The Effects of Virtual Reality-Induced Postural Threat on Performance of a Walking Balance Task

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science in Rehabilitation Science

Rehabilitation Sciences Institute
University of Toronto

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Abstract

Rapid motor learning may occur in situations where individuals perceive a threat of injury if they do not perform a task well. This may be facilitated by improved motor performance and consequently, more errorless practice. The purpose of this study is to determine if performance of a motor task improves in situations where perceived threat of injury is high. I hypothesized that perceived threat of injury in a virtual environment will result in improved performance of a walking balance task. The addition of perceived threat of injury yielded slightly greater, but not statistically significant, balance performance in virtual environments. These results may be partially attributed to habituation to threat over time and practice. A more robust threat manipulation may reveal greater differences in motor performance between high- and low-threat conditions. If implemented carefully, virtual reality technology can be an effective tool for investigating walking balance in environments perceived as threatening.
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1 Introduction

There is evidence that rapid motor learning occurs in situations where errors threaten an injury. For example, one may learn to swim quickly as drowning is a possible consequence of not learning the skill. Rapid motor learning in these situations may be facilitated by high motor performance and consequently, errorless practice. In such situations, perceived threat triggers fear, which provokes behavioural responses and defensive reactions that are necessary for survival; these defensive responses are initiated and regulated by the amygdala and hypothalamus. These responses mobilize energy to the heart, muscles, and brain to carry out the necessary actions for surviving the present situation, which may involve dedicating resources for optimizing motor performance. High arousal from a threat may also shift attention to only the most vital environmental information. Humans must use limited resources efficiently to actively search for and scrutinize sources of threat. Eliminating task-irrelevant cues and narrowing attention can enhance performance when highly focused attention is beneficial to performing the task.

Conversely, the Yerkes-Dodson law predicts that performance will begin to decline after reaching a certain level of arousal. However, the Yerkes-Dodson law may overgeneralize the relationship between arousal and performance, as it is unlikely that different stressors and magnitudes of arousal have identical effects on cognitive function. Psychological perception of the stressor and situation are also integral factors in modulating physical reactions, as arousal may be felt even in the absence of perceived threat. For example, thrill seekers could be aroused, but not threatened, by dangerous situations. Physiological measures of stress should be evaluated with behavior and motivational state kept in consideration.

It is challenging to research the effects of threat on motor performance while ensuring participant safety and eliciting an appropriate fear response. Fear experiments often present threatening stimuli through two-dimensional computer screens that do not reproduce the complexity of real world experiences. Virtual reality (VR) technology is used to simulate a realistic environment by providing the user with sensory information that resembles physical stimuli in the real world. The sense of presence (the sense of “being there”) is further enhanced by a user’s ability to control the virtual environment (VE) with his/her body.
VR-induced threat influences characteristics of normal over-ground walking, evident by slower walking and wider and shorter steps.\textsuperscript{16,17} Although gait characteristics are modified by VR-induced threat, it is not clear if such modifications are beneficial or maladaptive. Therefore, further investigation is needed to determine if motor performance is affected as a result of higher threat levels. In addition, much of the relevant research has not represented situations in which high arousal has been designed to be adaptive and functional, as would be the case for the protective effects of arousal to improve balance control in conditions that threaten balance. The link between arousal state and outcomes measures is often unrepresentative of situations where high arousal could be purposeful. A balance beam-walking task was chosen for this study because poor walking performance is directly connected to the negative consequence of stepping off the beam. A previous study did not find any significant differences in balance performance when comparing beam walking in VEs with and without threatening heights.\textsuperscript{18} However, including a secondary cognitive task in that study may have diverted attentional resources away from the balance task, potentially interfering with the dedication of resources to optimize motor functioning in the high-threat condition.

As a first step towards understanding the role of perceived threat on rapid motor learning, the purpose of this study is to determine if performance of a motor task improves in situations where perceived threat of injury is high. I was specifically interested in the influence of context-specific threat of injury; that is, the introduction of a scenario for which participants will perceive that an injury may occur if they do not perform the task well. Redistributed attention and optimized motor performance in the presence of threat likely leads to fewer motor errors, and therefore more errorless practice. VR technology provides us with the ability to test balance in environments perceived to be threatening. It has been reported that participants perform cognitive tasks better when they are threatened by unpleasant stimuli than when they are free of any harm.\textsuperscript{19-21} However, few studies have examined the effects of threat on walking balance using virtual environments. I hypothesize that perceived threat of injury in a VE will result in improved motor performance in a balance beam task. Threat learning in VEs could serve as a safe and affordable application to improve motor learning in rehabilitation, exposure therapy, athletics, and more. This work is also intended to inform future research by providing insight on the effectiveness of VR technology as a research tool.
2 Literature Review

2.1 Perceived threat

2.1.1 Responding to high emotional arousal

Emotion is a critical factor in determining human behavior. Emotions trigger physiological responses that ultimately motivate the execution of goal-directed behaviours that are most relevant to specific situations.\textsuperscript{22-24} Arousal describes an increase in alertness or activity from resting baseline.\textsuperscript{25} Certain states of high emotional arousal may motivate an individual to respond to situations more urgently. Fear is one such state of high emotional arousal that motivates defensive behaviours to counteract threatening stimuli in dangerous situations.\textsuperscript{2,3} As threatening stimuli present potential harm to an individual’s wellbeing, feeling threatened can motivate behaviours that are intended to increase the likelihood of survival.

The Yerkes-Dodson Law is an empirical relationship linking emotional arousal and performance behaviours.\textsuperscript{9} According to this law, performance increases with emotional arousal, but decreases when arousal is raised beyond a certain threshold (Figure 2.1).\textsuperscript{26} This perspective of performance assumes that at medium levels of emotional arousal individuals can attend to a greater amount of cues more effectively to perform better, whereas higher levels of emotional arousal hinder the ability to process multiple cues effectively.\textsuperscript{7} However, the Yerkes-Dodson Law may oversimplify the relationship between emotional arousal and performance. Emotional arousal is necessary, but not sufficient, for evoking adaptive survival responses. There are various associations between cognitive functions and emotional arousal, and many of the cases supporting the Yerkes-Dodson Law do not represent situations where high emotional arousal could be adaptive and functional,\textsuperscript{7} such as activities that can avoid harm and promote survival. States of emotional arousal and outcome measures of performance are often poorly connected,\textsuperscript{27} highlighting the lack of ecological validity in threat studies. For example, many studies investigating threat only examine the intensity of the perceived threat, but the extent to which an individual perceives their fear as facilitative or debilitating is also an important predictor of performance.\textsuperscript{24,28,29}
2.1.2 Measuring high emotional arousal and perceived threat

Stress is a state of high arousal in response to feeling fearful in situations that are perceived as threatening or dangerous.\textsuperscript{30} Stress activates the hypothalamic–pituitary–adrenal axis to ultimately restore homeostasis.\textsuperscript{4,31} Although physiological changes related to the stress response can be monitored to evaluate levels of perceived threat, there is no single unambiguous physiological indicator of perceived threat. Physiological responses are often complex and inconsistent, and must be considered with the behaviour and psychological context of the individual as well.\textsuperscript{11,32} Arousal is unlikely to facilitate adaptive responses without the potential for negative consequences.\textsuperscript{12} Cognitive appraisal processes are also important for determining if an arousing event is significant to one’s wellbeing, and ultimately affects emotional, physiological, and behavioural responses to potentially stressful situations.\textsuperscript{33,34} These processes include the perception of the degree of potential threat of a stimulus, and the perception of resources to cope with it.\textsuperscript{33}

Physiological indicators of stress are associated with activation of the sympathetic nervous system, which is closely linked with emotion.\textsuperscript{32} Cortisol is generated by the hypothalamic–pituitary–adrenal axis in direct response to stress, and although cortisol level is considered one of the best physiological indicators of stress, its measurement is invasive.\textsuperscript{18} Electrodermal activity (EDA), often referred to as skin conductance or galvanic skin response, measures changes in electrical conductance of the skin and is also a physiological indicator of arousal.\textsuperscript{32,33} Measuring
EDA is much less invasive than measuring cortisol. However, skin resistance varies with the changing state of sweat glands in the skin. Therefore, skeletomotor preparation and effort are also accompanied by increases in EDA. Separating the confounding effects of physical activity may complicate the use of EDA to measure feelings of perceived threat.

