Walk This Beam: Impact of Different Balance Assistance Strategies and Height Exposure on Performance and Physiological Arousal in VR

Dennis Dietz
LMU Munich
Germany
dennis.dietz@ifi.lmu.de

Carl Oechsner
LMU Munich
Germany
c.oechsner@lmu.de

Changkun Ou
LMU Munich
Germany
research@changkun.de

Francesco Chiossi
LMU Munich
Germany
francesco.chiossi@um.ifi.lmu.de

Fabio Sarto
University of Padova
Italy
fabio.sarto.2@phd.unipd.it

Sven Mayer
LMU Munich
Germany
info@sven-mayer.com

Andreas Butz
LMU Munich
Germany
butz@ifi.lmu.de

Figure 1: Scene view of the different learning experiences in virtual reality, ranging from imitation learning (middle) to gamified learning (right).

ABSTRACT

Dynamic balance is an essential skill for the human upright gait; therefore, regular balance training can improve postural control and reduce the risk of injury. Even slight variations in walking conditions like height or ground conditions can significantly impact walking performance. Virtual reality is used as a helpful tool to simulate such challenging situations. However, there is no agreement on design strategies for balance training in virtual reality under stressful environmental conditions such as height exposure. We investigate how two different training strategies, imitation learning, and gamified learning, can help dynamic balance control performance across different stress conditions. Moreover, we evaluate the stress response as indexed by peripheral physiological measures of stress, perceived workload, and user experience. Both approaches were tested against a baseline of no instructions and against each other. Thereby, we show that a learning-by-imitation approach immediately helps dynamic balance control, decreases stress, improves attention focus, and diminishes perceived workload. A gamified approach can lead to users being overwhelmed by the additional task. Finally, we discuss how our approaches could be adapted for balance training and applied to injury rehabilitation and prevention.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Applied computing** → Computer-assisted instruction.

KEYWORDS

virtual reality, physiological arousal, balance control

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1 INTRODUCTION

Balance control is an essential component of many daily activities and sports. Balance has been previously described as the body position dynamics that lessen the danger of or avoid the act of falling [81]. However, balance control can deteriorate across the lifespan or after injuries, leading to slow gait [54], postural instability [35], and fall risk [77]. Therefore, movement scientists investigated how to train balance control during static and dynamic tasks in different settings, such as calm standing [46] or running on a treadmill with constant speed [47]. In addition, new studies on dynamic balance control suggest that static balance assessment is insufficient to properly challenge and assess postural support for balance control [63–65]. As a result, performance while balancing on a beam may give further insight into how task difficulty, e.g., different heights, affects balance control. In this regard, Tersteeg et al. [78] reported that different visual heights in beam-walking influenced gait progression and that preserving the known danger of falling led to a changed stride. With the hazards of walking along a hanging beam or a lack of resources to design a safe and accurate height exposure, developing controlled settings that monitor dynamic balance control is critical for transferring the ability to unpredictable real-world scenarios. Thus, adequate and targeted training strategies deriving from learning and motivational theories could further improve the training effect of such environments, as with any physical or mental training [4, 18].

Research in virtual reality (VR) evaluated the effect of specific stimuli that challenge balance control and investigated dynamic balance reactions in controlled and realistic environments, e.g., the sudden motion of the visual scene or increased height exposure [13, 61]. VR height exposure is comparable to its real-world counterpart in terms of decreased balance confidence, increased physiological arousal, and posture changes [1, 9, 16, 57]. For instance, participants successfully adjust their behavior to the surrounding conditions when crossing a beam at a great height by taking smaller and slower steps [7, 39]. Researchers also showed that height exposure activated the sympathetic autonomic nervous system through cardiovascular [50] and electrodermal [48] measures. Based on these findings, VR exposure to high altitudes should affect stress levels and balance control in dynamic balance tasks.

While many approaches have been proposed for VR learning, this paper aims to determine which VR visualization method best supports balance control training. Thus, we want to investigate the role of design considerations in developing VR balance applications. Therefore, we compare *Gamified* and *Imitation* approaches against a no-support baseline in a high-fidelity VR beam-walking task. We based our *Gamified* approach on the self-determination theory by Deci and Ryan [18], suggesting that intrinsic motivation positively influences learning performance. Social Learning by Bandura and Walters [5] functioned as a base for our *Imitation* Approach, where learning behavior works through observation. As Tersteeg et al. [78] have shown an effect of height on balance training, we systematically studied the approaches in two conditions: *Low* and *High* height. With this, we conducted an experiment (N=18) where we recorded the participants' balance performance, physiological arousal, perceived workload, and subjective experience.

In summary, the findings of our study show that *Imitation* learning with a ghost avatar immediately helps the users to focus better on the balance task and perform better in balance control. Moreover, this is in stark contrast to the *Gamified* approach as it seems to distract the users from the balance task; therefore, this approach did not help to improve the balance control during the session. Thus, while several approaches used gamification to motivate the user, we conclude that in the future, imitation learning should be preferred over gamification as it leads to a better training outcome.

2 RELATED WORK

Below, we will summarize work on balance, how it is currently supported in virtual reality, the impact of fear of heights, and physiological correlates and their relevance to balance control.

2.1 Support of Dynamic Balance Control in VR

The vestibular, vision, and somatosensory systems control the balance in humans, i.e., the change of the center of mass (COM). When standing on two feet (static balance), the COM generally corresponds to the navel position. However, a person in motion adjusts their posture accordingly to prevent falling. This purposeful action of shifting the COM in the direction of movement is called dynamic balance [52].

