The feasibility of using virtual reality to induce mobility-related anxiety during turning

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Abstract

Background: The fear of falling, or mobility-related anxiety, profoundly affects gait, but is challenging to study without risk to participants. Purpose: To determine the efficacy of using virtual reality (VR) to manipulate illusions of height and consequently, elevated mobility-related anxiety when turning. Moreover, we examined if mobility-related anxiety effects decline across time in VR environments as participants habituate. Methods: Altogether, 10 healthy participants (five women, mean (standard deviation) age = 28.5 (8.5) years) turned at self-selected and fast speeds on a 2.2 m walkway under two simulated environments: (1) ground elevation; and (2) high elevation (15 meters above ground). Peak turning velocity was recorded using inertial sensors and participants rated their cognitive (i.e., worry) and somatic (i.e., tension) anxiety, confidence, and mental effort. Results: A significant Height × Speed × Trial interaction ($p = 0.013$) was detected for peak turning velocity. On average, the virtual height illusion decreased peak turning velocity, especially at fast speeds. At low elevation, participants decreased speed across trials, but not significantly ($p = 0.381$), but at high elevation, they significantly increased speed across trials ($p = 0.001$). At self-selected speeds, no effects were revealed (all $p > 0.188$) and only effects for Height were observed for fast speeds ($p < 0.001$). After turning at high elevation, participants reported greater cognitive ($p = 0.008$) and somatic anxiety ($p = 0.007$), reduced confidence ($p = 0.021$), and greater mental effort ($p < 0.001$) compared to the low elevation. Conclusion: VR can safely induce mobility-related anxiety during dynamic motor tasks, and habituation effects from repeated exposure should be carefully considered in experimental designs and analysis.

Keywords: Elevation; Fear of Falling; Inertial Sensor; Mental Effort; Turning.

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1. Introduction

Fear of falling, or mobility-related anxiety, profoundly impacts postural control [1], walking behavior [2], and recovery after a loss of balance [3]. Studying mobility-related anxiety is complicated by the challenge of imposing postural threat without causing actual risk to the participant. As a result, researchers have resorted to manipulating anxiety and evaluating associated physiological/behavioral consequences using simple postural tasks such as standing [4] or constrained locomotor tasks such as treadmill walking with a safety harness [5]. However, over 40% of daily steps involve turning [6] and 800-1000 turns are performed each day [7]; and few, if any, researchers have examined the effect of mobility-related anxiety on turning. Because turning increases the demands of maintaining balance [8] and the increases the risk [9] and frequency of falls while executing a turn [10], research is needed to enhance current understanding of how mobility-related anxiety impacts turning performance. Therefore, a critical step in understanding the interactions between mobility-related anxiety and locomotor behavior is to characterize the effect of mobility-related anxiety on real-world locomotor tasks such as turning.

In the seminal work examining the relationship between anxiety and gait, scientists used expensive hydraulic lifts to raise the support surface and induce mobility-related anxiety while participants stood at increased heights [11], but such approaches may not be appropriate for more dynamic tasks such as turning without sophisticated safety equipment. Alternatively, virtual reality (VR) technology provides a unique opportunity to probe the underlying mechanisms of mobility impairments using relatively safe, low-cost equipment. VR is an effective means of eliciting mobility-related anxiety; a virtual height illusion can elicit similar standing postural control responses as real-world height manipulations [12,13]. Yet, many existing VR-based studies depend on expensive motion capture equipment [14,15], examine abstract environmental simulations [16], or observe contrived motor tasks (e.g., treadmill-based [5,16] or balance beam walking [13]) that may not generalize to daily walking behavior. Additionally, the anxiety response appears to taper across time [1], but it remains unclear if participants adapt to a virtual height illusion with prolonged exposure. The potential utility of VR technology to investigate ecologically valid, complex locomotion, such as turning, has yet to be fully realized.

