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RESEARCH ARTICLE

# The effect of mobility-related anxiety on walking across the lifespan: a virtual reality simulation study

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## Abstract

Older adults who report a fear of falling are more likely to subsequently fall, yet, some gait anxiety-related alterations may protect balance. We examined the effect of age on walking in anxiety-inducing virtual reality (VR) settings. We predicted a high elevation-related postural threat would impair gait in older age, and differences in cognitive and physical function would relate to the observed effects. Altogether, 24 adults (age (y) = 49.2 (18.7), 13 women) walked on a 2.2-m walkway at self-selected and fast speeds at low (ground) and high (15 m) VR elevation. Self-reported cognitive and somatic anxiety and mental effort were greater at high elevations (all $p < 0.001$), but age- and speed-related effects were not observed. At high VR elevations, participants walked slower, took shorter steps, and reduced turning speed (all $p < 0.001$). Significant interactions with age in gait speed and step length showed that relatively older adults walked slower ($\beta = -0.05$, $p = 0.024$) and took shorter steps ($\beta = -0.05$, $p = 0.001$) at self-selected speeds at high compared to low elevation settings. The effect of Age on gait speed and step length disappeared between self-selected and fast speeds and at high elevation. At self-selected speeds, older adults took shorter and slower steps at high elevation without changing step width, suggesting that in threatening settings relatively older people change gait parameters to promote stability. At fast speeds, older adults walked like relatively younger adults (or young adults walked like older adults) supporting the notion that people opt to walk faster in a way that still protects balance and stability in threatening settings.

**Keywords** Aging · Falls · Fear of falling · Inertial measurement units · Gait · Peak velocity

## Introduction

An increasing population of older adults, and associated higher rates of falling, continues to place a heavy demand on healthcare resources (Burns and Kakara 2018). Poor self-efficacy related to balance control, sometimes referred to as 'fear of falling,' has emerged as a primary predictor of fall-risk in older adults (Gazibara et al. 2017), as well as a potential target for future interventions (Liu et al. 2018; Whipple et al. 2018). In older adults, self-reported fear of falling, or concerns about falling, are associated with poorer standing balance (Feldman et al. 2019), slower gait speed (Makino et al. 2017), and reduced stepping accuracy (Caetano et al. 2017). Up to 85% of older adults report a fear of falling, often without ever having fallen previously (Hadjistavropoulos et al. 2012). A fear of falling is typically a self-reported outcome that represents 'an anticipatory fear of future probable outcomes' (i.e., a fall). 'Mobility-related anxiety' is a state of physiological and psychological stress associated

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with the performance of mobility tasks (e.g., walking) which is typically worse for people who experience a fear of falling (Ellmers et al. 2022a). The potential protective and detrimental aspects of mobility-related anxiety on older adult mobility have yet to be adequately examined.

When induced by standing or walking on a high-elevation surface in laboratory conditions, mobility-related anxiety leads to a stiffening of standing posture away from an environmental threat (e.g., the edge of the high height surface) (Brown et al. 2006b). During walking older adults demonstrate a mix of slower gait speeds (Gage et al. 2003), faster gait speeds with more missteps (Schaefer et al. 2015), and reduced attention towards relevant visual targets (Ellmers et al. 2020b). Under height-related postural threat, older adults are thought to increase the attention devoted to 'consciously-monitoring' their standing/stepping (Young et al. 2016), impairing effective task prioritization between concurrent cognitive and motor demands (Schaefer et al. 2015). By dedicating more attention, individuals can compensate for any perceived balance difficulties (Ellmers et al. 2022b), avoid obstacles on the path (Brown et al. 2006a), and decrease reactive balance response time. Alternatively, perhaps due to the natural sensory declines that occur with age (i.e., reduced vision and hearing), older adults already use more of their cognitive resource capacity to walk than their younger peers, so devoting attention to walking might take critical resources away from the task at hand (Gage et al. 2003; Young and Williams 2015). For instance, when 'targeting' their steps to a specific position, older adults tend to look away from stepping targets too soon and make more stepping errors, reducing their ability to avoid obstacles in their path (Ellmers et al. 2020b). In everyday life, when a pothole or curb must be avoided along a sidewalk, mobility-related anxiety could therefore lead to compensations that 'distract' older adults, increasing the risk of tripping and/or falling (Young and Williams 2015).