For virtual reality to be used as a therapeutic intervention, the validity of the technology must first be evaluated. In this regard, Jacobson et al. [36] conducted early research on a system for treating balance disorders. Jacobson et al. [36] intended to aid vestibular disorders with their system. The NAVE Automatic Virtual Environment system used here creates a stereoscopic projection. Like a CAVE, the subject stands in a room projected from up to five sides while following visual instructions. While this project demonstrates an early stage of virtual environment usage, we saw a shift in recent years away from CAVE systems to head-mounted displays (HMDs). This shift allowed a more immersive experience influencing perception and affecting balance. Ferdous et al. [25], investigated the influence of the field of view, frame rate, and display resolution on the physical stability of people who suffer from Multiple Sclerosis (MS). Their experiment tested ten people with MS and another seven people without balance impairment. The study concluded that a reduced field of view, as well as increased latency, had a negative impact on people with MS. Display resolution, on the other hand, showed no relevant effects. As a result, the authors recommend improving the field of view and latency first.

While these papers are researching the technical challenges and their impact on human perception, other approaches focus on the software implementation of balance and coordination applications in a sporting context. Besides motivation, the focus here is on understanding one's own performance [10]. There is no common agreement on how to assess the performance of dynamic balance, therefore a variety of tests exists [52]. Wang et al. [80] address this problem with VRGaitAnalytics, a system for real-time visualization of walking performance. This environment, which can serve as additional support, allows users to receive in-situ visual feedback on their steps while walking. Motion is visible as embodied graphics, allowing users to review their performance and learn from it. Additionally, the speed, stride length, width, and success rate over time can be displayed directly in the virtual scene. The measurements and results were discussed among physical therapy students with the result that this system is relevant and valuable for clinical practice. However, even though this project shows the relevance of feedback, they do not discuss training methodologies.

Therefore, based on Social Learning Theory (SLT) [4], Shi et al. [69] presented a walking task for construction workers and investigated the influence of reinforced learning methods. They evaluated the walking performance of participants who had previously seen a positive walking example (virtual character walking over a plank and reaching the other side) vs. participants who had previously experienced a negative walking example (virtual character walking over a plank and falling off the plank). Their study shows that participants' walking performance becomes more unstable and uncontrolled when they have previously observed a negative example.

Observing others' behavior is also addressed by Cannavò et al. [10] on the subject of coordination improvement. They developed an interactive application in an immersive VR environment to improve basketball throws. They used a motion tracking system to record arm movements. At the same time, in VR, they showed the subject visualization by a transparent avatar ("ghost"), performing the correct throwing technique. While aiming for the basket, the user received visual feedback about his throwing performance. To evaluate the performance afterward, dynamic time warping was used to compare the user's attempt with an ideal throw. In addition, they used questionnaires to evaluate how much the system has helped. Finally, the study compared performance between the ghost method and imitating a training video that participants were asked to watch. As a result, timing and accuracy improved more using the ghost method compared to watching the training video.

2.2 Impact of Fear of Height

Fear is a highly sensitive research field, reaching from psychological aspects [30] to computational analysis and therapy [41]. In their work on treatment possibilities of *Acrophobia* (fear of heights) in VR, Coelho et al. [17] state that about 1 in 20 adults suffer from named anxiety disorder. Besides giving an overview of state-of-the-art work in this field, the authors claim the advent of VR-assisted *Acrophobia* treatments to have been as early as 1995. A first medical application was introduced by Opdyke et al. [53], showing positive improvements for their study participants after eight weeks. Giotakos et al. [29] and Levy et al. [41] conducted studies on virtual reality exposure therapy with elderly people suffering from a fear of heights. Participants who were undergoing the virtual reality treatment showed a significantly decreased fear compared to the control group. Moreover, Levy et al. [41] states that balance training can positively effect Acrophobia. Wuehr et al. [83] randomly exposed study participants to different heights in a VR scenario, concluding that body sway and musculoskeletal stiffening saturate at 20 meters, while anxiety reaches a maximum at 40 meters.

2.3 Peripheral Physiological Correlates of Balance Control in Stressful Environments

Injury prevention is a significant function of balance control [43, 62], required to prevent postural instability when improper or inefficient behaviors might otherwise lead to a fall. As a result, changes in stabilized balance should be viewed as dangerous to the person and as an emergency requiring timely action.

Similarly, the sympathetic branch of the autonomic nervous system is associated with the fight-or-flight response in stressful or dangerous situations [48]. Increases in heart rate (HR), vasoconstriction, and increased electrodermal activity (EDA) are all sympathetic reactions to imminent, impending danger. EDA, especially in its tonic component, reflecting sympathetic activation, has been shown to predict performance in a dynamic balance task [79]. It has been proposed that sympathetic physiological arousal may contribute to the coordinated compensatory postural reflex given the urgent threat to safety caused by disturbances to stability [74]. Sympathetic activity is involved in visceral reflexes during upright stance [37], impairment of balance control [12, 71] and, during modulation of affective states during shifts in postural control [66].

Most work focused on sympathetic modulation not linked to a specific stimulus but rather to continuous stimulation. Specifically, the most used paradigm to investigate the relationship between physiological arousal state on balance control is height exposure [74], showing how stressful stimuli can evoke physiological arousal and impact balance control. Anticipatory postural adjustments and variations in postural sway are correlated with changes in underlying physiological arousal as measured by tonic EDA [2] while phasic responses were elicited by unexpected balance perturbations [72]. Regarding electrocardiography (ECG)-derived measures, blood pressure correlated with postural performance with increased balance challenge [11] and HR increased upon VR height exposure [20]. However, results are conflicting as HR was not found to be modulated by postural threats [59] or not able to discriminate different heights in a VR environment [75].

In conclusion, physiological arousal, especially when measured by EDA, was a reliable measure of stress induced by postural instability. However, gaps remain to be clarified regarding measures extracted from ECG during height exposure or dynamic balance tasks. For these reasons, this study also investigate EDA and ECG metrics as sympathetic arousal to verify and replicate results across different training approaches and height exposures.

