)=8.89, p=0.0056, and partial η^2=0.13). This indicates a clear increase in sweating during exposure to extreme virtual heights. The *GG* condition showed no significant difference in EDA from *PG* and *PP* conditions. Similar to HR, the condition *PG* had no significant difference from the *PP* condition.

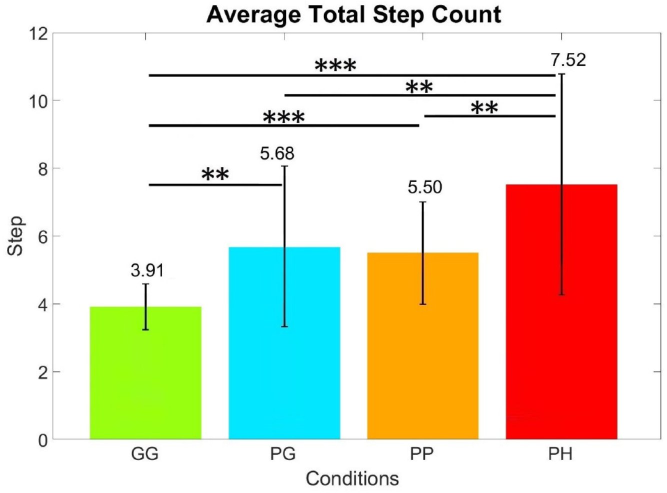

Fig. 9. Bar plot of the average step count per trial.

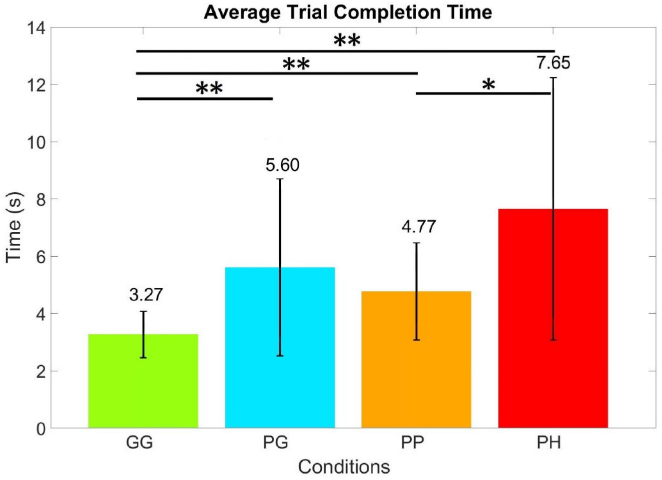

Fig. 10. Bar plot of the average trial completion time.

5.4 Gait

Figure 8 presents the average step length (*GG* M=0.42m and SD=0.07, *PG* M=0.36m and SD=0.09, *PP* M=0.35m and SD=0.07, and *PH* M=0.29m and SD=0.08) across 18 participants. The step length demonstrated a significant difference between the *GG* condition and the other conditions, *PG* (W=152, Z=2.90, p=0.0038, and r=0.68), *PP* and *PH*W=171, Z=3.72, $p<0.001$, and r=0.88), on the elevated platform conditions. The step length in the *PH* condition was significantly different from that of the *PG* condition (W=157, Z=3.11, p=0.0018, and r=0.73) and the *PP* condition (W=166, Z=3.51, $p<0.001$, and r=0.83). No significant difference was found between *PG* and *PP* conditions.

Figure 9 illustrates the step count (*GG* M=3.91 steps and SD=0.66, *PG* M=5.68 steps and SD=1.88, *PP* M=5.50 steps and SD=1.27, and *PH* M=7.52 steps and SD=2.99) per trial for each condition. There was a significant difference when comparing the *GG* condition to the *PG* (W=3.5, Z=-3.46, $p<0.001$, and r=0.84, *PP* (W=0, Z=-3.52, $p<0.001$, and r=0.85), and *PH* (W=1, Z=-3.57, $p<0.001$, and r=0.87) conditions. There was also significant difference when comparing the *PH* condition to the *PG* condition (W=18.5, Z=-2.75, p=0.0060, and r=0.67) and the *PP* condition (W=10.5, Z=-2.82, p=0.0048, and r=0.68). Similar to the step length, no significance was found when comparing the *PG* condition to the *PP* condition.