We evaluate the viability of using a realistic VR simulation to induce mobility-related anxiety during turning in healthy adults. A secondary aim was to determine the rate of adaptation to the VR illusion. We developed this method with the aim of using the approach in the future to investigate fear of falling in older adults and examine the viability of using VR for studying the effects of the mobility-related anxiety on dynamic locomotor tasks.

2. Methods

All procedures were approved by the University's Institutional Review Board and informed consent was provided. Participants were excluded if they had any neurological, orthopedic, or cardiovascular conditions that would affect walking, or if they suffered from excessive motion sickness or vertigo. Participants were between 18-65 years old, had vision and hearing corrected to normal, and were able to walk unassisted without discomfort. No other inclusion criteria were enforced in this healthy population. Altogether, 10 healthy participants (five women, mean (standard deviation) age = 28.5 (8.5) years) reported normal visual (Snellen eye test [17]), cognitive (Stroop [18], Trail Making Test [19]) and physical function (Short Physical Performance Battery (SPPB) [20], Timed Up and Go (TUG) [21], Dynamic Gait Index (DGI) [22]).

Participants wore their usual corrective eyewear and were fitted with a HTC Vive (version 2.0, Bellevue, WA) head-mounted display (HMD) presenting a 0.40 m x 2.2 m virtual path in two types of immersive environments: (1) ground level (low elevation; Figure 1b); and (2) at 15 meters above ground to induce anxiety (high elevation; Figure 1a). A real-world path (0.02 m high, 0.40 m wide, and 2.20 m long) matched the VR path dimensions and location in the virtual simulation (Figure 1c). The virtual path dimensions were captured using hand controllers that marked the four corners of the actual walkway. Participants wore motion trackers (HTC Vive, version 2.0) on both ankles to provide a continuous representation of their feet in the virtual environment that was depicted as a pair of tennis shoes. We recorded foot tracker position and rotation at 90 Hz using gyroscopes and two lighthouse-based infrared sensors to track each object. We placed inertial sensors (APDM Inc, Portland, OR) containing tri-axial accelerometers, gyroscopes, and magnetometers on the lumbar spine and both feet to measure accelerations and recorded data at 128 Hz.

Participants were fitted with the HMD, instructed to adjust the inter-pupillary distance, and underwent a familiarization period prior to the experiment. First, participants were instructed to adjust the inter-pupillary distance of the HMD display so that they could see the VR environment clearly. Then, the familiarization period lasted for two minutes, during which the participant's foot trackers were aligned to their feet. During this familiarization period, participants were encouraged to walk along the pathway in the low elevation environment (Figure 1b) and gain a sense of where they were in relation to the real-world walkway. A research assistant followed participants at all times to ensure safety. We used the familiarization period to ensure the accuracy of the walkway representation and foot trackers. If the participant reported their feet or the walkway were not accurately represented in the virtual setting, the plank coordinates and foot trackers were recalibrated. We presented blocks of five trials in low and high elevation settings to the participants following the familiarization period in a pseudorandom counterbalanced order (Figure 1a-b). Prior to high elevation trials, participants stood at the beginning of the walkway to be 'transported' 15 m above ground instantaneously (i.e., 100 ms). Participants walked to the end of the path, turned 180°, and returned to the starting position. To elicit different levels of locomotor demand on the turning task, both low and high elevation turning trials were completed at two speeds; a self-selected comfortable walking speed, and at the participants' 'fastest comfortable pace'.