3 DESIGN & USER STUDY

We investigated balance performance in stressful situations and developed two strategies to teach stable posture control and reduce emotional arousal in the given situation, this is based on our first on insights [21]. Our expert team consists of computer scientists, movement scientists, and experienced slack-liners. In addition, we based our strategies on a literature review, identifying imitation learning as a successful learning method used effectively in sports [10]. We used a *ghost avatar* to be imitated by the participant, intending a shift of focus from being overwhelmed by the situation's complexity that must be solved to observing and imitating the avatar to do the balancing task. We based the ghost's movements on pre-recordings conducted by a slack-line expert to ensure proper balancing, focusing primarily on an upright posture and a low COM. Gamification is a concept evolving around motivation by utilizing game elements in non-game settings [19]. Our second strategy differs from the imitation strategy by the shift of focus being created not through directing the user but by playful distraction induced by game elements. We introduced a second gender-neutral avatar representing the user itself to increase the presence and support the user's visual perception of himself in VR. Especially the visual perception of the feet is an essential factor in performing accurate movements [40].

We used a within-participants experimental design to understand how to support balance training. The first independent variables were **Method** with three levels: *No Instructions*, *Imitation*, or *Gamified* which has shown to support VR training in other domains. The second independent variable is **Height** with levels *Low* and *High*; this variable is directly inspired by Tersteeg et al. [78]. The order of training methods was Latin square-randomized. In the study, we asked participants to balance over a beam that spans two islands rendered in a high-fidelity VR environment, see Figure 2.

In the *No instructions* condition, it was left to participants how to control their balance or walk over the beam. This served as a control condition. In the *Imitation* condition, we instructed participants to imitate the actions of an avatar performing the balance task in front of the user. Hence, instructions for posture correction were communicated explicitly. Lastly, in the *Gamified* condition, we instructed participants to collect items directly placed over the beam. Half of them could only be collected with their heads, the other half only with their pelvises. Hence, they implicitly received instructions on posture correction. The intended focus was on collecting one head-pelvis-pair of collectibles after the other. To investigate the influence of height exposure on balance control, we implemented two different heights (**Height**). Wuehr et al. [84] reported that physiological reactions to height exposure in VR, like sway and stiffening, are highest at a depth of 20 meters. Since our goal was to create a believable feeling of height, not fear, we chose 20 meters for the high height condition.

3.1 Apparatus

In accordance to Schulz et al. [68] using props in VR helps increase the realism and anxiety. Therefore, we asked participants to control their dynamic balance on a six meters long six-cm-wide wooden beam placed on gym tiles in an open space of a gym, Figure 3. They were wearing a safety harness fixed to a rope slide attached to a 4-point truss cage surrounding the setup.

Figure 2: An aerial shot of the VR environment, presenting the two islands with the connecting beam.

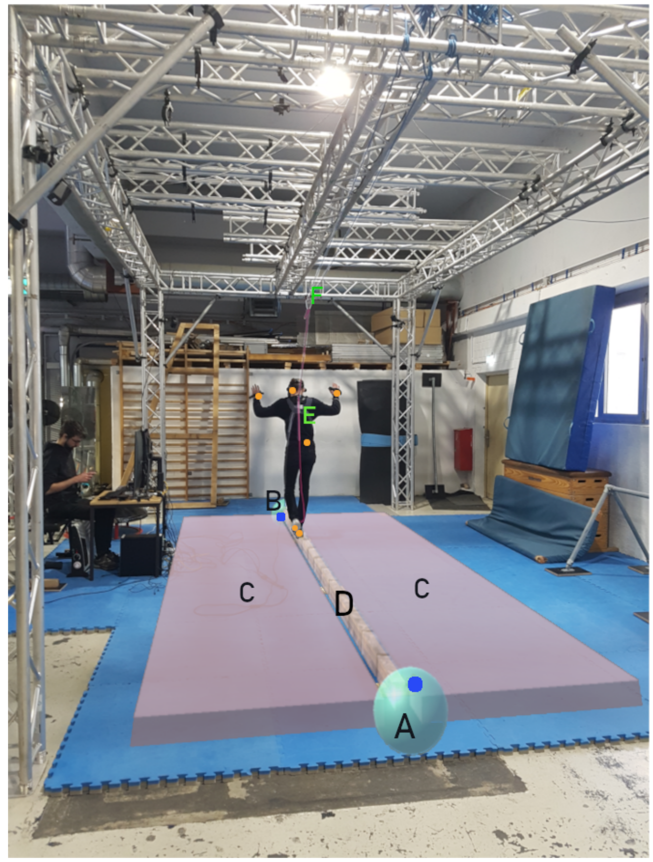

Figure 3: Study apparatus with trigger zones overlay. A: Start Zone, B: End Zone, C: Fall Zones, D: Step Zone; E: Safety Harness, F: Rope Slide; Orange dots: 6 on-body position trackers (head, hands, feet, waist), blue dots: 2 beam position trackers used for scene matching. Each trigger zone was activated or deactivated by one of the feet trackers entering or leaving it.

We placed participants in a VR scene comprised of two remote islands amidst high seas. We placed a timber that spans between the two islands' cliffs to create the experience of the feeling of height. We designed the virtual environment using Unity 3D, as headset we used a Valve Index headset connected to a Windows 10 PC (Intel Core i7-9700 CPU @ 3.00GHz, 32GB RAM). We used the Valve Index Controllers and HTC Vive Trackers for position tracking of the user's head, hands, pelvis, and feet. A virtual avatar was mapped to the user's body using FinalIK[1] using a gender-neutral to reduce biases. We further supported the users' feeling of embodiment and positively affecting immersion [28] using a virtual representation of the user's body. To reduce the risk of injury, in case of a detected fall i. e., a tracker entering Zone C (see Figure 3), everything except the beam faded to black, and a virtual floor was shown at the height of the physical floor.