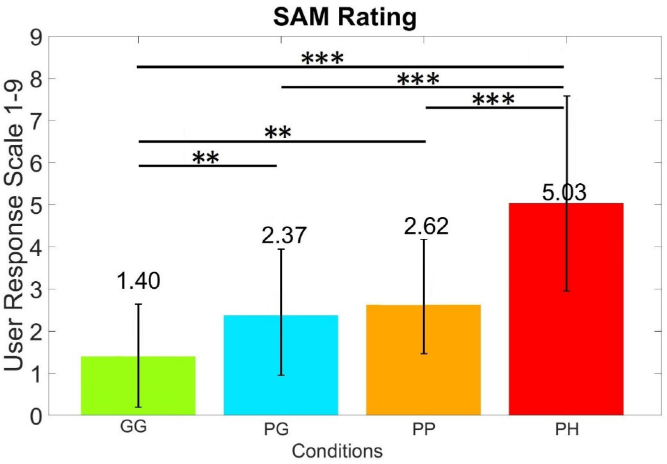

Fig. 11. Bar plot of the average SAM rating with the standard error bars.

TABLE 2
The mean and standard deviation of participant's SAM responses (rating 1-9) based on the sequence of conditions

Condition	1st	2nd	3rd	4th
GG	1.76 ± 1.19	N/A	N/A	1.04 ± 0.13
PG	3.85 ± 1.20	2.29 ± 1.59	1.10 ± 0.10	1.80 ± 1.01
PP	3.90 ± 1.10	3.24 ± 1.30	2.09 ± 1.42	1.00 ± 0.00
PH	3.30 ± 1.30	5.87 ± 1.63	5.14 ± 2.06	4.27 ± 2.72

Figure 10 shows the average trial completion time (*GG* M=3.27 and SD=0.88, *PG* M=2.55 and SD=5.60, *PP* M=1.65 and SD=4.77, and *PH* M=3.23 and SD=7.65) of each condition. The notable finding of this measure was the significant difference between the *GG* condition and the *PG* (W=20, Z=-2.67, p=0.0075, and r=0.65), *PP* (W=15, Z=-2.91, p=0.0036, and r=0.71), and *PH* (W=10, Z=-3.15, p=0.0016, and r=0.76) conditions. There was also a significant difference between *PP* and *PH* (W=29, Z=-2.25, p=0.0245, and r=0.54).

5.5 Questionnaire Responses

5.5.1 Self-Assessment Manikin

Figure 11 shows a plot of the SAM results (*GG* M=1.40 and SD=0.94, *PG* M=2.37 and SD=1.58, *PP* M=2.62 and SD=1.54, and *PH* M=5.03 and SD=2.21) across the 18 participants. The results in the *PH* condition were significantly different (W=0, $Z<-3.41$, $p<0.001$, and $r>0.80$) from all the other conditions (*PP*, *PG*, and *GG*). There is also a significant difference when comparing the *GG* condition to the *PG* condition (W=0, Z=-3.18, p=0.0015, and r=0.75) and the *PP* condition (W=4, Z=-3.05, p=0.023, and r=0.72). Based on the average value and significance, the trend of the SAM ratings was *PH*>*PP*=*PG*>*GG*. Table 2 depicts the SAM scores (mean and standard deviation) sorted by the sequence the participant experienced each condition.

5.5.2 Depression Anxiety Stress Scale (DASS)

Figure 13 and Figure 12 depicts the DASS questionnaire results (Table 3) for each condition. The anxiety results

TABLE 3
DASS mean, standard deviation, Normative Rating (NR, from Table 1), and Normative Range (from Table 1)

	Mean	SD	NR	Range
Stress				
GG	2.500	2.256	Normal	Normal-Mild
PG	2.667	2.029	Normal	Normal-Mild
PP	2.722	2.024	Normal	Normal-Mild
PH	4.611	2.453	Mild	Normal-Moderate
Anxiety				
GG	1.556	1.789	Mild	Normal-Moderate
PG	1.944	2.182	Mild	Normal-Moderate
PP	1.722	1.775	Mild	Normal-Moderate
PH	4.111	2.564	Moderate	Mild-Severe