Few published reports exist examining age differences in gait performance in anxiety-inducing settings (for exceptions see, Brown et al. 2002; Gage et al. 2003; Schaefer et al. 2015). Moreover, previous efforts have only included distinct younger (e.g., 18–25 years old) and older adult (e.g., 65–75 years old) groups, rather than examine the effects of age across the lifespan. In this study, we aimed to investigate how mobility-related anxiety influences cognitive-motor control during walking across ages by building upon evidence demonstrating the efficacy of inducing mobility-related anxiety using virtual reality (VR) in younger adults (Raffegeau et al. 2020a, b). A VR high height simulation induces pronounced anxiety levels that can be detected in subjective self-report ratings, as well as objective measures of turning, heart rate variability, and standing balance (Raffegeau et al. 2020a, b). We extend previous research by assessing mobility performance (i.e., walking and turning) and perceived anxiety responses to a VR height illusion as a function of age. Additionally, we include a novel spatial analysis of gait performance (e.g., gait speed, step length, and step width) using commercial tracking sensors placed on the ankle (HTC Vive, v.2, Redmond, WA, USA) and a secondary analysis of turning speed with validated inertial measurement units (APDM Opals, Portland, OR, USA).

Given the propensity for older adults to exhibit larger gait deficits under postural threat settings when compared to young adults (Brown et al. 2002), we predicted that age would be associated with a greater disruption to gait performance in anxiety-inducing (virtual) settings. Because older adults who are at risk of falling exhibit greater mobility deficits during fast (Middleton et al. 2016; Baudendistel et al. 2021) and constrained walking (Schaefer et al. 2015), we further expected that the effect of age on mobility would be greater when participants were instructed to walk at faster speeds in anxiety-inducing settings. Specifically, we predicted that if older adults tend to experience more mobility-related anxiety in anxiety-inducing settings (i.e., balance challenging environments), then an interaction between age and walking elevation would show that increased age would be associated with slower walking speed at virtual high elevation relative to virtual ground-level. We also expected age would be associated with shorter and wider step adaptation from low to high VR elevation. Second, we predicted that relatively older people would exhibit greater deficits in gait performance when asked to increase their walking speed (i.e., decreased capacity for adaptation resulting in a smaller change in walking speed), particularly in anxiety-inducing settings. We expected an interaction between instructed walking speed, walking elevation, and age, supporting the prediction that relatively older adults tend to adopt a more conservative gait strategy when instructed to walk at faster-than-comfortable speeds in anxiety-inducing settings, evidenced by walking at slower speeds and taking wider and shorter steps.

## Methods

### Participants

Altogether, 24 adults (women = 13; mean age: 49.2 years, *standard deviation*: 18.7 years) completed a battery of self-report instruments, assessments of physical function, and cognitive tests. A portion of the young adult participant data included herein has been previously published in a feasibility study using identical protocols (Raffegeau et al. 2020a); however, this study represents a novel set of hypotheses and distinct analyses utilizing a larger, more diverse population. Participants were free of any neurological or physical ailments that impaired balance and agreed to participate through written informed consent. Ethical approval was received from the local Institutional Review Board.

## Individual differences

### CHAMPS Physical Activity Questionnaire

Participants completed the Community Health Activity Monitoring Program for Seniors (CHAMPS) Physical Activity Questionnaire survey to quantify the average amount of moderate physical activity they engaged in each week (Stewart et al. 2000). CHAMPS data were scored as frequency of engagement per week (hours/week).

### Activities balance confidence (ABC) scale

Participants rated their balance confidence during tasks of daily living using ABC, a common method for evaluating fear of falling in older adults (Powell and Myers 1995). Higher scores on the ABC indicate greater impairment.