Between blocks, participants used the (Mental Readiness Form 3, MRF-3) [23] to report the cognitive (i.e., worry) and somatic (i.e., arousal) components of anxiety, as well as confidence in their ability to complete the task using an11-point Likert-scale. Specifically, ratings of cognitive anxiety were prompted with the root "my thoughts were" and the participant rated their response from 1, 'very calm,' to 11, 'very worried,' which reflects the degree that cognition was influenced by the experimental manipulations. Ratings of somatic anxiety were prompted by the root "my body feels" and the participant rates their response from 1, 'very relaxed,' to 11, 'very tense,' reflecting their perceived physiological response. Finally, ratings of confidence were prompted with the root "I am feeling," and participants rated their level of confidence in their ability to complete the task from a 1, 'very confident,' to 11, 'not confident at all,' reflecting the way the manipulation influences their balance confidence. Participants also rated the level of mental effort required to complete the task using the Rating Scale of Mental Effort (RSME) [24], which ranges from "absolutely no effort" to "extreme effort." Both the MRF and RSME have been widely used in previous research on anxiety and performance. The instructions for all self-report measures emphasized that participants should indicate their feelings during the most recent block of five trials.

The inertial sensor data were analyzed using a custom Matlab program (version 2018b, Natick, MA). Sensor-based coordinates were rotated to a body-fixed frame initially aligned with the global inertial frame.[25] Angular velocities were filtered using a phaseless 4^{th} order, 6 Hz low-pass Butterworth filter, and the peak yaw angular velocity was extracted for each turning trial.

We fitted linear mixed-effect regression models to the data to determine the effect of walkway height, instructed speed, and adaptation across repeated trials on turning performance. For peak turning velocity, models included the fixed effect of height (low vs. high), speed (self-selected vs. fast) and trial number (one through five), and all two- and three-way interactions. Measures of affective rating scales of anxiety, confidence, and mental effort, were obtained after blocks of five trials to determine the effect of height and speed on affective responses. Thus regression models included the fixed effect of height (low vs. high) and speed (self-selected vs. fast) and all two-way interactions. Height and Speed variables were contrast coded for ease of interpretation (low = -1, high = +1, self-selected = -1, fast = +1). The reference condition for the Trial factor was the first trial.

To determine whether differences in turning behavior from the low to high elevation environment were associated with changes in self-reported anxiety, we calculated confidence and mental effort change scores for each participant in both the self-selected and fast speed trials. The dependent measures were averaged for each speed in both low and high elevation trials, and the difference between the high and low elevation was calculated for each speed (high − low elevation). Spearman's rho (ρ) rank correlations evaluated the relationship between changes in self-reported anxiety, confidence, and mental effort and change in turning velocity. The significance threshold for all statistical analyses was set at $\alpha = 0.05$.

To promote transparency and future use, we have shared our data, analyses scripts, and the VR program on github for the reader's reference (see here: https://github.com/benbeezy/VR_gait for VR program and here for data/analyses: https://github.com/keithlohse/Gait_VR).

3. Results

The parameter estimates for peak turning velocity as a function of Height, Speed, and Trial are reported in Table 1. The regression analysis revealed a significant Height × Speed × Trial interactions ($p = 0.011$). To understand the three-way interaction, we examined smaller models to test Speed × Trial effects at different heights and Height × Trial effects at different speeds (for detailed results, see Supplemental Table 1).

The model was first decomposed by walkway height (Supplemental Table 1). At high elevations, there was a significant Speed × Trial interaction ($\beta = 6.12$, $p = 0.009$). This interaction was driven by a negative effect of Trial at self-selected speeds, but not significant ($\beta = -2.85$, $p = 0.381$) (Figure 2 a-b), whereas the effect of Trial was positive at fast speeds, and statistically different from zero ($\beta = 9.39$, $p < 0.001$) (Figure 2c-d). The impact of the Trial effect at self-selected versus fast speeds is illustrated in Figure 2e and 2f. At low elevations, the effect of Speed was significant ($\beta = 40.50$, $p < 0.001$) (Figure 2a, c), exhibiting a much larger increase in turning speed than at high elevations (Figure 2 b, d), but there was no statistically significant effect of Trial ($\beta = 0.49$ $p = 0.851$), nor a Speed × Trial interaction ($\beta = 40.50$, $p = 0.353$).