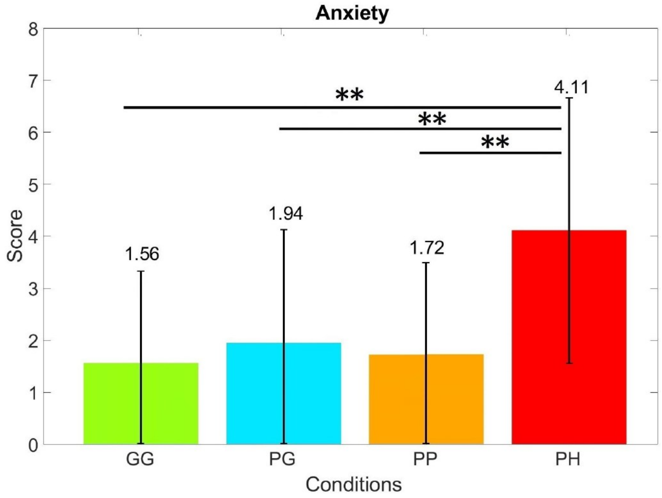

Fig. 12. DASS average anxiety scores with significance lines.

showed a significant difference between the *PH* condition and the *PP* (F(1,34)=10.56, p=0.0026, and partial η^2=0.24), *PG* (F(1,34)=7.45, p=0.01, and partial η^2=0.18), and *GG* (F(1,34)=12.02, p=0.0014, and partial η^2=0.26) conditions. Similarly, the stress results demonstrated a significant difference between the *PH* condition and the *PP* (F(1,34)=6.35, p=0.0166, and partial η^2=0.16), *PG* (F(1,34)=6.72, p=0.0140, and partial η^2=0.16), and *GG* (F(1,34)=7.22, p=0.0111, and partial η^2=0.18) conditions.

5.5.3 User Ranking

Figure 14 presents the results of this retrospective ranking. The *PH* condition was definitively ranked 1st based on the votes by every participant. Based on the majority votes, the subsequently ranked conditions were the *PP* (2nd), *PG* (3rd), and *GG* (4th) conditions.

6 DISCUSSION

The results suggested that exposure to experimental conditions induced physiological and behavioural changes in the participants. The *PH* condition received the highest SAM rating, assessed after each trial, and was ranked as the most stressful condition by participants in the retrospective user ranking questionnaire. In contrast, the *GG* condition received the lowest SAM rating and was ranked as the least stressful condition. The main contention in the SAM questionnaire results is the comparison between the *PG* and *PP* conditions. There was no significant difference between the SAM ratings of the *PG* and *PP* condition. However, most participants ranked the *PP* condition as more stressful than the *PG* condition. The participants retrospectively ranked the *PP* condition as more stressful than the *PG* condition, but this does not indicate the degree of the difference between the two conditions.

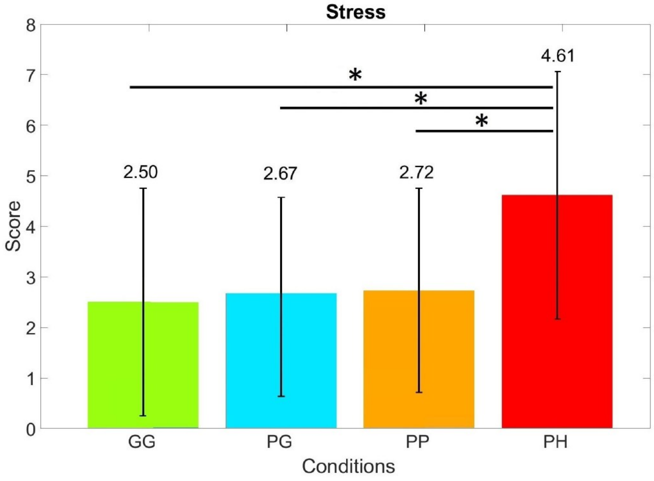

Fig. 13. DASS average stress scores with significance lines.