### Recent falls

All participants self-reported their falls history over the previous 6 months; a fall was defined as 'coming to a lower level unintentionally' (Marrero et al. 2019).

### Dispositional anxiety

Anxiety was assessed using the State-Trait Anxiety Inventory (STAI; Spielberger 2010). Scores range from 20 to 80, with higher scores indicating either greater trait anxiety (i.e., in general) or state anxiety (i.e., on the day of the experiment).

### Physical function

Older adult participants completed three common physical function tests: the Short Physical Performance Battery (SPPB; Lauretani et al. 2019); the Dynamic Gait Index (DGI; Herman et al. 2009); and the Timed Up and Go (TUG; Richardson 1991). The younger adult participants only performed the DGI stair test and the TUG as objective measures of lower limb strength. Higher scores on each of these tests are indicative of poorer physical function.

### Cognitive function

Participants completed two common clinical tests of cognition (i.e., executive functioning), the Stroop Task and the Trial Making Test, which are strongly related to cognitive-motor performance and mobility with age (Ble et al. 2005; Langeard et al. 2021). The version of the Stroop Task used in this study consists of two parts: (1) Congruent, a test of response time, requiring participants to name as many colored letters (e.g., "XXXXX") as possible within 45 s; and (2) Incongruent, a measure of response inhibition, requiring participants to name as many ink colors of mismatched color-words in 45 s (Homack and Riccio 2004). Subtracting scores on Stroop Congruent trial performance from Incongruent trials yields a difference score (Stroop = Stroop Incongruent – Stroop Congruent) representing the interference effect of executive functions that inhibit pre-potent responses, with a more negative score indicating better cognitive flexibility. The Trail Making Test (TMT) consists of two parts: (A) measuring visual scanning and response time; and (B) measuring executive function maintenance and set switching (Arbuthnott and Frank 2000). Subtracting response time on the TMT A test from TMT B yields a difference score (TMT = TMTB – TMTA) representing cognitive flexibility, with higher scores indicating reduced cognitive flexibility.

## Instrumentation and task

Participants wore the HTC Vive (version 2.0, Bellevue, WA, USA) HMD system displaying a $0.4 \times 2.2$ m virtual walkway matched to a real path, as reported previously (Raffegeau et al. 2020a). Participants were fitted with a motion tracker strapped around each ankle (HTC Vive version 2.0, Bellevue, WA, USA) to provide an ongoing representation of where their feet were in the virtual space. Lightweight sensors on the lumbar spine and both forefeet measured movement accelerations at 128 Hz using an internal magnetometer, gyroscope, and inertial sensor (APDM Inc, Portland, OR, USA).

During experimental trials, participants walked and turned 180° along the walkway at their self-selected and 'fastest comfortable' speed in virtual low (ground level) and high (15 m above ground) elevation settings (Fig. 1a, b). To reduce the risk of participants becoming accustomed to the height illusion across time (Raffegeau et al. 2020a), the order of the walking and turning tasks was pseudorandomized and counterbalanced. We used five random sequences for all participants. One older adult voluntarily withdrew from the experiment due to an adverse reaction when exposed to the high elevation simulation and these data were excluded.

After each condition, participants removed the HMD and completed brief self-assessments representing their experience during the preceding block of five trials. The Mental Readiness Form 3 (MRF-3; Krane 2016) was administered to assess cognitive (i.e., worry) and somatic (i.e., arousal) components of anxiety, as well as participants' level of confidence in their ability to complete the task based on an 11-point Likert-scale. Cognitive anxiety ratings were prompted with the root statement 'my thoughts were', with