Next, the model was decomposed by turning speed (Supplemental Table 1). At self-selected speeds, there was no statistically significant effect for Trial ($\beta = 0.04$, $p = 0.985$), Height

(β = -6.22, p = 0.248), or a Height × Trial interaction (β = -2.89, p = 0.188). As such, people tended to decrease their turning velocity when walking at high elevations, but not to a degree that was statistically significant or that changed reliably across time. At fast speeds, the effect of Height was statistically significant (β = -29.49, $p < 0.001$), showing a large decrease in velocity when turning quickly at high elevation. However, there was no statistically significant effects for Trial (β = 3.72, p = 0.255), nor a Trial × Height interaction (β = 5.67, p = 0.084).

The parameter estimates for self-reported ratings of cognitive anxiety (i.e., worry), somatic anxiety (i.e., tension), confidence, and mental effort were significantly affected by the height manipulation (Figure 3a-d, Table 2). Mixed-effect regression tests revealed significant main effects of Height for cognitive anxiety (p = 0.008), somatic anxiety (p = 0.007), confidence (p = 0.021), and mental effort ($p < 0.001$). Participants self-reported greater levels of worry, tension, and mental effort, as well as less confidence in their ability to do the task, when turning in the high elevation virtual environment. No main effects of Speed or Height × Speed interactions were documented for self-reported ratings of cognitive anxiety, somatic anxiety, confidence, or mental effort (all p's > 0.100, Figure 3a-d, Table 2).

Spearman's rank correlations were used to evaluate the relationships between change scores (high–low elevation) in self-report ratings and turning speed. No significant correlations were reported between peak velocity change scores and any change scores for self-report measures during either self-selected speed (Δ Cognitive Anxiety: ρ = -0.168, p = 0.642; Δ Somatic Anxiety ρ = -0.079, p = 0.827; Δ Confidence ρ = 0.006, p = 0.987; Δ Mental Effort ρ = -0.037, p = 0.919) or fast speed turning trials (Δ Cognitive Anxiety: ρ = -0.194, p = 0.591; Δ Somatic Anxiety ρ = -0.093, p = 0.799; Δ Confidence ρ = -0.082, p = 0.823; Δ Mental Effort ρ = -0.068, p = 0.853).

Among the psychological variables, however, change in ratings of mental effort exhibited strong, positive correlations with more anxiety at self-selected (Δ Cognitive Anxiety: $\rho = 0.905$, $p < 0.001$; Δ Somatic Anxiety $\rho = 0.960$, $p < 0.001$) and fast speeds (Δ Cognitive Anxiety: $\rho = 0.876$, $p < 0.001$; Δ Somatic Anxiety $\rho = 0.862$, $p = 0.001$) and exhibited strong, negative correlations with reduced confidence during self-selected (Δ Confidence : $\rho = -0.858$, $p = 0.001$) and fast speed turns (Δ Confidence : $\rho = -0.975$, $p < 0.001$).

4. Discussion

We examined the efficacy of a virtual height illusion for eliciting mobility-related anxiety during a complex turning movement in healthy adults. Due to the possibility that participants may become desensitized to virtual and/or height manipulations, a secondary objective was to determine if the effectiveness of the VR illusion changed across multiple trials. The elevated walkway height reduced peak turning velocity and confidence while increasing worry, tension, and mental effort, suggesting the VR illusion is an effective manipulation inducing both subjective self-reported changes and objective indices of mobility-related anxiety. A three-way interaction between turning speed, walkway height, and trial, suggested that the effect of the VR illusion on peak turning speed may change as a result of the constraints of walking speed and the number of trials.