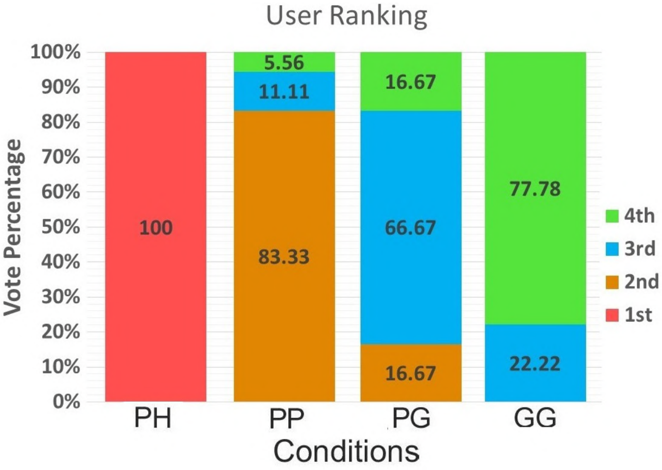

Fig. 14. Retrospective user ranking (1st-4th) of the conditions based on perceived stress levels with 1st being most stressful and 4th being the least stressful.

The gait parameters corroborate the findings of the SAM rating, with the *GG* and *PH* conditions being significantly different across all conditions, while the *PG* and *PP* conditions showed no significant difference. The results showed a correlation between the level of height exposure and the stepping length, total steps, and trial completion time. The general trend was that the increase in threat (height) perception caused the participant to change their gait behaviour, employing a more cautious walking style with a reduction in step length, an increase in steps taken and trial time. This result concurs with the findings of the study by Schniepp et al. [52]. Note that one factor for the observed difference in gait behaviour could be due to the contrast in walking surface and safety harness support when comparing the

GG condition to the other conditions. However, a similar change in gait behaviour occured when comparing the *PG* condition and the *PP* condition to the *PH* condition. In this case, the physical environment was consistent across these conditions. Therefore, this behavioural shift was more likely due to the change in perceived height.

A higher level of stress, in general, induces higher HR and EDA, and a lower HRV [43], [46], [53]. This phenomenon was observed in the Meehan et al. [14] and Diemer et al. [54] studies, in which the HR and EDA showed a significant increase when exposed to virtual height. The *PH* condition reflects this behaviour with a substantial increase in both HR and EDA compared to the other conditions. Surprisingly, there was no significant difference between the *GG* condition and the *PG* and *PP* conditions in HR and EDA data, even though these conditions received significantly different SAM ratings and user rankings. One potential explanation could be that in the *GG* condition, the participants engaged in a stepping strategy that required a higher level of physical exertion, i.e. a larger step distance and higher cadence, due to a less stressful condition, which resulted in an increased HR and EDA. We suspect that the lack of significance in the HRV results may also be due to the level of physical exertion and the short duration of each trial (3-7 seconds, Figure 10) compared to the 5 minute rolling average for the calculation. In the future, increasing the experiment duration or including a longer stationary component to each condition may yield a more observable effect for these measurements. Peterson et al. [15] also observed a similar masking effect of HR, HRV, and EDA changes due to physical exertion.

The DASS questionnaire provided scores for the symptomatic behaviours of stress, and anxiety [50], [55], [56]. The normative ratings show that *PH* is slightly higher level of stress and anxiety rating one category above the other conditions (Table 3). We collected DASS scores at the end of each condition for evaluation, as opposed to SAM ratings at the end of each trial. The significantly higher DASS scores in the *PH* condition indicated sustained symptoms of anxiety and stress after the completion of the condition. While these symptoms were non-existent or were subdued at a faster rate for the other three conditions, the result seemed to suggest that the combination of both physical and virtual height exposure could induce an observable change in anxiety and stress.

6.1 Effects of Virtual Elevation

The comparison of the *PG*, *PP*, and *PH* conditions provides insight into the effects of virtual height on inducing different levels of stress (*H1*). As expected, at the extreme level of virtual height, SAM, HR, and EDA increased while step length decreased. Contention occurred when evaluating the lower levels of virtual height (*PG* and *PP*). *H1* expected the *PP* condition at a mid-level elevation would induce an in-between level of stress (between *PH* and *PG*) and the *PG* condition would lead to a lower level of stress. In contrast, there were no significant differences between the *PG* and *PP* conditions for most of the measurements (except user ranking), which suggests an equivalent level of stress.