To assess the extent that threat is perceived, both physiological and psychological changes should be measured. Self-report measures, such as questionnaires, can be used to gauge individual attitudes towards certain situations and provide more insight into the cognitive appraisal of potentially stressful situations. Anxiety, the sustained experience of fear that involves an individual appraising their situation as threatening, is subjective. Situations that induce anxiety for some do not necessarily have the same effect on others. Trait anxiety refers to one’s general predisposition to feel anxious, while state anxiety refers to fleeting experiences of anxiety in specific situations. The Endler Multidimensional Anxiety Scales measure an individual’s intrinsic level of trait anxiety, as well as their perception of specific situations to determine their state anxiety. This measure allows researchers to compare situation-induced anxiety to baseline levels of anxiety. Although questionnaires that scrutinize perceived threat can be used to assess stress in specific situations, these self-report measures are often susceptible to intentional and unintentional biases. Using physiological and psychological indicators of stress concurrently provides a more comprehensive understanding of stress in any given situation.

2.1.3 Effects of perceived threat on task performance

While the experience of anxiety is often perceived as negative, it may actually facilitate performing in threatening situations. Activation of the hypothalamic–pituitary–adrenal axis provokes the rapid mobilization of energy from carbohydrate, fat, and protein stores to the heart, muscles, and brain. These physiological changes can enhance physical activity and improve the chances of surviving a threatening event.

One of the most common methods for studying the effects of perceived threat on task performance is the threat of shock paradigm, where participants perform a task in a condition where they are either: 1) safe from any aversive stimuli or 2) at risk of receiving an electrical shock if they do not perform the task well. These studies often evaluate the performance of
novel tasks, such as memory tests and simple computer games, that the participant has no previous knowledge of. It is well documented that participants perform these tasks better when they are at risk of a shock than when they are free of any harm. Accelerated skill acquisition and improved performance in these tasks are facilitated by enhanced attentional processing and memory consolidation. These improvements are often retained across multiple sessions. The effect of perceived threat on the performance of more complex motor tasks, such as walking balance control, is less established.

Increased arousal from negative stimuli narrows attention, and while this reduction in behavioural flexibility may seem unfavourable, the inability to process larger amounts of information is not necessarily disadvantageous. Individuals can respond to situations quickly or slowly by using less or more environmental information, respectively. By executing cognitive control to inhibit the processing of unwanted information, finite resources of conscious awareness can be allocated towards more important tasks. Prioritizing attention on only the most vital information can ultimately facilitate withdrawal from a harmful situation. These attentional processes occur at the cost of processing less important stimuli that could be distracting. Fear-relevant stimuli are often processed more efficiently than fear-irrelevant stimuli, and focusing attention mobilizes the body to deal with the most urgent problems. Thus, these states of high emotional arousal can be considered adaptive since they facilitate optimal results when experiencing adversity with restricted resources.

2.2 Walking balance

2.2.1 Testing and measuring walking balance performance

Posture describes the orientation of a body segment relative to the gravitational vector, while balance describes the dynamics of body posture to prevent falling. The control mechanisms to maintain posture (i.e., ‘static’ balance) during quiet sitting and standing are different from those used to maintain dynamic balance during walking. When sitting or standing still, the main objective is to keep the fluctuating centre of mass (COM) within the stationary base of support (BOS) by limiting COM sway. During walking, the COM and BOS both move, therefore the COM momentarily moves outside of the BOS during the single-limb support periods.
COM is continually restored within the BOS by safe placement of the swing foot during double-limb support.\textsuperscript{46} Falls occur when an individual experiences a loss of balance, such as a slip or trip while walking, and fails to react with a successful corrective action.\textsuperscript{51-53} As such, deteriorations in balance control can lead to falls, an ensuing fear of falling, and potentially a loss of independence.\textsuperscript{18}

Three-dimensional motion capture can be used to track the motion of multiple parts of the body in space over time. These data can be used to assess COM motion, and to make inferences about balance control. Traditional assessments of dynamic balance control during walking focus on measures of the lower extremities, such as stride length and width, to assess dynamic balance control.\textsuperscript{54} However, examining trunk motion also provides valuable insights for understanding dynamic balance control, as the ability to control the trunk over the moving lower extremities is critical to maintaining stability.\textsuperscript{54} Trunk accelerations can be used to assess multiple spatial-temporal gait parameters, such as stride cycles, step length, and walking speed.\textsuperscript{55} The variability of medial-lateral trunk movement can also be used to assess dynamic balance control during walking.\textsuperscript{56,57} High movement variability is considered an indicator of poor balance control and is associated with an increased risk of falls.\textsuperscript{58-60} However, another perspective suggests that movement variability may be functional, as it may promote exploratory behaviours to find an efficient pattern for completing a task in a changing environment.\textsuperscript{61,62} Therefore when interpreting movement variability to investigate walking balance, it is also important to consider the influence of contextual factors, such as environment and emotional state.

Motor performance can also be quantified with behavioural outcomes, such as performance measures, that are externally observable.\textsuperscript{63} However, balance assessments of over-ground or treadmill walking pose few challenges for non-impaired individuals. Normal walking tasks that do not reduce the medial–lateral BOS beneath the feet are unlikely to induce balance control failures in non-impaired individuals, limiting their ability to accurately assess balance.\textsuperscript{64,65} There are fewer tests that probe for failures in walking balance to quantify balance control.\textsuperscript{66,67} Walking on a narrow surface introduces a greater challenge to balance control, and simple balance beam-walking tasks provide a safe means of detecting differences in walking balance control by observing the proportion of failed steps.\textsuperscript{64,65,68}
2.2.2 Effects of perceived threat on balance performance

The autonomic nervous system (ANS) is critical for maintaining bodily homeostasis and modulating physiological responses during specific emotional states.\(^{69}\) Maintaining this homeostasis involves preserving balance control during threats to posture that may lead to physical harm, such as falls.\(^{70}\) Perceived threat of injury activates the sympathetic branch of the ANS, which can stimulate physiological processes to facilitate motor activity.\(^{32}\) The central nervous system (CNS) adapts control strategies to deal with environmental changes in order to prevent falls and maintain motor function.\(^{71}\) This can lead to increases in muscle activity and motor-related autonomic responses to support motor behaviour.\(^{32,48,72,73}\) There is evidence that individuals engage in tighter control of posture, with limited displacement and velocity of their centre of mass, under conditions of increased postural threat.\(^{48,74,75}\)

The potential for adverse consequences, such as the threat of injury, can promote rapid motor learning of balance tasks. For example, there is evidence that fall-resisting skills can be rapidly acquired through repeated exposure to slips during a sit-to-stand task.\(^{76,77}\) This ability to rapidly acquire fall-resisting skills across different functional tasks remains intact into older age, and is paralleled by adaptive improvements in stability control and limb support.\(^{78}\) There is also evidence that fall-resisting skills can be rapidly acquired during dynamic balance tasks, such as preventing a backwards loss of balance during perturbed walks.\(^{1,71,79}\) Individuals can adapt to perturbations within just a single session by rapidly improving both proactive and reactive balance control strategies, such as improved COM stability and reactive stepping.\(^{71,79,80}\) These fall-resisting skills are often retained beyond the single session in which they were acquired (e.g., up to six months later).\(^{79,80}\) Losses of balance often lead to falls which can cause injuries. These perceived penalties may motivate the CNS to quickly learn fall-resisting skills that will be retained for an extended period.\(^{48,80}\) Rapid balance skill acquisition is particularly evident among individuals who are more at-risk of falls, as the fear developed from previous falls might have further motivated the rapid adaptation.\(^{80}\)

Errorless motor learning is a form of implicit learning which involves strategies that reduce the number of outcome errors during practice.\(^{81}\) The learner inhibits the acquisition of explicit knowledge by reducing the number of error-correcting hypotheses to consciously meet task demands.\(^{81-85}\) The skills acquired during errorless practice reduce the demand for explicit
attentional resources to control movement and represent an implicit and robust mode of learning that is better protected against breakdown from distractions. The rapid motor learning of balance skills in situations of high perceived threat may be facilitated by errorless practice, as individuals resist errors to avoid injury. However, the role of perceived threat of injury on rapid motor learning is still unclear and requires further investigation.