When walking at high elevations participants consistently decreased their peak turning velocity, supporting the effectiveness of the VR illusion. We are unaware of similar studies that have evaluated the effect of anxiety on complex behaviors such as turning for direct comparison; however, this result is consistent with other published reports indicating that individuals reduce their gait velocity when on an elevated walkway [26]. Manipulating the speed of the locomotor task revealed that when turning at higher elevations, participants felt less comfortable achieving their peak turning velocity. We were surprised to find that effects of the height illusion on turning velocity were strong at fast speeds, but were not detectable at self-selected speeds. Participants' apparent resistance to the effect of height at self-selected speeds could result from a reduced threat of falling at slower speeds for healthy adults. Alternatively, this result could be due to a 'floor effect' in peak turning velocity at self-selected speeds. Participants may not be able to walk slower than their self-selected speed without increasing energy expenditure [27] or hindering gait automaticity [28]. Thus, greater changes may only be detectable during fast turns in this healthy young adult sample. In the future, researchers should include additional motor outcome measures to clarify this distinction.

Self-report measures of affective responses supported the effectiveness of the VR height illusion. Greater levels of cognitive and somatic anxiety have been previously reported when individuals are exposed to the threat of a balance perturbation [29]. We speculate that reduced confidence and greater levels of cognitive and somatic anxiety might be indicative of a perceived sense of threat to stability in the virtual simulation, even though participants were standing two cm off of the ground in reality. Participants also reported greater levels of mental effort to turn within the elevated virtual environment, which aligns with previous published reports showing that individuals devote added attentional resources to standing and walking at high elevations [26]. At high elevations, people tend to direct their attention toward movement processes, threat relevant stimuli, and self-regulatory strategies when performing a dynamic postural task (rise to toes) [11]. However, given the lack of detailed measures of affective responses, it is unclear what features of the turning task required more mental effort while walking in the threatening environment. In future, researchers should further evaluate the perceptual-cognitive processes necessary to regulate complex movement behavior within threatening environments through direct and indirect measures of attention.

We analyzed associations between height-induced changes (mean high–mean low elevation scores) in self-report measures and turning behavior to ascertain whether the direction of effects was consistent across participants. While researchers have shown that changes in simple reaction time correspond to ratings of mental effort [24], none of the self-report measures were correlated with changes in peak turning velocity. One potential explanation for the lack of significant correlations is that peak turning velocity represents a brief portion of the motor task, whereas the affective ratings were based on average perceptions after completing blocks of five trials. Such different scales between the two measures may limit the insight traditional analyses can provide. However, strong associations between mental effort, anxiety, and confidence suggest anxious participants may have attempted to regulate their turning performance at high elevation. Measures of overall turning quality are reflective of underlying changes in cognitive and perceptual processing [30], and in the future, researchers should pursue the relationships between turning strategies and affective responses to environmental threat.

Our secondary aim was to determine if the effectiveness of the VR illusion diminished across time. Our findings suggested that changes in turning performance across trials might occur when walking in elevated virtual environments (i.e., positive β coefficients for Trial main effects and interactions), with participants tending to increase their peak turning velocity across trials. A change in turning velocity of approximately 5°/sec per trial, a total of 25° from the first to last trial, may affect experimental results in a clinically meaningful way. A similar magnitude of differences in peak turning velocity is found in comparisons between controls and people who have suffered a mild traumatic brain injury (~15-20°) [31] and those with mild (~28°) and severe

Parkinson's disease (~33°) [32]. Moreover, the Trial effect was only present while participants were undergoing the height illusion, suggesting the changes in speed across trials was not a result of task repetition, but an acclimation to the height illusion. The adaptation across trials revealed in this study aligns with studies demonstrating physiological and postural adaptation to threat across trials using traditional anxiety-inducing paradigms [1]. Habituation across trials is also a concern for researchers seeking to use VR to induce anxiety for research purposes. The validity of the VR illusions and comfort of the participant within the virtual environments may change across trials, potentially damping the effects of anxiety manipulations. Although results confirm that the VR illusion was successful, less than five trials may be ideal for capturing the effects of anxiety before participants habituate to the environment.