The reason for this unexpected result could be due to the level of virtual height in the *PP* condition not reaching the threshold required to induce the fear of heights. Wuehr et al. [57] investigated this idea and found that the fear of heights and the exposure to heights do not share a linear proportional relationship. Instead, the study found that the most significant behaviour change occurs after experiencing virtual height for 20 m and begins to saturate at approximately the 40 m mark [57]. This finding suggests that there is a minimum height threshold for virtual height to be effective in causing fear. Under this threshold, the physiological response will be more moderate compared to an overt response after passing the height threshold. It is highly likely that virtual heights at 0.65 m and below do not cause a noticeable behaviour change. In contrast, the height in the *PH* condition of 150 m was above the upper maximal threshold. Hence there is an observable effect from the virtual height.

In summary, *H1* is partially correct as in extreme virtual heights (*PH*), there was a distinct level of high stress; however, at lower levels of virtual height (*PP* and *PG*), there was a less discernible difference in the levels of stress. This finding suggests that low level virtual height cannot reliably induce multiple levels of stress when on the elevated platform.

6.2 Effects of Physical Elevation

The efficacy of physical elevation was assessed through the comparison of the *GG*, *PG*, and *PP* conditions, which had different physical elevations and negligible (below the threat threshold) levels of virtual elevation. There was a significant difference in the SAM ratings and gait parameters between the *GG* condition to the *PG* and *PP* conditions. In contrast, the absence of behavioural and physiological differences between the *PG* and *PP* conditions indicates that the participant perceived a similar level of threat. This indication suggests that the elevated platform is inherently threatening regardless of the visual input. This finding is unique because from a tactile sensory point of view, the participants should be unable to differentiate the elevation between the two platforms when using VR.

A possible explanation could be that the instability of the platform and the tactile surface caused stress due to postural imbalance. Another suggestion is that participants may have had a fear of falling off the elevated platform. The evaluation of this is difficult due to the safety harness, which may have provided a sense of safety [58].

A plausible explanation for this phenomenon could be a presupposition of height affecting the person's perception of height. The implication is that prior knowledge of environmental height affects the perceived height and fear response experienced [7], [8], [59]. Even though, the participant does not directly see the elevated platform when in VR, the presupposed knowledge of the platform's height from visually seeing the platform before wearing the VR headset and the memory of physically stepping up onto an elevated surface is enough to induce a sense of height.

Overall, this result confirms our *H2* that the elevated physical platform, at low levels of virtual height, would induce an increase in physiological stress levels when compared to the physically non-elevated platform. At the same time, the combination of different virtual and physical elevations can induce a broader range of physiological stress levels.

6.3 Incongruence between Physical and Virtual Environments

The *PG* and *PH* conditions are incongruent with a disparity between the physical and virtual environment. *H3* proposed that visual stimuli would be the dominant factor during height exposure. In that case, the *GG* and *PG* conditions would share the same visual stimuli of a lowered virtual plank on the ground and should induce a similar level of stress. Conversely, the *PH* condition induces a high level of stress, as supported by previous literature [14], [15], [16], [17].

The significant difference in the stress levels between the *GG* and *PG* conditions is particularly surprising, as it partially contradicts the established consensus that visual stimuli, i.e. virtual height, is the dominant factor in dictating stress levels. At the same time, the physical environment complements and supports the virtual height [14], [15], [54], [57], [60]. The expected effect would be very similar to VR distraction studies [61], [62] in which the VE could induce a sense of safety to detract the user from the stressful exposure of the physical environment. However, the opposite effect was observed with the VE failing to distract the participant from the physical perception of danger. Instead, it seems that the sense of physical elevation persists over the otherwise less stressful virtual environment.

Based on the comparison of *GG* and *PG* conditions, one could reject *H3* and argue that the physical environment is dominant over the virtual environment when incongruence occurs. However, the comparison of *GG*, *PP*, and *PH* condition aligns with previous literature in that visual stimuli influence and induce stress. This comparison partially aligns with *H3*, which asserted that visual stimuli could dictate the increase in stress level but would be unable to distract the participant and decrease stress.

The rationale conclusion is that there is no particular (physical or virtual) persistent bias for threat perception. Instead, the participants tended to focus on the most dangerous or higher source of perceived threat, which dictated their stress levels. In the *PG* condition, the most significant threat was physical height; on the other hand, virtual height was the most significant threat in the *PH* condition.