2.3 Virtual reality

2.3.1 Benefits and limitations of using virtual reality as a research tool

Virtual reality (VR) technology is used to simulate realistic environments by providing the user with sensory information that resembles physical stimuli in the real world. When successfully experiencing virtual reality, individuals treat their perceptions as real events. The sense of presence, or the sensation of being in a real place while in a simulated environment, is further enhanced by a user’s ability to interact with the virtual environment (VE) with their body. VR systems can support certain sensorimotor contingencies, which are the natural actions that individuals perform in order to perceive their environment. For example, being able to move your head and eyes to change your direction of gaze is a sensorimotor contingency. The sensorimotor contingencies supported by a system contribute to sustaining a sense of presence within a VE.

When studying the relationship between threat and motor performance in humans, it is challenging to accurately simulate environmental contexts that are linked to conditioned emotional behaviors. VEs can address this challenge by incorporating features that reflect the complexity of the real world. By using VR, experimenters are better equipped to tailor fear paradigms to test specific hypotheses. It is possible to create virtual experiences that are not feasible to recreate in the physical world due to safety concerns. However, threatening events often occur in complex environments that engage not only vision, but all sensory modalities. Much of the quality of a virtual experience depends on the technical limitations of the equipment used, such as the graphics frame rate, tracking latency, image quality, field of view, and range of sensory modalities accommodated. The sense of presence is restricted by sensorimotor contingencies that could be limited by the technical specifications of a VR system; for example,
if a user reaches out to grasp a virtual objects but feels nothing due to a lack of haptic feedback in the VR system.\textsuperscript{14} VR systems with lesser technical specifications may not only be insufficient to elicit a real sense of presence, but may also provoke simulator sickness (a type of motion sickness). For example, tracking latencies that exacerbate discrepancies between head movement and the visual display can increase the risk of motion sickness.\textsuperscript{88}

There are multiple types of VR systems capable of producing different levels of immersion, the perception of being absorbed in a non-physical environment through simulated content that stimulates the senses.\textsuperscript{89} Non-immersive VR systems often include two-dimensional screens, such as desktop computers.\textsuperscript{90} Immersive VR systems restrict outside sensory information and update the visual scene with physical movements from the user. Cave automatic virtual environments (CAVEs), rooms with graphics projected onto the walls,\textsuperscript{91} and head-mounted displays (HMDs), wearable displays covering the eyes,\textsuperscript{92} are the most common types of immersive VR systems.

2.3.2 Virtual reality in balance and perceived threat research

Balance assessments are usually performed in controlled testing environments that are unalike regularly experienced situations.\textsuperscript{93} VR provides a unique opportunity to research balance through personalized sensory experiences in similarly controlled testing environments.\textsuperscript{18,94} VR offers useful features for clinical settings, such as real-time multisensory feedback, that is not as conveniently implementable in more traditional rehabilitation practices.\textsuperscript{95,96} Using VR to simulate real-world tasks is especially beneficial because integrating balance training into everyday activities can help reduce falls.\textsuperscript{97} For example, researchers and therapists can use VR to remotely expose individuals to community scenarios to practice balance control in a low-risk, graded manner.\textsuperscript{98,99} Task-specificity and customization of virtual experiences allows for more ecological assessments of balance that simulate problematic situations that occur in daily activities.

Standard laboratory tests of fear in humans do not replicate the complexity of real world experiences as threatening stimuli are often presented through non-immersive media, such as computer screens.\textsuperscript{13} Immersive VR systems can be used to evaluate motor performance in environments that would otherwise be avoided due to feelings of fear and a lack of safety, such as standing at a high elevation or in a moving vehicle.\textsuperscript{16} VR has demonstrated to be a useful tool for studying the effects of perceived threat on balance. It is often used to produce real feelings of
perceived threat by asking individuals to stand or walk over a virtual surface that overlooks dangerous levels of elevation.\textsuperscript{17,18} Control of static and dynamic balance in VEs with simulated high heights have been shown increase physiological and psychological indicators of perceived threat similar to that of real-world experiences,\textsuperscript{16,18,100} and individuals walking in a more threatening VE demonstrate a more cautious gait pattern.\textsuperscript{17} Although VR is being increasingly used in balance and gait rehabilitation, there is still a lack of standardized guidelines for its use.\textsuperscript{94} Further experimentation with VR is required to inform future research, especially with respect to guiding its implementation in assessments of dynamic balance in threatening environments.

Although VR can be used to test balance control, there is evidence that balance performance is intrinsically worsened in virtual environments due to reduced dependency on visual perception to maintain posture.\textsuperscript{88} Visual, somatosensory, and vestibular information is processed concurrently to maintain balance.\textsuperscript{101} Sensory conflicts can occur when the perceived visual information does not match other sensory information.\textsuperscript{102} This may occur when the visual display shows movement when the individual is actually physically stationary. Low tracking latency, limited field of view, and equipment weight may negatively affect physical and cognitive performance during balance tasks.\textsuperscript{18,103} Technical limitations related to sense of presence and sensory conflicts are common contributors to negative experiences in VEs.\textsuperscript{16} However, periods of familiarization in VEs can be used to mitigate these negative experiences.\textsuperscript{104} Walking balance control necessitates the use of sensory feedback and planning to execute the correct motor responses. However, large head movements are often not well translated by HMDs.\textsuperscript{93} Increased latencies between head movements and visual feedback may introduce challenges for completing dynamic balance tasks in VEs. Smith (1972) demonstrated that although visual feedback delays as high as 80 milliseconds can go undetected, visual feedback delays as brief as 17 milliseconds can still affect motor performance.\textsuperscript{105} Delayed visual feedback may be even more damaging during longer movements where there is more opportunity to utilize online visual information.\textsuperscript{106}

\textbf{2.4 Summary}

Fear is a state of high emotional arousal that motivates adaptive responses to survive threatening events. However, there is often a lack of ecological validity in studies that connect states of perceived threat and outcome measures of performance. VR can recreate situations that would
otherwise not be safe to test in the real physical world. With VR, experimenters can customize fear paradigms to test individual responses to specific types of threat. There is evidence that perceived threat of injury can promote the rapid learning of balance skills. However, this relationship is still unclear and requires further investigation. VR can provide a safe method to successfully produce feelings of perceived threat during walking balance tasks without actually putting individuals in any real danger. The purpose of this study is to determine if performance of a motor task improves in VEs where individuals perceive a threat of injury. I hypothesize that perceived threat of injury due to falling will result in improved performance of a balance beam walking task.
3 Methods

3.1 Participants

Twenty-four participants completed the study. Written informed consent was obtained from all participants. The University Health Network Research Ethics Board approved the study protocol and all other study materials. Participants received a $30 gift card as compensation.

**Inclusion criteria:** Participants were adults between the ages of 20 and 35 years.

**Exclusion criteria:** Participants were excluded if they had: difficulty understanding verbal or written English; a history of epilepsy, or other neurological conditions that could affect balance or mobility or prevent use of virtual reality (VR) hardware; a history of motion sickness; a diagnosis of acrophobia; a recent injury to the eyes, face, or neck that would prevent comfortable use of VR hardware; surgery or recent injury to the lower extremity that could affect balance or mobility; difficulty in hearing that was not corrected with a hearing aid; difficulty in vision that was not corrected with contact lenses; sensitivity to flashing light or motion; and/or 6 months of formal dance or gymnastic training in the last 10 years. Due to hardware limitations, glasses were not permitted and contact lenses were required for those who usually require corrective lenses during daily activities. Participants were also excluded if they had participated in any previous studies that involved walking on a balance beam, as prior experience may affect the results.