[1] https://assetstore.unity.com/packages/tools/animation/final-ik-14290

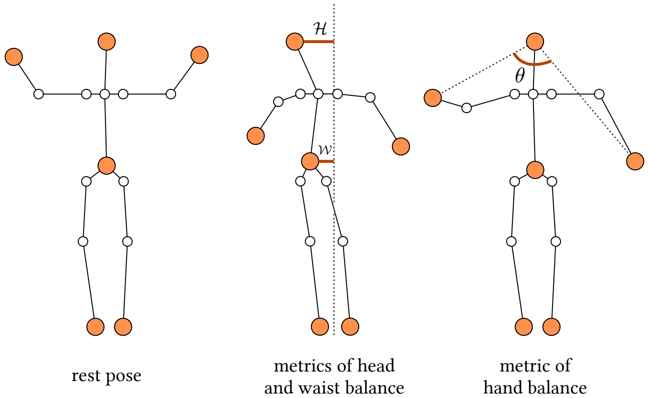

Figure 4: Body metrics for measuring balance performance. Solid orange dots represent the key points of a body that trackers measure. $\mathcal{H}$, $\mathcal{W}$, and θ are our considered oscillation balance metrics regarding head, waist, and hands.

We acquired the users' EDA data using a BITalino biomedical toolkit [32] via Bluetooth connection with a sampling rate of 1000 Hz, following the guidelines by Babaei et al. [3]. The acquisition setup featured two Ag/AgCl electrodes (5 mm surface diameter) attached to the distal phalanx of the middle and index fingers of the participant's non-dominant hand. Moreover, we recorded the ECG data with a Polar H10 (Polar, Finland) placed over the xiphoid process of the sternum below the chest muscles. Before data collection, we moistened the ECG electrodes with lukewarm water. The sampling rate is 130 Hz. We streamed the raw ECG and EDA data using the Lab Streaming Layer[2] to the acquisition PC.

3.2 Procedure

After welcoming participants, we inform them about the study's voluntariness, duration, risks, purpose, compensation, data processing, and publishing of results. Then we asked them to sign an informed consent form. Next, they entered their demographic information into a web form and equipped the safety harness. As the next step, we invited them to walk forth and back on the beam to get an initial impression and test the safety system. After that, we introduced them to the VR headset while we attached electrodes, chest band, controllers, and trackers: we asked them to hold the controllers in their hands, and we attached trackers to their rear waistband (around the location of the coccyx) and at the arch of each foot using velcro fasteners, see Figure 3. Then, we calibrated the virtual avatar to the participant, i.e., the rotation and position of the feet and pelvis and general body height. During the setup procedure, the participants had no visual input through the headset.

A *trial* consisted of a combination of the independent variables Height and Method. We equally balanced the order of Height participants that the participant experiences first. Within Height, the order of training methods was Latin square-balanced. Each trial consisted of four "laps", i. e., participants had to walk the beam forth and back twice. Per trail they walked 24 meters. At the end of the beam, they had to step off and back on it to start the next lap.

[2]https://github.com/labstreaminglayer/

After each trial, subjects were to answer the Physical Activity Enjoyment Scale (PACES) [38] and raw NASA-TLX questionnaires [34]. After completing each Height, we asked them to fill in an Igroup Presence Questionnaire (IPQ) [67]. The institutional ethics committee approved the study procedure.

3.3 Participants

We recruited 18 participants (age range 21-66, M = 31.89, SD = 13.92; 7 female, 11 male, none diverse) using convenience sampling. Inclusion criteria required not to have Acrophobia (i.e., fear of height). Moreover, we followed the guidelines by Babaei et al. [3]; thus, no participant practiced intense physical activity, consumed coffee or substances containing caffeine or nicotine, or smoked in the 3 hours before the study. None of the participants reported neurological, psychological, or psychiatric symptoms. All participants received monetary compensation of 10 EUR upon participation. However, due to technical issues, we obtained the full data only for 15 participants (age range 21-66, M = 33.60, SD = 14.71; 6 female, 9 male). We will present our results based on these 15 participants.

3.4 Measurements & Data Preprocessing

We evaluated different methods for dynamic balance control training across two different heights of exposure. The dependent variables were: (I) balance performance, namely time spent on the beam, number of falls, and oscillations of significant body key-points (waist, head, and hands), (II) physiological arousal as measured by EDA in the form of SCL and non-specific skin conductance responses (nsSCRs) and ECG by HR, and (III) perceived workload (raw NASA-TLX) [34], sense of presence (IPQ) [67], and PACES [38].

3.4.1 Electrodermal Activity. We processed the raw EDA data using the Neurokit Python Toolbox [45]. First, we used a 3Hz, high-pass, fourth-order Butterworth filter to remove high-frequency noise. Second, we decomposed the signal into its tonic and phasic components by non-negative deconvolution analysis [6]. Third, we derived two measures: 1) the average tonic SCL and 2) the average amplitude of nsSCRs. Note that SCRs were defined as peaks from the decomposed signal using a threshold value of $.05\mu S$ [26].

3.4.2 Electrocardiogram. We evaluated ECG activity in the time domain, focusing on HR. As with EDA, the ECG signal was also processed by Neurokit Python Toolbox [45]. We first filtered the ECG signal by the Finite Impulse Response (FIR) band-pass filter (3–45 Hz, 3rd order), and then segmented by Hamilton's method [33] to identify the QRS complexes and extract mean HR.

3.4.3 Balance Metrics. According to the seminal review by Paillard [55], postural balance characterizes the ability to maintain a particular segmental organization without falling. Thus, we evaluated the postural balance based on body segment oscillations obtained from six on-body position trackers (placed on the head, hands, feet, and waist). Moreover, we assumed that quicker successful completion of the walking task reflects a superior postural balance performance. Therefore, we consider five metrics to represent the overall balance performance: 1) the total time to complete the task ($\mathcal{T}$); 2) the number of falls ($\mathcal{F}$); 3) the head oscillation ($\mathcal{H}$); 4) the waist oscillation ($\mathcal{W}$); 5) the hand balance oscillation (θ). We present a visualization of body-related metrics in Figure 4.