6.4 Limitations

6.4.1 Condition Selection

The time length of the experiment was a critical limiting factor for this study. Ideally, a complete 2 by 3 experimental design that includes 2 levels of physical heights (ground and plank) and 3 levels of virtual heights (ground, plank, and extreme height) would explore more research questions. However, from our pilot experiment, the four conditions required at least 2 hours and 15 minutes to complete. This duration varied between participants (some requiring further rest breaks or equipment adjustments), with some experiment runs reaching 3 hours. Overall, an experiment lasting more than 3 hours of continuously wearing an HMD would be pushing the limits of a participant's physical stamina and mental capacity. Six conditions would probably have introduced severe cognitive fatigue resulting in either skewed results or additional early terminations of the experiment. Thus, the two interesting conditions, i.e. the ground platform with a virtual plank and extreme heights, were excluded. We chose to remove these two conditions because there were already multiple previous works examining the effect of virtual heights [14], [15], [16], [17]. The primary objective was to investigate the effects of using the elevated platform, and the conditions of *GG*, *PP*, and *PH* provided three levels of comparison between virtual and physical heights.

6.4.2 Habituation and Condition Sequence Effect

Habituation and sequence effects are major confounding factors when performing a long experiment using a within-subject design. There is an expected decrease in the stress level over time, which affects the participant's behavioural and physiological measures in various possible condition orders. A between-subjects experimental design could have resolved this issue. However, it would require a much larger sample size, which was challenging to obtain due to the presence of the global pandemic when we conducted the experiment. Instead, the order of the conditions was randomised to mitigate the issue. Note that the *GG* condition was randomised to either be first or last (see Figure 3). It was impractical to switch between the elevated and ground platform (which took a significant amount of time) more than once per participant. The SAM results in Table 2 provides insight into the effect of the sequence condition. From the results, it is apparent that there is a decreasing trend for the conditions *GG*, *PG*, and *PP* based on the sequence of conditions. Interestingly, two participants who experienced the *PH* first rated their SAM response lower than the other participants. However, the imbalance of condition distribution could be a possible reason for the lower rating. Overall, it is clear that the *PH* is least affected by the sequence effect which is a likely reason why the stress effect is more visible in the *PH* condition. A better distribution of conditions and participants will likely yield more accurate findings to this sequence effect.

7 FUTURE APPLICATIONS

The findings of this experiment could allow for future research opportunities to investigate different behaviours and other possible applications further.

7.1 Physical and Virtual Height Threshold

The results showed that the physical platform had a more dominant impact on the perception of height when the virtual height was below a certain threshold. Based on the findings of Wuehr et al. [57], this experiment still has quite a few unknowns on the virtual height bounds of saturation for fear of heights. One unknown is determining if a reliable set of boundaries could be determined using this experimental setup. Another unknown is the influence of the physical environment on the virtual height boundaries. An expanded experimental design with a broader range of virtual and physical heights ($>$0.65 m) would provide a greater understanding of the relationship between height perception and acrophobia. It would be worthwhile to investigate whether different levels of physical elevation modify the relationship between virtual height and stress.

Another factor is the presupposed knowledge of physical height. As discussed previously, the participants were aware of the physical height of the platform before putting on the VR HMD. This knowledge is a contributing factor to the participant's stress level as they knew the height of the physical elevation. It would be interesting to investigate further the effects of unknown physical elevation (participant do not see the platform beforehand) or deception-based paradigm (participant see a certain platform but then walks on a differently elevated one). These potential paradigms may yield interesting results as they will inherently alter the participant's perception of the physical and virtual heights.

7.2 Larger Sample and Wider Demographics

It would be worthwhile to explore modifications to the experimental design. The inclusion of the previously eliminated conditions in a condensed format (direct comparison of two conditions) may provide more insight into the difference between the ground and the elevated platform when subjected to extreme heights. Another possibility is to recruit a larger sample of participants and subdivide the sample into groups based on the level of acrophobia. This addition would reduce the interparticipant variance and provide a better understanding of height exposure on a demographic scale.

7.3 Stress Measurement and Classification

The development of a reliable metric for measuring and classifying stress has always been a prevalent challenge [1]. Stress is a complex physiological response that involves emotional, cognitive, and physiological activation. The measures outlined in this experiment focus on quantifying individual symptoms or signs of stress. For example, the use of HR, gait and EDA measure sympathetic and parasympathetic activities, which can provide some indication of activation [43], [46]. Other metrics, such as questionnaires and scoring scales, provide a participant's self-reflection and perception of stress [48], [50]. While questionnaires are generally reliable, they do not provide a real-time measure of stress. This experimental paradigm can produce significant changes in stress levels and can produce varying degrees of stress. Therefore, further investigation into possible other measurements or mixed modality analysis could provide substantial contributions towards improving real-time detection and measuring of stress.