**Participant randomization:** Participants completed the balance beam-walking task in 3 separate conditions. To address the possible confounding variable of increased practice influencing performance, the sequences of conditions were counterbalanced across participants. Since all participants would complete the task in each of the 3 conditions, there were 6 possible sequences in which the conditions could have been completed. With a total of 24 participants, 2 male and 2 female participants were randomly assigned to each of the 6 sequences.
3.2 Apparatus

The study was completed in FallsLab within Toronto Rehabilitation Institute. FallsLab is a 6x3 metre motion platform, that can be programmed to translate in any direction. For the purpose of this study, the motion platform remained static.

**Balance beam:** A balance beam (8.5 cm tall, 300 cm long, and 3.8 cm wide) was bolted onto the platform within FallsLab. **Figure 3.1A** shows the testing area where participants completed the balance task.

![Figure 3.1A: Apparatus](image)

**Figure 3.1: Apparatus.** Participants walked across the balance beam (A) equipped with a harness and with an experimenter walking along each side of them for safety precautions. There was sufficient space on each side of the beam for participants to safely return to the starting position for each walking trial. The cameras (B) were positioned behind the participant to record marker position and video footage during beam passes. Participants could not see the cameras when completing walking trials.

3.2.1 Data collection

**Motion capture:** Two Optotrak 3D Investigator (Northern Digital Inc., Waterloo, Canada) cameras were used with Northern Digital Inc. First Principles motion capture software to measure kinematic data, as well as update the visual scene in the virtual environment (VE) in real time (**Figure 3.1B**). The Optotrak cameras tracked the three-dimensional positions of single markers placed at the sacrum and neck as a measure of movement variability of the upper trunk.
and pelvis, as well as rigid body markers placed on the head to update the visual scene. Motion data were recorded at a 100 Hz.

**Video footage:** Data collection sessions were recorded using a digital video camera. All balance beam walks were video recorded.

**Physiological arousal:** Electrodermal activity (EDA) was recorded to measure sympathetic arousal. EDA was collected by placing electrodes on the palmar surfaces of the index and middle fingers of the non-dominant hand, which were first cleaned with alcohol wipes. Reusable silver/silver chloride finger electrodes filled with conductive paste were placed on the fingers. EDA was sampled at 100 Hz. This EDA setup is based on previous research.107

**Questionnaires:** The Endler Multidimensional Anxiety Scale - Trait38 and the International Physical Activity Questionnaire (IPAQ)108 were administered at the beginning of each data collection session to evaluate trait anxiety and physical activity over the previous week, respectively. The IPAQ calculates the metabolic equivalent of task minutes to measure physical activity. The Endler Multidimensional Anxiety Scale - State38 was administered after each block of trials to evaluate participants’ perceptions of the preceding task. The Presence Questionnaire109 was administered after each block of trials in a VE to evaluate the effectiveness of the virtual setup in producing the sense of presence in the VE.

### 3.2.2 Virtual reality

**Virtual reality:** An Oculus DK1 (Oculus VR, Menlo Park, California, USA) head mounted display (HMD) was used to immerse the participant in the VE. The HMD was 1280 pixels wide x 800 pixels high (640 x 800 per eye) with a 110º field of view and displayed stereoscopic graphics. The VE contained visual depth cues, resembling depth cues in the physical lab, that helped participants perceive the VE in 3 dimensions. The viewpoint in the VE was controlled by motion capture data from the Optotrak cameras, which synchronized the participants' position and movement using a rigid body with infrared light emitting diodes attached to the HMD. By determining head and body position, the Optotrak cameras updated the visual scene of the HMD accordingly; this allowed the viewpoint to update in real-time so that the visual motion was consistent with the physical motion during walking, ensuring a critical sensorimotor
contingency. Use of the HMD ensured that participants did not gain any visual inputs from the real world. The HMD was disinfected with alcohol wipes before and after every session.

### 3.3 Protocol

**Procedures:** Data collection occurred within a single session that lasted 2-3 hours. Rest breaks were scheduled between blocks of trials and participants were informed that they could request a break at any time. Participants were instructed to attempt to walk across the entire balance beam without stepping off, and if they stepped off the beam, to step back on at the point of descent. Participants were instructed to look forward when walking on the beam, as well as to walk at their normal walking speed to avoid any additional cognitive loading from trying to maintain a specific speed. Following completion of a beam pass, participants returned to the starting position for the subsequent trials. Participants were instructed to walk backwards when returning to the starting position in order to prevent tripping on the cables and to keep the motion capture markers within the field of view of the cameras. Participants completed the balance beam walking task in a block of 4 trials for familiarization, and blocks of 10 trials in each of the 3 testing conditions: 1) low-threat real environment; 2) low-threat VE; and 3) high-threat VE (Figure 3.2). These 3 testing conditions were included in order to test for differences in performance between the low-threat environments and virtual environments to assess the effects of using virtual reality technology and high threat, respectively.
**Figure 3.2: Procedure.**

**Familiarization trials:** Participants first performed 4 trials, 2 in a real environment and 2 in a VE, to familiarize themselves with the task. At the beginning of every trial in a VE, participants completed a series of object identification tasks as part of an immersion protocol (Figure 3.3A). They verbally identified the shape and colour of all objects and answered questions regarding their proximity. For example, they were asked to state the colour of the nearest cube or furthest sphere. Successful completion of the object identification tasks confirmed that participants were able to perceive relative depth within the VE. They were also instructed to contact the beam in
various ways, such as by tapping and stepping on it, to understand that the virtual beam was matched with the physical beam in space. This immersion period also allowed participants to acclimate to the VE and adapt to mechanical factors, such as the weight of the HMD, to ultimately enhance their sense of presence. This protocol was not intended to test participants’ ability to make relative depth judgments.

**Low threat, real environment (Figure 3.3B):** While walking in the real environment, participants wore the HMD over their foreheads (i.e., not obscuring their eyes) to adapt to mechanical factors, such as the added weight, which may affect postural control. Participants also wore basketball ‘dribble’ goggles that obscured the lower portion of their field of view, similar to the visual display of the HMD. These obscured fields of view were closely matched through visual inspection. This hardware was worn to resemble the experience of walking in a VE, as gait parameters can differ due to the weight of the HMD and smaller field of view.

**Low threat, VE (Figure 3.3C):** The VE in the low-threat condition simulated the real environment. A virtual rendering of the beam was visible in the VE in the ‘real world’ location of the beam. As the virtual beam and real beam were matched in space, a step off the real beam resulted in a step off the virtual beam.

**High threat, VE (Figure 3.3D):** In the high-threat VE condition I virtually simulated the balance beam elevated over heights that appeared to be dangerous; there is evidence that a height of 3.2 m is sufficient to produce feelings of threat. At the beginning of each trial, participants viewed the platform in the VE descend until it was 10 m below the beam. A step off the beam resulted in bright red flashes representing a negative consequence.
3.4 Data processing

The primary outcome was performance of the balance beam-walking task, quantified by step success. A step was recorded as a success when the swing foot landed and stabilized on the beam. A step was recorded as a fail when the swing foot contacted the floor, or contacted the beam but then immediately contacted to the floor. A step was also considered a fail if the stance foot contacted the floor as the swing foot approached the beam. The number of successful and failed step attempts for each trial were coded from video footage. Performance was measured by counting steps on the beam, as a proportion of total steps taken (i.e., percentage of ‘successful steps’) and the numbers of steps taken before the first failed step. The time to initiate walk was
calculated as the time elapsed between the beginning of the trial and the first attempted step, which may reflect reluctance to walk in certain conditions. The time to first fail was calculated as the time elapsed between the onset of the first attempted step and first failed step, which may reflect the exerted effort to not step off of beam.

\[
\text{Step Success \%} = \frac{\text{successful steps}}{\text{failed steps} + \text{successful steps}} \times 100
\]

Secondary outcomes were EDA, movement variability, and state anxiety (described further below).