Table 1: An overview of all mean and standard deviation in physiological measures and questionnaire measures. Highlighted median values are the ones that ART tests show significant main effects, and highlighted mean values are the ones that two-way parametric ANOVA shows significant main effects.

	METHOD									HEIGHT					
	No Instructions			*Imitation*			*Gamified*			*High*			*Low*		
	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
HR	100.85	**100.18**	16.05	99.72	**99.46**	15.85	102.92	**103.27**	17.12	102.29	**101.83**	17.33	100.03	**100.53**	15.29
SCL	8.09	7.98	3.49	7.76	7.44	3.36	7.97	8.14	3.31	8.41	**8.50**	3.21	7.47	**6.99**	3.49
nsSCRs	0.79	**0.70**	0.53	0.61	**0.55**	0.42	0.66	**0.55**	0.40	0.66	**0.51**	0.42	0.77	**0.68**	0.48
NASA	**43.11**	40.00	29.05	**45.28**	40.00	27.89	**53.39**	55.00	26.94	**49.96**	55.00	28.14	**44.56**	40.00	28.19
PACES	**5.59**	6.00	1.14	**5.41**	6.00	1.22	**5.09**	5.00	1.26	5.46	6.00	1.24	5.26	5.00	1.20

4 RESULTS

We present quantitative findings retrieved from our objective measures and subjective questionnaires. We consider four laps per participant as four repeated measurements to leverage multi-level mixed models analysis (i.e., participant as random effects). Then, depending on the normality assertion using the Shapiro-Wilk test [60], we use two-way ANOVAs for parametric analysis and use ART ANOVAs [82] for the non-parametric data. Furthermore, for post-hoc comparisons, we use either t-test or Wilcoxon tests depending on the normality if no interaction was found; otherwise, we use ART-C test [23] to report our results.

4.1 Electrocardiogram

Since the normality assumption is violated ($W = .98, p < .001$), we conducted ART ANOVA which revealed that HR is statistically significantly influenced by METHOD ($F_{2,340} = 5.02, p = .007, \omega^2 = .02$), HEIGHT as well ($F_{1,340} = .5.53, p = .019, \omega^2 = .01$), but no interaction effect ($F_{2,340} = .75, p = .47, \omega^2 = .001$), see the upper left in Figure 5. Descriptive statistics are shown in Table 1. We performed the Wilcoxon test on METHOD. We could not show any pairwise statistical significance: *No Instructions* vs. *Gamified* ($W = 6715.00, p = .368; r = -.07, CI_{95\%} = [-.21, .08]$), *Gamified* vs. *Imitation* ($W = 8063.00, p = .109; r = .12, CI_{95\%} = [-.03, .26]$), and *No Instructions* and *Imitation* ($W = 7549.00, p = .517; r = .05, CI_{95\%} = [-.10, .19]$).

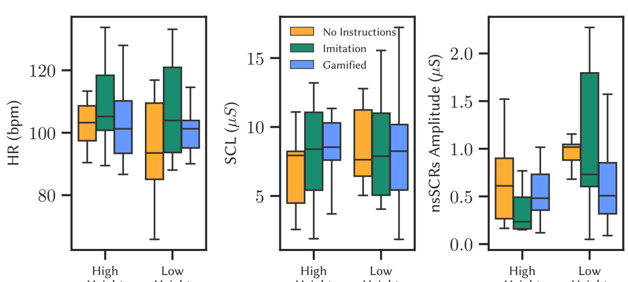

Figure 5: Results from HR, SCL and nsSCRs. The left figure reports the HR measure: HR is significantly influenced by METHOD and HEIGHT. The middle and right figures report the average tonic and amplitude measures in EDA: METHOD influence tonic SCL significantly, and both METHOD and HEIGHT influence nsSCRs amplitude significantly.

4.2 Electrodermal Activity

4.2.1 Skin Conductance Level (SCL). Due to a Shapiro-Wilk tested normality assumption violation ($W = .99, p = .007$), an ART ANOVA showed that average tonic SCL is significantly influenced by HEIGHT ($F_{1,340} = 56.08, p =< .001, \omega^2 = .14$) but not by METHOD ($F_{2,340} = 2.63, p = .073, \omega^2 = .009$). Moreover, the ANOVA could not show a significant interaction effect ($F_{2,340} = 1.05, p = .350, \omega^2 = .003$). Descriptive statistics are shown in Table 1.

4.2.2 Non-specific Skin Conductance Responses (nsSCRs). The average amplitude measure showed normality assumption violation ($W = .92, p < .001$). We performed an ART ANOVA, which revealed that the average amplitude is influenced by both METHOD ($F_{2,340} = 8.99, p < .001, \omega^2 = .04$) and HEIGHT ($F_{1,340} = 25.58, p < .001, \omega^2 = .07$) significantly, and no interaction effect was found ($F_{2,340} = .82, p = .441, \omega^2 = -.001$). We performed a Wilcoxon test on METHOD. We could show statistical significance between *No Instructions* vs. *Imitation* ($W = 8701.00, p = .005; r = .21, CI_{95\%} = [.07, .34]$), but could not show statistical significance for other pairs: *No Instructions* vs. *Gamified* ($W = 8140.00, p = .081; r = .13, CI_{95\%} = [-.02, .27]$), and *Gamified* and *Imitation* ($W = 7767.00, p = .292; r = .08, CI_{95\%} = [-.07, .22]$). Descriptive statistics are shown in Table 1.

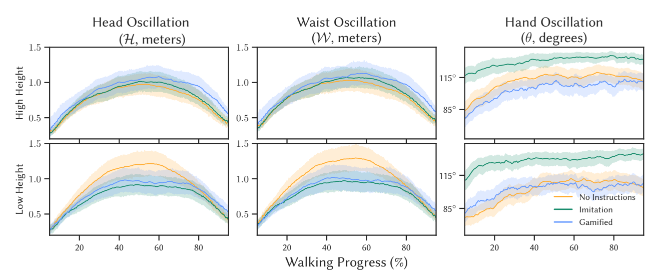

Figure 6: Visualized balance performance metrics changes over the entire progress of the walking over the beam. The upper row shows at the level of high height, and the lower row shows at a level of low height.