4.1 Limitations

Although this study was primarily conducted to determine the feasibility of using more-realistic virtual environments to induce anxiety during a complex movement task, several limitations are worth acknowledging. First, although we included a visual representation of the feet during the walking trials, foot size was not scaled for each participant. We did not observe any major issues with the 'average' virtual foot, but in future researchers should apply a scaling factor to match participants' virtual foot representation to their actual foot size for added comfort within VR environments. Second, we selected one outcome measure of gross motor performance from one point in time, but in future scientists should seek to adopt additional measures of performance such as turning quality, gaze behavior, or head position data to provide a more comprehensive understanding of complex motor behavior. Third, our walkway was linear and demanded only a single 180° turn, but it would be interesting to manipulate the complexity of virtual walkways and observe varying degrees of turning to generalize the results to more typical walking behavior. Fourth, we did not include any measures of physiological responses that could further support our results; however in our on-going program of work we are including measures of heart rate similar to previous published reports that have quantified changes in physiological arousal due to anxiety [13,14]. Fifth, to reduce the number of self-report measures throughout the experiment, we relied on affective ratings that were captured between blocks of five trials. Thus, we are unable to distinguish changes to affect across trials as we did for peak turning velocity. We expect that measuring physiological responses in our future work will help elucidate how affect changes across trials.

5. Conclusions

The virtual height illusion successfully induced behavioral and self-reported changes as intended. Participants demonstrated potential habituation to the height illusion across five trials, which could influence future research procedures/analysis. Our approach shows promise for investigating anxiety-induced changes to locomotor behavior in future studies using older adult populations. Moreover, this method holds significant translational impact for clinical settings and in-home application to enhance interventions for those with a fear of falling.

Conflict of Interest Statement

The authors have no conflict of interest to report.