EDA was measured throughout the beam walk to measure sympathetic arousal. It is possible that feelings of perceived threat of injury may wear off with repeated exposure to the virtual threat, particularly if participants commit errors without the expected consequences in VEs. Habituation to the threat, measured by EDA, was investigated to reveal any changes in perceived threat and to inform future studies using perceived threat of injury in a virtual environment. EDA data were low-pass filtered at 5 Hz using a 2nd order Butterworth filter. To separate the influence of physical activity on physiological arousal and measure physiological stress as a function of walking condition, I recorded EDA during each walk and subtracted EDA values from a one-second standing baseline immediately before the walk (Figure 3.4).

\[
\text{Physiological Stress} = EDA_{\text{Walk}} - EDA_{\text{Baseline}}
\]
Figure 3.4: Example of time series of EDA changes within a single trial. The different segments of EDA data collection over the course of a single trial are shown.

Peak EDA values were also calculated for all beam passes. Electrodermal responses can occur up to 5 seconds following a stimulus. Therefore, EDA values that were recorded up to 5 seconds after completion of a walking trial were included as part of the beam pass.

State anxiety was measured using the Endler Multi-Dimensional Anxiety State questionnaire. This self-reported measure of anxiety supplemented EDA recordings to assess perceived anxiety during walking trials.

High movement variability is an indicator of poor balance control. Two separate values of movement variability were calculated from the standard deviation of the medial-lateral positions of the markers on the sacrum and neck, only during instances when the participant was walking on the beam. I used a low pass Butterworth filter with a cutoff frequency of 6 Hz to smooth the marker position data. This procedure for calculating movement variability is based on research by Domingo and Ferris. Movement variability was calculated using Visual3D (C-Motion, Germantown, Maryland, USA).
3.5 Data analysis

I calculated the mean percentage of successful steps across all participants for each condition. I also evaluated how step success was affected by the order in which conditions were presented. Stress was assessed by analyzing EDA and scores from the Endler Multidimensional Anxiety Scale - State. Changes in EDA over the course of a walking condition were also measured to detect any habituation to threat. I calculated the mean of movement variability for all instances where the participant was walking on the beam for each walking trial. I then calculated the mean of these values for each walking condition.

Non-parametric tests were used to assess balance beam walking performance, self-reported state anxiety, and movement variability because these are scalar quantities. A Friedman test was completed to test for differences in these measures between the three conditions. When a difference was observed between the three conditions, a Wilcoxon signed-rank test was used for further pairwise comparisons between the: 1) low-threat real environment and low-threat VE; and 2) low-threat VE and high-threat VE. A Bonferroni-adjusted significance level was calculated for post-hoc testing to account for the increased likelihood of a Type I error when making multiple comparisons (adjusted alpha=0.025). Friedman and Wilcoxon signed-rank tests were performed in SAS (Version 9.4, Cary, North Carolina, USA).

A one-way repeated measures analysis of variance (ANOVA) was used to test for differences in EDA between the three conditions. When a difference was observed between the three conditions, a Tukey's honestly significant difference (HSD) post hoc test was used for further pairwise comparisons between the: 1) low-threat real environment and low-threat VE; and 2) low-threat VE and high-threat VE.

As an additional exploratory analysis, linear regressions were performed to predict how EMAS-T (physical danger subscale) scores predict EMAS-S scores, and how EMAS-T and EMAS-S scores predict percentage of successful steps and movement variability in VEs (Appendix 1).
3.6 Sample size

The sample size was determined from previous studies where 18 and 24 healthy young adults performed balance tasks in high-threat VEs.\textsuperscript{16,17} I finalized a sample size of 24 participants to allow for an equal number of male and female participants per condition and sequence. Using power = 0.8 and alpha = 0.05, I calculated that I would be able to detect an effect size (Cohen’s $d$) of 0.57 for a sample size of 24.
4 Results

4.1 Participants and missing data

Twenty-seven participants were recruited; however, 3 did not complete the full protocol due to feeling motion sick. Therefore, 24 completed the full protocol and are included in the analysis (Table 4.1).

Table 4.1: Participant characteristics. Values shown are mean ± standard deviation.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22.8 ± 1.8</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.7 ± 15.5</td>
</tr>
<tr>
<td>Sex (number)</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>12</td>
</tr>
<tr>
<td>Female</td>
<td>12</td>
</tr>
<tr>
<td>EMAS-T subscales (score)</td>
<td></td>
</tr>
<tr>
<td>Social Evaluation</td>
<td>40 ± 8.0</td>
</tr>
<tr>
<td>Physical Danger</td>
<td>57 ± 8.4</td>
</tr>
<tr>
<td>Ambiguous Situations</td>
<td>42 ± 11.6</td>
</tr>
<tr>
<td>Daily Routines</td>
<td>23 ± 5.3</td>
</tr>
<tr>
<td>IPAQ (metabolic equivalent of task minutes)</td>
<td>4632 ± 4265.9</td>
</tr>
</tbody>
</table>

EMAS-T=Endler Multi-dimensional Anxiety Scale - Trait
IPAQ=International Physical Activity Questionnaire

4.2 Step success

Balance beam-walking performance was significantly different between the 3 conditions ($\chi^2(2) = 43.80$, $p < 0.0001$; Table 4.2). Although step success appeared to be higher in the high-threat virtual environment (VE) compared to the low-threat VE, this difference was not statistically significant ($S = 57.5$, $p = 0.10$; Table 4.3). The effect size (Cohen’s d) for step success between the 2 VEs was 0.28. Figure 4.1 shows the distribution of step success across all conditions. The number of successful steps before first fail was significantly different between the 3 conditions ($\chi^2(2) = 36.77$, $p < 0.0001$; Table 4.2). The number of successful steps before the first fail was significantly greater in the low-threat real environment compared to the low-threat VE ($S = 150$, $p < 0.0001$; Table 4.3). Time to initiate walk was significantly different between the 3 conditions ($\chi^2(2) = 39.97$, $p < 0.0001$; Table 4.2). Time to initiate walk was significantly greater in the high-threat VE compared to the low-threat VE ($S = 150$, $p < 0.0001$; Table 4.3). Time to first
fail was significantly different between the 3 conditions ($\chi^2(2) = 27.41, p < 0.0001$; **Table 4.2**). Time to first fail was significantly greater in the low-threat real environment compared to the low-threat VE ($S = 127, p < 0.0001$; **Table 4.3**).

**Table 4.2: Outcome measures between conditions.** Values are presented as medians (interquartile ranges) for all balance and state anxiety outcomes, and their p-values are from the Friedman tests comparing outcome measures between conditions. Values are presented as means (standard deviation) for all EDA outcomes, and their p-values are from the repeated measures ANOVA comparing the transformed EDA values between conditions.