Table 2: An overview of all analyzed results using two-way ANOVAs. Significant results are highlighted in bold font.

	METHOD					HEIGHT					METHOD × HEIGHT				
	f	df	F	p	ω^2/η^2	f	df	F	p	ω^2/η^2	f	df	F	p	ω^2/η^2
HR	2	340	5.02	**.007**	.020	1	340	5.53	**.019**	.010	2	340	0.75	.471	.001
SCL	2	340	2.63	.073	.009	1	340	56.08	**<.001**	.140	2	340	1.05	.350	.003
nsSCRs	2	340	8.99	**<.001**	.040	1	340	25.58	**<.001**	.070	2	340	0.82	.441	−.001
$\mu_{\mathcal{T}}$	2	340	89.43	**<.001**	.340	1	340	6.14	**.013**	.010	2	340	0.38	.682	−.004
$\mu_{\mathcal{H}}$	2	340	1.35	.260	.002	1	340	0.05	.817	−.002	2	340	3.72	**.025**	.020
$\sigma_{\mathcal{H}}$	2	340	6.55	**.002**	.030	1	340	0.33	.567	−.002	2	340	1.92	.148	.005
$\mu_{\mathcal{W}}$	2	340	1.72	.180	.004	1	340	0.00	.963	−.003	2	340	3.89	**.021**	.020
$\sigma_{\mathcal{W}}$	2	340	6.70	**.001**	.030	1	340	0.31	.576	−.002	2	340	2.21	.111	.007
μ_θ	2	340	107.59	**<.001**	.380	1	340	8.33	**.004**	.020	2	340	2.34	.097	.008
σ_θ	2	340	16.47	**<.001**	.080	1	340	0.38	.539	−.002	2	340	1.49	.226	.003
$\mu_{\mathcal{F}}$	2	340	20.93	**<.001**	.100	1	340	55.32	**<.001**	.140	2	340	11.23	**<.001**	.060
NASA	2	28	9.34	**<.001**	.400	1	14	4.68	**.048**	.250	2	28	0.48	.621	.030
PACES	2	28	4.81	**.016**	.260	1	14	1.69	.215	.110	2	28	0.46	.637	.030

4.3 Balance Performance

We conducted an ART ANOVA, as the Shapiro-Wilk normality test showed that the data are not normally distributed ($W = .89, p < .001$). This analysis revealed that the total time spend $\mu_{\mathcal{T}}$ is significantly influenced by METHOD ($F_{2,340} = 89.43, p < .001, \omega^2 = .34$) and by HEIGHT ($F_{1,340} = 6.14, p = .013, \omega^2 = .01$). Moreover, no interaction effect was found ($F_{2,340} = .38, p = .682, \omega^2 = -.004$).

Moreover, Wilcoxon tests on METHOD could show statistical significance between all pairs: *No Instructions* vs. *Gamified* ($W = 2378.00, p < .001; r = -.67, CI_{95\%} = [-.74, -.58]$), *Gamified* vs. *Imitation* ($W = 10219.00, p < .001; r = .42, CI_{95\%} = [.29, .53]$), and *No Instructions* and *Imitation* ($W = 4590.50, p < .001; r = -.36, CI_{95\%} = [-.48, -.23]$).

Similarly, we further tested the following metrics: 1) $\mu_{\mathcal{F}}$: mean of number of falls; 2) $\mu_{\mathcal{H}}$: mean of $\mathcal{H}$; 3) $\sigma_{\mathcal{H}}$: standard deviation of $\mathcal{H}$, 4) $\mu_{\mathcal{W}}$: mean of $\mathcal{W}$, 5) $\sigma_{\mathcal{W}}$: standard deviation of $\mathcal{W}$, 6) μ_θ: mean of θ, 7) σ_θ: standard deviation of θ. For all these metrics, Shapiro-Wilk normality tests showed that all metrics are not normally distributed (all $p < .001$). Therefore, we employed ART ANOVA and found that none of $\mathcal{H}$ and $\mathcal{W}$ metrics are significantly influenced by HEIGHT. On the other side, we report significant main effects for METHOD on μ_θ, σ_θ, $\mu_{\mathcal{F}}$, $\mu_{\mathcal{T}}$, $\sigma_{\mathcal{H}}$, and $\sigma_{\mathcal{W}}$. For a more complete overview of all ART-ANOVA results, see Table 2.

More specifically, we show the post-hoc pairwise significance by Figure 8 using either t- or Wilcoxon test, depending on the normality. For visualizations, Figure 6 shows the comparison of the oscillation of head, waist, and hand balance over time, and Table 1 shows the distributions of metrics that are influenced by METHOD significantly.

4.4 Questionnaires

4.4.1 Perceived Workload. A Shapiro-Wilk test showed that the reported raw NASA-TLX meets the normality assumption ($W = .97, p = .069$). Thus, we performed the two-way ANOVA. The main effect of METHOD is statistically significant ($F_{2,28} = 9.34, p < .001; \eta^2 = .40$). The main effect of HEIGHT is statistically significant and small ($F_{1,14} = 4.68, p = .048; \eta^2 = .25$), see Figure 7. The interaction effect between METHOD and HEIGHT is statistically *not* significant and very small ($F_{2,28} = .48, p = .621; \eta^2 = .03$). The post-hoc Wilcoxon tests on METHOD could show statistical significance between *No Instructions* vs. *Gamified* ($W = 257.50, p = .005; r = -.43, CI_{95\%} = [-.43, -.16]$), as well as *Gamified* vs. *Imitation* ($W = 621.50, p = .011; r = .38, CI_{95\%} = [.11, .60]$), but not significant between *No Instructions* and *Imitation* ($W = 400.00, p = .464; r = -.11, CI_{95\%} = [-.39, .18]$).