7.4 Evaluating Behaviour and Cognitive Performance

A benefit of this experimental paradigm is that added physical elevation can provide a higher level of realism, which amplifies the response in a stressful environment. This paradigm can be applied to other studies as a tool to reliably induce stress. Areas such as spatial awareness, target recognition, and cognitive loading can all be considered when investigating the influences of stress. Another benefit of the platform is the enabling of locomotion which provides opportunities to investigate balance, unique gait, and muscle activation behaviour when walking at elevation.

8 CONCLUSION

This paper proposed a novel experimental setup that investigated the efficacy of physical and virtual elevation on a person's stress levels. The results showed that a physical change in elevation regardless of the virtual height resulted in smaller stepping distances, higher HRs, and higher EDAs among participants. These responses and the higher SAM rating indicated that the elevation of one's physical environment indeed induced stress. In contrast, the condition that combined both physical elevation and extreme virtual height induced a significantly higher stress level that was sustained beyond the completion of all the trials in the condition. Further investigation into the effects of stress across a more diverse range of physical and virtual heights will improve our ability to differentiate different levels of stress.

APPENDIX A
MODIFIED DASS QUESTIONNAIRE

The following Questionnaire was used between conditions during the rest period.
Rating Scale:

- 0- Did not apply to me at all
- 1- Applied to me to some degree, or some of the time
- 2- Applied to me to a considerable degree, or a good part of time
- 3- Applied to me very much, or most of the time

DASS Question

- **A** - I was aware of dryness of my mouth
- **A** - I experienced breathing difficulty (eg, excessively rapid breathing, breathlessness in the absence of physical exertion)
- **A** - I had a feeling of shakiness or trembling
- **S** - I found it difficult to relax
- **S** - I was most relieved when the walks ended
- **S** - I felt that I was using a lot of nervous energy
- **A** - I found myself getting impatient when I was doing the tasks
- **S** - I had a feeling of faintness

APPENDIX B
SAM

Figure B.1 shows the SAM figure used in the experiment.

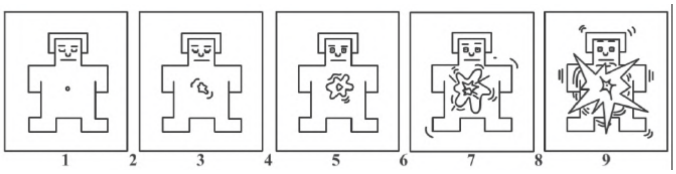

Fig. B.1. The SAM figures used for the SAM Arousal Question

APPENDIX C
CONDITION ORDER PER PARTICIPANT

Table 4 shows the order of conditions for each participant.

TABLE 4
The sequence of conditions per participant.

Participant	1st	2nd	3rd	4th
S1	*GG*	*PP*	*PH*	*PG*
S2	*PP*	*PH*	*PG*	*GG*
S3	*GG*	*PG*	*PH*	*PP*
S4	*PH*	*PG*	*PP*	*GG*
S5	*GG*	*PP*	*PH*	*PG*
S6	*PP*	*PG*	*PH*	*GG*
S7	*GG*	*PG*	*PP*	*PH*
S8	*PH*	*PG*	*PP*	*GG*
S9	*GG*	*PH*	*PP*	*PG*
S10	*PG*	*PP*	*PH*	*GG*
S11	*PG*	*PH*	*PP*	*PG*
S12	*PP*	*PH*	*PG*	*GG*
S13	*GG*	*PP*	*PH*	*PG*
S14	*GG*	*PG*	*PP*	*PH*
S15	*PG*	*PH*	*PP*	*GG*
S16	*GG*	*PP*	*PH*	*PG*
S17	*PG*	*PH*	*PP*	*GG*
S18	*GG*	*PG*	*PP*	*PH*
Conditions	1st	2nd	3rd	4th
GG	9	0	0	9
PG	4	7	2	5
PP	3	5	9	1
PH	2	6	7	3

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