<table>
<thead>
<tr>
<th></th>
<th>Real + Low Threat (RL)</th>
<th>Virtual + Low Threat (VL)</th>
<th>Virtual + High Threat (VH)</th>
<th><strong>p-value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step success (%)</strong></td>
<td>78.8 (20.6)</td>
<td>48.3 (11.7)</td>
<td>55.2 (17.8)</td>
<td><strong>&lt;0.0001</strong></td>
</tr>
<tr>
<td><strong>SSBFF</strong></td>
<td>2.8 (3.6)</td>
<td>0.9 (0.4)</td>
<td>1.0 (0.6)</td>
<td><strong>&lt;0.0001</strong></td>
</tr>
<tr>
<td><strong>TTIW (s)</strong></td>
<td>3.2 (1.0)</td>
<td>4.5 (1.7)</td>
<td>6.4 (2.1)</td>
<td><strong>&lt;0.0001</strong></td>
</tr>
<tr>
<td><strong>TTFF-W (s)</strong></td>
<td>2.7 (1.9)</td>
<td>1.1 (0.7)</td>
<td>1.4 (0.9)</td>
<td><strong>&lt;0.0001</strong></td>
</tr>
<tr>
<td><strong>Movement variability (cm)</strong></td>
<td>4.62 (1.98)</td>
<td>2.89 (0.94)</td>
<td>4.04 (2.56)</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>EMAS-S score</strong></td>
<td>36 (19.5)</td>
<td>46 (20)</td>
<td>53 (20.5)</td>
<td>0.0042</td>
</tr>
<tr>
<td><strong>EDA (µS)</strong></td>
<td>0.23 (0.16)</td>
<td>0.23 (0.12)</td>
<td>0.24 (0.12)</td>
<td>-</td>
</tr>
<tr>
<td><strong>EDA transformed (µS)</strong></td>
<td>0.20 (0.12)</td>
<td>0.20 (0.09)</td>
<td>0.21 (0.10)</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>EDA peak (µS)</strong></td>
<td>2.06 (0.95)</td>
<td>2.05 (0.95)</td>
<td>2.13 (0.92)</td>
<td>-</td>
</tr>
<tr>
<td><strong>EDA peak Transformed (µS)</strong></td>
<td>1.07 (0.31)</td>
<td>1.06 (0.33)</td>
<td>1.10 (0.30)</td>
<td>0.92</td>
</tr>
</tbody>
</table>

SSBFF=successful steps before first fail  
TTIW=time to initiate walk  
TTFF=time to first fail  
EMAS-S=Endler Multidimensional Anxiety Scale – State
EDA=electrodermal activity
Figure 4.1: Step success. The percentage of successful steps is shown for each condition for all participants. The median for each condition is displayed as a horizontal red bar.

Table 4.3: Pairwise comparisons of outcome measures. Values are from the Wilcoxon signed-rank test for pairwise comparisons of balance and state anxiety outcomes. The Bonferroni-adjusted significance level is $\alpha=0.025$.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>S</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL vs. VL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step success</td>
<td>150</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>SSBFF</td>
<td>150</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TTIW</td>
<td>-139.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TTFF-W</td>
<td>127</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>EMAS-S score</td>
<td>-98.5</td>
<td>0.0026</td>
</tr>
<tr>
<td>VL vs. VH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step success</td>
<td>57.5</td>
<td>0.10</td>
</tr>
<tr>
<td>SSBFF</td>
<td>57.5</td>
<td>0.060</td>
</tr>
<tr>
<td>TTIW</td>
<td>150</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TTFF-W</td>
<td>55.5</td>
<td>0.037</td>
</tr>
<tr>
<td>EMAS-S score</td>
<td>99</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

SSBFF=successful steps before first fail
TTIW=time to initiate walk
Although the order in which testing conditions were completed were counterbalanced, we tested for any order effects that may have occurred as a result of practice and exposure. For example, we considered whether participants, on average, performed better in the third block of trials than in the first block of trials. There were no significant differences in step success between the order that a block of trials was completed ($\chi^2(2) = 0.30, p = 0.86$; Table 4.4). There were no significant differences in successful steps before the first fail between trial blocks ($\chi^2(2) = 0.21, p = 0.90$; Table 4.4). There were no significant differences in time to initiate walk between trial blocks ($\chi^2(2) = 0.60, p = 0.74$; Table 4.4) or time to first fail between trial blocks ($\chi^2(2) = 2.43, p = 0.30$; Table 4.4).

**Table 4.4: Outcome measures between trial blocks.** Values are presented as medians (interquartile ranges) for all balance and state anxiety outcomes, and their p-values are from the Friedman tests comparing outcome measures between trial blocks. Values are presented as means (standard deviation) for all EDA outcomes, and their p-values are from the repeated measures ANOVA comparing the transformed EDA values between trial blocks.

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step success (%)</td>
<td>60.5 (28.4)</td>
<td>60.0 (28.0)</td>
<td>53.1 (24.2)</td>
<td>0.86</td>
</tr>
<tr>
<td>SSBFF</td>
<td>1.2 (1.3)</td>
<td>1.2 (1.4)</td>
<td>1.0 (1.1)</td>
<td>0.90</td>
</tr>
<tr>
<td>TTIW (s)</td>
<td>4.1 (2.8)</td>
<td>4.9 (2.6)</td>
<td>4.8 (2.5)</td>
<td>0.74</td>
</tr>
<tr>
<td>TTFF-W (s)</td>
<td>1.5 (1.2)</td>
<td>1.2 (1.4)</td>
<td>1.6 (1.4)</td>
<td>0.30</td>
</tr>
<tr>
<td>Movement variability (cm)</td>
<td>3.11 (2.33)</td>
<td>3.41 (2.02)</td>
<td>4.63 (2.38)</td>
<td>0.60</td>
</tr>
<tr>
<td>EMAS-S score</td>
<td>52 (25)</td>
<td>47 (23.5)</td>
<td>41 (16.5)</td>
<td>0.17</td>
</tr>
<tr>
<td>EDA (µS)</td>
<td>0.20 (0.12)</td>
<td>0.23 (0.14)</td>
<td>0.27 (0.13)</td>
<td>-</td>
</tr>
<tr>
<td>EDA Transformed (µS)</td>
<td>0.17 (0.10)</td>
<td>0.20 (0.11)</td>
<td>0.23 (0.11)</td>
<td>0.13</td>
</tr>
<tr>
<td>EDA peak (µS)</td>
<td>1.86 (0.86)</td>
<td>2.15 (0.96)</td>
<td>2.23 (0.96)</td>
<td>-</td>
</tr>
<tr>
<td>EDA peak Transformed (µS)</td>
<td>1.01 (0.29)</td>
<td>1.10 (0.31)</td>
<td>1.13 (0.32)</td>
<td>0.39</td>
</tr>
</tbody>
</table>

SSBFF=successful steps before first fail
TTIW=time to initiate walk
TTFF-W=time to first fail-walk
EMAS-S=Endler Multidimensional Anxiety Scale – State
EDA=electrodermal activity
4.3 Movement variability

Due to technical issues with the sacrum marker going undetected by the motion capture cameras, only the neck marker positions were used for calculating movement variability. There were no significant differences in movement variability between conditions ($\chi^2(2) = 4.58, p = 0.10$; Table 4.2). Figure 4.2 shows the distribution of movement variability for all participants in each condition.

![Figure 4.2: Movement variability](image)

**Figure 4.2: Movement variability.** Movement variability is shown for each condition for all participants. The median for each condition is displayed as a horizontal red bar.

There were no significant differences in movement variability between the order that a block of trials was completed ($\chi^2(2) = 1.03, p = 0.60$; Table 4.4).
4.4 Anxiety

Electrodermal activity (EDA) was log transformed to fit a normal distribution. There were no significant differences in EDA between conditions (F(2,69) = 0.13, p = 0.88; Table 4.2). There were also no significant differences in EDA between trial blocks (F(2,69) = 2.09, p = 0.13; Table 4.4). There were no significant differences in peak EDA values between conditions (F(2,69) = 0.09, p = 0.92; Table 4.2). There were also no significant differences in peak EDA values between trial blocks (F(2,69) = 0.96, p = 0.39; Table 4.4).

Changes in EDA were analyzed over the course of all 10 trials within a block to explore any trends pertaining to habituation to threat (Figure 4.3). EDA decreased over the course of a beam walking block for all 3 conditions. Changes in EDA were calculated from 1) the first trial to the second trial and 2) the second trial to the tenth trial (Table 4.5). There was a considerable drop in EDA after just 1 trial in the high-threat condition.
Figure 4.3: EDA changes throughout trials. Mean EDA is shown for each walking trial. The standard deviation for each trial and condition is displayed as horizontal bars.