4.4.2 Physical Activity Enjoyment Scale. Since PACES ratings are normally distributed ($W = .97, p = .07$), we performed a two-way ANOVA. We found statistically significant differences in METHOD ($F_{2,28} = 4.81, p = .016; \eta^2 = .26$) but not HEIGHT ($F_{1,14} = 1.69, p = .215; \eta^2 = .11$), and there is no interaction effect ($F_{2,28} = .46, p = .637; \eta^2 = .03$), see Figure 7. Moreover, Wilcoxon tests on METHOD

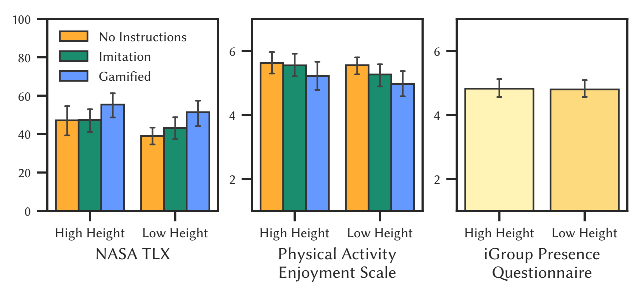

Figure 7: Left: Raw NASA-TLX rating (lower is better). The main effect of METHOD is statistically significant; Middle: PACES ratings (higher is better) are significantly influenced by METHOD but not HEIGHT. Right: IPQ measured only for the HEIGHT factor (no statistically significance was found).

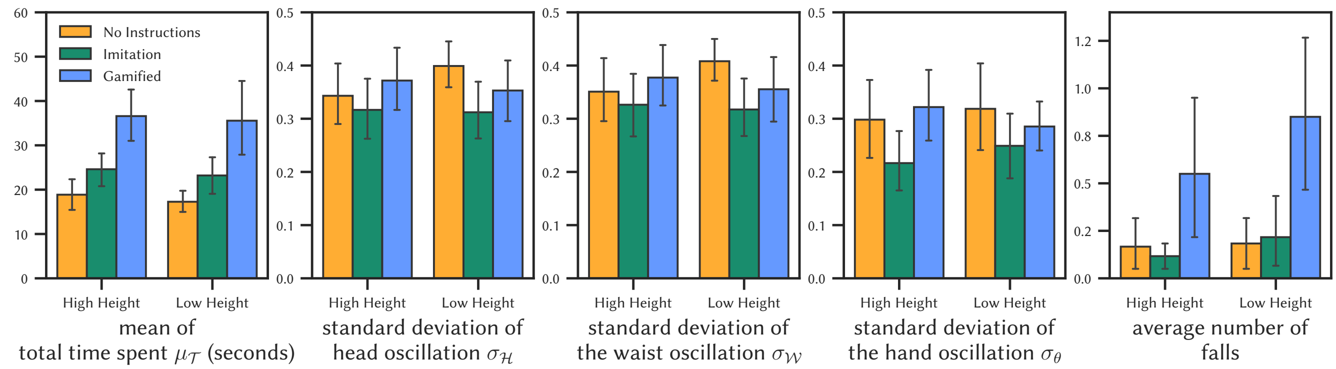

Figure 8: Averaged measures of balance performance: Our analysis indicates that METHOD influences the standard deviation of all metrics, and the mean of hand balance oscillation, but HEIGHT does not. No interaction effects were found.

could show statistical significance between *No Instructions* vs. *Gamified* ($W = 613.50, p = .016; r = .36, CI_{95\%} = [.09, .59]$), but not the other pairs: *Gamified* vs. *Imitation* ($W = 332.00, p = .082; r = -.26, CI_{95\%} = [-.51, .03]$), and *No Instructions* and *Imitation* ($W = 502.00, p = .446; r = .12, CI_{95\%} = [-.18, .39]$).

4.4.3 Presence. Because our collected IPQ ratings are normally distributed ($W = .95, p = .17$), we used a t-test and were unable to prove a significant difference between *High* and *Low Height* ($t = .12, p = .91$).

5 DISCUSSION

In this section, we combine the quantitative results presented above with our participant's subjective comments to discuss and reflect on what implications we think these observations have.

5.1 Physiological Measures

Results from both ECG and EDA suggest that physiological arousal is mainly affected by VR height exposure, accompanied by alterations in dynamic balance control. We found that HR increased when users were exposed to virtual high heights. This result replicates previous work on stress [8, 56], adding credibility to HR's capacity to discriminate between different height exposure [20, 48]. Furthermore, it indicates that our photorealistic implementation evoked a realistic height perception and related stress response. Specifically, increased visual fidelity appears to be a relevant factor when designing VR environments [31] that involve height exposure both for psychological VR therapy [20] and assessment of fall-prevention strategies [39, 75]. Moreover, increased height exposure requires dynamic balance adjustments, which is reflected by sympathetic variations [27, 74] and confirmed by our results.

Together with HR, height exposure similarly affected the tonic component of EDA. This result depicts a sympathetic reaction to the evoked postural instability [74]. From a functional perspective, an autonomic reactivity indexed by HR and SCL should facilitate the corrective dynamic balance response [70, 73]. VR height exposure increased the stress level, interfering with the need to promptly react to the postural perturbation, as shown by SCL [42, 44]. Our results confirm the results of Meehan et al. [49] and Diemer et al. [20], particularly the effect of VR height exposure on physiological arousal. This interpretation is in line with our finding that nsSCRs showed increased amplitude in the *No Instructions* condition. When no instructions were given, participants invested more effort in controlling their dynamic balance. Lastly, we report an increased nsSCRs amplitude in the low height condition. Even though nsSCRs reflect tonic activity, SCRs were less sensitive to height exposure [84] and attenuated when postural perturbations are generated by external factors [72]. Furthermore, given the high movement required by the task, artifacts like participants' motion can be confounded with nsSCRs, and SCRs [58].