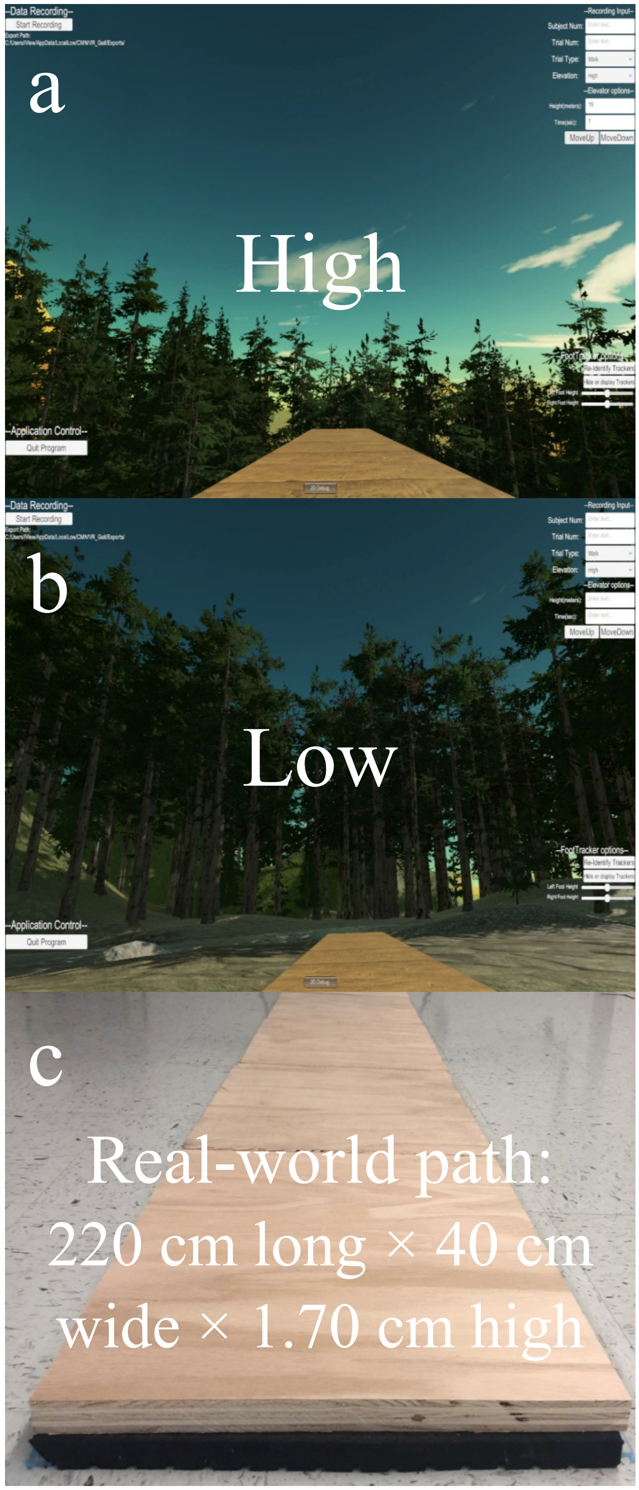

Figure 1a-c. Images captured from the high (a.) and low (b.) elevation settings in the VR paradigm and the matched real-world path (c.). Note, the VR view is from the researcher's perspective and the participant interface does not include the menus pictured here.

Table 1. Mixed effect regression parameter estimates for peak lumbar turning velocity as a function of Height, Speed, and Trial.

Random-Effects	*Variance*	*SD*			
Speed:Subject	190.00	13.78			
Height:Subject	767.60	27.71			
Subject	4018.00	63.39			
Residuals	1115.60	33.25			
Fixed-Effects	*β*	*SE*	*df*	*t*	*p*
Intercept	198.77	21.59	10.49	9.21	**< 0.001**
Height	-17.86	7.41	15.61	-2.41	**0.029**
Speed	28.86	5.11	29.20	5.65	**< 0.001**
Trial	1.88	1.66	170.00	1.13	0.260
Height × Speed	-11.64	4.07	170.00	-2.86	**0.005**
Height × Trial	1.39	1.67	170.00	0.84	0.405
Speed × Trial	1.84	1.66	170.00	1.11	0.270
Height × Speed × Trial	4.28	1.66	170.00	2.58	**0.011**

Note: Significance denoted by bolded *p*-value. Parameter estimates: Standard deviation (*SD),* slope estimate (*β*), standard error (*SE*), degrees of freedom (*df*), t-value (*t*), and p-value (*p*).

Table 2. Mixed effect regression parameter estimates for self-reported cognitive anxiety (worry), somatic anxiety (tension), confidence, and mental effort as a function of Height and Speed.

Fixed-Effects	*β*	*SE*	*df*	*t*	*p*
Cognitive Anxiety					
Intercept	3.35	0.48	21.99	7.02	**< 0.001**
Height	1.35	0.45	18.18	2.98	**0.008**
Speed	0.05	0.18	10.35	0.28	0.789
Height × Speed	0.05	0.11	9.93	0.48	0.645
Somatic Anxiety					
Intercept	3.58	0.49	10.00	7.18	**< 0.001**
Height	1.48	0.44	10.00	3.37	**0.007**
Speed	-0.03	0.17	10.00	-0.15	0.887
Height × Speed	-0.03	0.08	10.00	-0.30	0.768
Confidence					
Intercept	9.40	4.53	9.99	20.75	**< 0.001**
Height	-1.10	4.03	9.99	-2.73	**0.021**
Speed	-3.90	1.46	1.00	0.00	1.000
Height × Speed	0.00	6.12	9.99	0.00	1.000
Mental Effort					
Intercept	32.63	3.37	21.49	9.68	**< 0.001**
Height	13.13	3.19	18.60	4.12	**< 0.001**
Speed	2.28	1.54	11.52	1.48	0.165
Height × Speed	-1.03	1.08	9.34	-0.95	0.366

Note: Model parameters: slope (*β*), standard error (*SE*), degrees of freedom (*df*), t-value (*t*), p-value (*p*). Note that all models included random-effects of Subject, Height:Subject, and Speed:Subject, to account for the within-subject nature of the manipulations, but these statistics are omitted for brevity.

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