Table 4.5: EDA habituation. Values are presented as the mean change (standard deviation) in EDA from: 1) trial 1 to trial 2 and 2) trial 2 to trial 10.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\Delta_{\text{Trial } 1 \rightarrow 2}$</th>
<th>$\Delta_{\text{Trial } 2 \rightarrow 10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real + Low Threat</td>
<td>-0.06 (0.20)</td>
<td>-0.04 (0.16)</td>
</tr>
<tr>
<td>Virtual + Low Threat</td>
<td>-0.05 (0.12)</td>
<td>-0.09 (0.22)</td>
</tr>
<tr>
<td>Virtual + High Threat</td>
<td>-0.14 (0.20)</td>
<td>-0.03 (0.12)</td>
</tr>
</tbody>
</table>

EMAS-S scores differed significantly between conditions ($\chi^2(2) = 10.94, p = 0.0042$; Table 4.2). EMAS-S scores were significantly higher in the high-threat VE compared to the low-threat VE ($S = 99, p = 0.0010$; Table 4.3). Figure 4.4 shows the distribution of EMAS-S scores across all conditions.
Figure 4.4: State anxiety. EMAS-S scores are shown for each condition for all participants. The median for each condition is displayed as a horizontal red bar.

Examining state anxiety scores across trial blocks shows that state anxiety decreased with continued exposure to the balance beam-walking task; however, this difference was not statistically significant ($\chi^2(2) = 3.5, p = 0.17$; Table 4.4).

4.5 Sex analysis

Baseline measures were calculated for both male and female participants (Table 4.6).
Table 4.6: Baseline measures between sexes. Values are presented as means (standard deviation) for all baseline measurements.

<table>
<thead>
<tr>
<th></th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22.8 (1.8)</td>
<td>22.7 (1.9)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.63 (0.06)</td>
<td>1.76 (0.08)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>64.8 (15.4)</td>
<td>76.6 (13.7)</td>
</tr>
<tr>
<td>EMAS-T subscales (score)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social Evaluation</td>
<td>41 (7.6)</td>
<td>39 (8.5)</td>
</tr>
<tr>
<td>Physical Danger</td>
<td>58 (5.9)</td>
<td>55 (10.3)</td>
</tr>
<tr>
<td>Ambiguous Situations</td>
<td>41 (13.2)</td>
<td>42 (10.4)</td>
</tr>
<tr>
<td>Daily Routines</td>
<td>21 (5.3)</td>
<td>24 (5.1)</td>
</tr>
<tr>
<td>IPAQ (metabolic equivalent of task minutes)</td>
<td>4836.2 (4050)</td>
<td>4428.8 (4643)</td>
</tr>
</tbody>
</table>

There were no significant differences in outcome measures between male and female participants (Table 4.7).
Table 4.7: Outcome measures between sexes. Values are presented as medians (interquartile ranges) for all balance and state anxiety outcomes, and their p-values are from the Friedman tests comparing outcome measures between sexes and conditions. Values are presented as means (standard deviation) for all EDA outcomes, and their p-values are from the repeated measures ANOVA comparing the transformed EDA values between sexes and conditions.

<table>
<thead>
<tr>
<th></th>
<th>Female</th>
<th>Male</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RL</td>
<td>VL</td>
<td>VH</td>
</tr>
<tr>
<td>Step success (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>83.0</td>
<td>45.1</td>
<td>56.2</td>
</tr>
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SSBFF=successful steps before first fail
TTIW=time to initiate walk
TTFF-W=time to first fail-walk
EMAS-S=Endler Multidimensional Anxiety Scale – State
EDA=electrodermal activity
5 Discussion

The purpose of this study was to determine if performance of a balance beam walking task improves in situations where perceived threat of injury is high. This is a first step towards understanding the role of perceived threat on motor learning. I hypothesized that performance would be greater in situations where an individual perceived a threat of injury if they did not perform the task well. I used virtual reality (VR) technology to elicit feelings of perceived threat. A secondary purpose of this study was to help inform future research by providing insights on the effectiveness of using VR technology in studies that investigate threat and dynamic balance.

5.1 Differences in walking balance between conditions

Although the addition of perceived threat yielded greater step success in the virtual environments (VEs) compared to the low-threat condition, the difference was not statistically significant. Furthermore, the high threat produced only a small effect size of 0.28 for step success. Whether they were aware or not, participants may have been more motivated to not step off the beam in the presence of threat. This finding did not fully agree with previous studies that demonstrated statistically significant improvements in task performance when individuals perceived a threat of injury if they did not perform well in cognitive and simple motor tasks.\textsuperscript{1,20,21,48,71,74,78} Similarly, there was no statistically significant difference in movement variability between the three conditions. I predicted that movement variability would be reduced in the high-threat condition to reflect improved balance control. Although it has been reported that individuals engage in tighter control of posture under conditions of increased postural threat,\textsuperscript{48,74,75} these findings were not fully reproduced in this study (Table 4.2). I only calculated movement variability for instances when participants were stable on the beam. Assessing movement variability under these restrictive circumstances may have contributed to the differences with previous findings. When nearing a loss of balance in the low-threat VE, participants may have conceded the fail and stepped off the beam. However, participants in the high-threat VE were likely more motivated to not concede fails as easily. They may have been attempting more reactive trunk adjustments to control their centre of mass, resulting in more trunk variability, in order to not lose their balance on the beam. Another perspective suggests that increased movement variability reflects exploration of an efficient movement pattern in a changing environment.\textsuperscript{61,62} Exploratory
behaviours may have been prompted as the beam walking task was a novel experience for all participants. Time to initiate walk was significantly greater in the high-threat VE than in the low-threat VE. Although time to first fail was also greater in the high-threat VE than in the low-threat VE, this difference was not statistically significant. Together, time to first fail and time to initiate walk may reflect increased motivation to maintain balance when perceiving a threat, but also indicate delayed initiation of a walking trial in high-threat environments. Another perspective suggests that negative stimuli can be distracting. For example, it has been reported that threatening stimuli can attract visual attention even when participants are required to focus their attention elsewhere.\textsuperscript{113-115} It is therefore also possible that some participants may have been more attentive to the threat than the beam-walking task, which could have negatively impacted performance.

When comparing the two low-threat environments, step success, the number of successful steps before the first fail, and time to first fail were significantly greater in the real environment than in the VE. This mismatch in step success may indicate a need for design improvement or reflect inherent differences in walking in a VE; it is likely a combination of both factors. Posture has previously been reported as intrinsically less stable in VEs.\textsuperscript{88,103,116} Any conflict between the visual, somatosensory, and vestibular information used to control balance can negatively affect balance performance.\textsuperscript{18,101-103} End-to-end latencies in VR reflect the time elapsed between head movement and the consequent update of the visual scene. These latencies may cause conflict between the visual and vestibular systems. The HMD used in this study has an end-to-end latency of 50-60ms, and although this level of latency is not an issue for static tasks, large head movements are often not well translated by HMDs.\textsuperscript{93} Sensory conflict, especially in dynamic balance tasks where visual information is important, could negatively impact walking performance.\textsuperscript{93} The significant discrepancy between real and virtual environments supports my rationale for comparing virtual experiences against each other to evaluate the effect of perceived threat.

5.2 Differences in anxiety between conditions

Increasing elevation in a VE has been previously found to increase feelings of perceived threat in both static and dynamic balance tasks.\textsuperscript{16-18} This study reported similar findings, as the high-threat
VE produced significantly greater state anxiety than the low-threat VE. Continuing to improve the quality of the VE would further contribute to an even more convincing experience, and as a result a more convincing threat.

Although there were no significant differences in mean electrodermal activity (EDA) between the 3 conditions, the trial-by-trial changes in EDA revealed noteworthy trends on habituation to threat. EDA declined substantially following the first trial in all 3 conditions (Table 4.7). This decline continued until the completion of all 10 trials. The drop-off in EDA from the first to second trial was most apparent in the high-threat virtual environment. The trial-by-trial waning of EDA may partially explain the lack of significant differences in self-reported state anxiety between conditions. As the Endler Multidimensional Anxiety Scale - State (EMAS-S) was administered at the end of the trial block when EDA had already declined substantially, the initial anxiety from the high-threat condition may have been depleted by the time the questionnaire was completed. If individuals habituated to feelings of perceived threat, there is likely a downstream effect on the performance measures, such as step success and movement variability, that I predicted to improve as a result of perceived threat. Participants may have engaged in cognitive reappraisals throughout the task. People engage in either task-oriented or emotion-oriented coping strategies depending on the stressful situation and the consequent state anxiety. Participants may have begun with task-oriented coping, by attempting to perform the task well, to avoid the negative consequences. However, the difficulty of the task in the VE may have provoked participants to eventually engage in emotion-oriented coping, reappraising the virtual threat as non-threatening. Emotion-oriented coping is more efficacious in situations that individuals perceive as uncontrollable.