Our results also contribute to the physiological computing perspective [24] for exergaming [51]. Future work should focus on designing physiologically-based exergames not only in the area of motivation [76] or user experience [14], with the goal to adapt displayed information [15], e.g., heights for dynamic balance adjustments. Our work supports the overarching relationship between autonomic activity for dynamic balance control and height exposure in a VR environment.

5.2 Balance Measures

As the most striking result for the motion analysis, it turns out that the evaluation of the gamified method provides a significant difference compared to the baseline (*No Instructions*). This difference exists in all measured areas; time, counted falls, and oscillation of head, hips, and hands. Similarly, there is a significant increase in time and swaying of the hands compared to imitation learning. These results suggest that the gamified method was experienced as the most complex regardless of water height. The intended effect of positively influencing the body posture by gathering collectibles could not be realized within one training session only. However, observed over several sessions, the effect of a more challenging task could lead to better postural balance control adaptation [55]. Although correlated movements of the head and hips were detected, balance control became more difficult with the additional effort, which did not lead to a more stable balance. It could be argued that the hands should have been used for collecting game elements as well, but that would again have increased the complexity of the task. Since the hands were not assigned to the task, the movement of the hands shows an above-average sway that does not contribute to stability.

In contrast, imitation learning shows a positive effect on hand sway. The technique led to a significantly lower sway of the hands compared to the baseline. From this, we can conclude that using the hands in a guided way gives a significant advantage in dynamic balancing. Furthermore, regarding the imitation technique, only the measured deviations in time were significantly different from the baseline. In this case, the time was affected by the task and, therefore, by the avatar's speed.

5.3 Questionnaire Feedback

As supported by the significantly higher perceived workload assessed by the raw NASA-TLX questionnaires [34], the gamified approach was the most demanding for participants. The error rate in this scenario was significantly higher, which could be visually confirmed by the study investigators. The additional collection task added workload to the basic balance control task, which overwhelmed users and made them rate this method the highest in workload. Furthermore, additional and controlled head movement was necessary to collect items that were potentially outside their field of view, which also explains the high value of $\sigma_{\mathcal{H}}$. This prolonged the sessions and further contributed to tiring the participants. The overextension is also reflected in the lowest PACES rating for the gamified approach. In addition to that, four participants felt distracted from the height and the surroundings by the additional task, while three reported that the collectibles made the task more difficult since they blocked their view on the beam.

In contrast, imitation did not seem to overwhelm participants compared to the no-instruction method ($p = .464$). This could have several reasons: firstly, imitating is a natural learning strategy humans apply from an early age. Secondly, the "additional task" of having to imitate an avatar had the same purpose as the primary task of crossing the gorge, in contrast to the extraneous task of collecting floating items. Hence, the proximity of the secondary to the primary task may have led to higher performance at a lower perceived effort.

Despite significantly higher measures in HR and SCL, users rated high height and low height conditions indifferently in terms of enjoyment and generally reported the experience to be pleasant and enjoyable.

6 LIMITATIONS & FUTURE WORK

During the study, we were liable for the participants' physical integrity. Hence, a lot of time, money and effort was put into safety mechanisms. The harness itself could have had an effect on user performance: the procedure and feeling of putting it on could have limited the amount of immersion into the scene and led to participants feeling more careless about falling. Furthermore, the expenditure of installing such mechanisms at home would probably defy the "easily-train-at-home" premise one might have. In a private context, however, users would only be responsible for themselves and for playing in a safe environment. However, the study of suitable safety equipment for exertion games in VR and its effect on immersion is not in the scope of this paper.

For exact movement tracking, three additional VR trackers were used. For private use, this would mean higher acquisition cost and less ease of use. However, there are cheaper and more convenient camera- or marker-based solutions in the market that provide comparable precision, e.g., Microsoft XBox, OptiTrack, Xsens Motion-Capture. Future work, therefore, can focus on evaluating different tracking systems for VR balance training, keeping in mind the speed and accuracy of tracking.

In addition, future studies should focus on multi-session and long-term observation to further investigate the effects of different training designs. For example, our study results indicate that the gamified approach seems to be an undesired design decision. However, it should be investigated over several weeks since training improvement usually evolves over time. It could be the right decision for training experts who benefit from the added task load. It increases the challenge while focus maintains on the balancing task. Interestingly, height did not significantly affect the head and hip movements but had a small significant effect on perceived workload. This shows that the learning method is essential in developing training approaches.

7 CONCLUSION

This paper presents a virtual reality environment to train to balance at varying heights. Hereby, we compared the benefits of two training approaches. Based on the recorded data consisting of EDA, ECG, movement data, and questionnaires, we concluded that imitation learning positively affects the training of balance ability while walking in stressful environments. Furthermore, based on the physiological data, we could also confirm existing studies on the influence of height [20, 49]. The observed positive effect of the imitation training variant forms a basis for future work and could be further evaluated in long-term training sessions.

In contrast to the imitation approach, execution with the gamified approach was significantly worse than the baseline in almost all cases. In addition, no significantly positive training results could be obtained, in contrast to imitation learning. The data shows that participants perceived the task as a burden and not as support. As previously discussed, how the task is perceived can be influenced by the context where it is used, e.g., in therapy or as expert training. Therefore, long-term training sessions should consider the context further to investigate the change in perceived difficulty during task performance.

8 OPEN SCIENCE

We encourage readers to reproduce and extend our results. Our collected datasets, simulated VR scenarios, and analysis scripts are open-sourced and made available on GitHub[3] and the DaRUS Open Data platform[4] [22].

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[3] https://github.com/mimuc/walk-this-beam
[4] https://darus.uni-stuttgart.de/dataset.xhtml?persistentId=doi:10.18419/darus-3139

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