5.3 Using virtual environments to investigate the effects of perceived threat on walking balance

The perception of threat in a VE is highly dependent on the quality of the virtual experience. The sense of presence is further enhanced by a user’s ability to control the virtual environment with their body, and is constrained by sensorimotor contingencies that are limited by the setup of the VE. Although participants were not able to see their feet in either the real or virtual environments, they often reported feeling disorientated from not being able to see their hands in
the VE. Future work should either restrict arm movements from participants’ field of view in all environments or implement avatars, virtual representations of body parts, to make the walking experience more consistent across different environments. Participants also reported that hearing sounds that were external to the VE, such as instructions from the experimenters, disrupted their sense of presence. Incorporating virtual representations of all study elements would likely reinforce feelings of presence. For example, having all instructions and signals presented visually within the VE or having avatars of the experimenters would improve the sense of presence.

Although virtual stimuli would be more capable of inducing perceived threat with a higher quality of virtual experience, it is difficult to prevent habituation to threat when a participant realizes the threat is not real following their first instances of failure. The design of the virtual threat was based on balance studies where failure was not possible, so participants did not experience a fail that might disrupt their perceptions of threat throughout the task. I considered supplementing the virtual threat with sustained consequences such as a diminishing virtual health status or the loss of monetary reward with each fail. However, threatened and challenged individuals perceive a potential for loss and gain in a given situation, respectively. Introducing the opportunity for gaining rewards could interfere with producing the intended state of perceived threat by producing a state of perceived challenge instead. Therefore, gamifying the walking balance task must be considered carefully in order to successfully separate the effects of threat and challenge on performance.

Improvements in virtual experiences are largely dependent on advancements in VR technology. Graphics frame rate, tracking latency, image quality, and field of view are some of the most important features for dictating the quality of a virtual experience. Technical limitations of these features can hinder both physical and cognitive performance during balance tasks. By supporting as many sensorimotor contingencies as possible and reducing any sensory conflict, individuals would be more likely to perceive their virtual experiences as realistic.

5.4 Limitations

The beam used in this study was at a fixed length that was the same for all participants. However, participants had varying foot sizes, which created variability in the number of
successful steps possible during the task. Although the primary outcome was percentage of successful steps, those who were able to take more steps may have benefited from the additional practice. Furthermore, different walking speeds across participants may also affect balance performance. For example, a previous study found that walking faster can improve stability in a similar balance beam-walking task. Movement variability was calculated only for instances when participants were stable on the beam. Participants were instructed to attempt to walk across the entire balance beam without stepping off, and if they stepped off the beam, to step back on at the point of descent. Therefore, individual trials contained multiple segments in which the participant was stable on the beam. Since longer walks produce more data points and consistent measures of gait variability, I may be unable to draw reliable conclusions from walking trials that were particularly fragmented with short periods of stability.

To supplement state anxiety scores from the EMAS-S, I measured EDA to assess levels of perceived threat throughout walking trials. Habituation to threat, exposed by trial-by-trial changes in EDA, revealed that participants likely felt less anxious as they completed more trials within a condition. However, EDA is a measurement of physiological arousal, which does not necessarily suggest anxiety. This limitation may be especially apparent in dynamic balance tasks, where there is a large influence of physical exertion affecting physiological arousal. In the initial trials, increases in EDA were likely more attributed to increased anxiety. However, as perceptions of threat decreased in the latter trials, changes in EDA were likely more attributed to increased physical exertion. Longer periods of rest between trials and blocks may have helped participants return to near-baseline levels of EDA at the start of each trial. In this study, self-report measures were only administered 3 times, once at the end of each walking condition. However, it remains unclear how perceptions of threat may have changed throughout a block of trials. Adding further self-report measurements within blocks of trials may provide valuable insight into assessing the mental processes that lead to habituation to threat as a function of time and fails.

One of the advantages of using virtual reality is the ability to simulate real-world scenarios. In the case of walking balance control, there are more challenges for simulating a real-world experience than would be the case for more stationary tasks. The sense of presence in a VE should be maintained throughout the entire task. Sensory stimuli external to the VE should be limited as much as possible, and avatars should be used to represent limbs in the VE. Lag may
also negatively affect the experience in a VE. This lag can be caused by end-to-end delays from the motion capture system tracking marker positions to ultimately updating the visual scene in the HMD. The temporal binding window reflects the permissible temporal difference between cues from different sensory modalities for them to be integrated as a unified percept.\textsuperscript{118} Individual differences in this temporal binding window can affect the susceptibility to sensory illusions,\textsuperscript{119} and therefore may also create individual differences in perceiving VEs. Any disruptions in feeling present in a VE make it more problematic to compare virtual experiences to real events.

5.5 Future directions

Movement variability was calculated by measuring trunk movement in the medial-lateral direction. However, there is evidence that reducing sensory information, as is the case in VEs, has a harsher impact on lateral control of balance during gait.\textsuperscript{50} Future work should consider other gait parameters to assess walking balance performance. Future work may want to explore dynamic balance tasks in environments where failure is not actually possible. For example, expanding the width of the beam would result in fewer fails, and as a result fewer affirmations that the virtual consequences are not real. In this case, more kinematic parameters of gait would also need to be considered as the primary outcomes.

I hypothesized that individuals would perform the walking balance task better in situations where they perceived a threat of injury if they did not perform the task well. Although participants demonstrated higher task performance in the high-threat VE than in the low-threat VE, this difference was not statistically significant. The effect of perceived threat of injury on motor performance should be retested with more robust manipulations. If performance continues to improve in conditions of high perceived threat with more robust manipulations, I believe this would provide support that perceived threat of injury promotes rapid motor learning through improved performance. However, further investigation is required to determine the role of increased errorless practice following improved performance. The next steps would involve investigating how the amount of errors committed in threatening conditions affect motor learning. Future work may consider adding multiple sessions to assess any long-term retention of the balance skills acquired during initial task performance. This would provide more information
for understanding the role of perceived threat of injury on rapid motor learning. Understanding how perceived threat and errors affect motor learning can have greater implications for rehabilitation by providing insight for integrating these elements into therapies to promote motor learning.

5.6 Conclusion

Although step success was greater in the high-threat VE than in the low-threat VE, this difference was not statistically significant. The manipulation to produce feelings of perceived threat may not have been sufficiently robust. This was likely at least partially attributed to participants realizing the threat was not real as they committed their first fails and was reflected in the trial-by-trial reductions in EDA within a block of trials. Habituation to threat likely affected self-reported state anxiety and walking performance, both of which I predicted to increase in the high-threat condition. More robust manipulations should be tested to provoke the adaptive reactions that facilitate enhanced motor control. Improving the quality of the virtual experience would contribute to sustaining the perception of threat throughout multiple walking trials. Future work should focus on maintaining a sense of presence by incorporating more virtual representations of elements in the real environment. To further understand the role of perceived threat on rapid motor learning, future studies should investigate any lasting improvements in balance control by measuring walking performance over additional sessions.
References


40. Braun TP, Marks DL. The regulation of muscle mass by endogenous glucocorticoids. *Front Physiol.* 2015;6:12.


Appendices

Appendix 1: Linear regression of trait anxiety, state anxiety, and step success. Values presented are point estimates of the slopes of the regression lines (β) with confidence intervals in brackets, and R² for the model. The p-value is for the slope of the regression line.

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