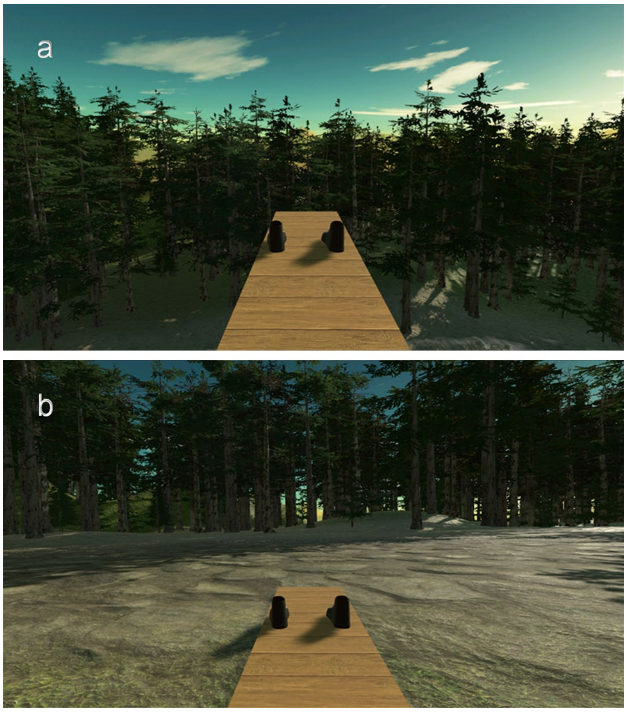


**Fig. 1** **a**, **b** A depiction of virtual environment and foot trackers on walkway at the high (**a**) and low (**b**) elevation settings. Walkway dimensions matched a real-world walkway sized 0.4 m wide × 2.2 m long × 0.05 m high. Figure adapted with permission from Raffegeau et al. (2020a)

responses ranging from 1, 'very calm,' to 11, 'very worried.' Somatic anxiety ratings were prompted by the root statement 'my body feels,' and ranged from 1, 'very relaxed,' to 11, 'very tense.' As part of the MRF-3, participants reported confidence in their ability to complete the task with the root statement 'I am feeling,' and response ranging from 1, 'very confident,' to 11, 'not confident at all'. Participants indicated the level of mental effort required to complete the task using the Rating Scale of Mental Effort (RSME; Zijlstra 1993), which is a 0–150 scale that ranges from '0: absolutely no effort' to '150: extreme effort.'

## Data processing

Step length, step width, and gait speed were calculated per-step using a custom MATLAB script (version R2022b, Natick, MA, USA). Linear position data from the HMD and the two tracking accessories placed on the lateral aspect of both ankles was extracted for each trial. The 3D position of the walkway was recorded in the virtual space by capturing the coordinates of each corner of the physical walkway using a hand controller, matching the coordinates of the real-world walkway to the virtual simulation. In accordance with International Society of Biomechanics Standards, the center and starting point of the walkway was defined as the origin, x was the sagittal path of progression, z was the mediolateral axis, and y was the vertical axis (International Society of Biomechanics Standardization and Terminology Committee 2002).

The HTC Vive collects variable position sampling rates, for example, frame rates for one fast trial range from 89 to 93 Hz, depending on the relative speed of motion and the independent sampling rates of the lighthouses and tracker accessories (Borges et al. 2018). Consequently, we resampled the data to 100 Hz using the *resample* function with linear interpolation. Gaps in position tracking were identified by removing erroneous position data that were recorded below the origin (the walkway) and replacing resultant missing data with spline-filled data points. The gap-filled data were then filtered with a zero-pass fourth order Butterworth filter. Foot contacts were identified as the peak distance between the HMD and each foot tracker and 3D position of the feet and time at each identified peak was extracted as a foot strike (Zeni et al. 2008).

Straight steps were isolated by retaining the steps taken within the central 1.6-m portion of the walkway and removing turning steps from the gait analysis. For each identified foot contact, step length was the absolute distance between the ankle-worn sensors in the anterior posterior direction, and step width was the absolute distance between the sensors in the mediolateral direction for successive steps. Gait speed was calculated as step length divided by the time between two consecutive footfalls. Left and right step values were averaged to represent overall gait performance. Because we had only a few steps for each trial, we calculated the median value for step length, step width, and gait speed. In addition to the position data extracted from the HMD and tracking accessories, acceleration data were collected at the lumbar spine using inertial measurement units (IMUs) from a previously well-validated (Morris et al. 2019) portable system (APDM Opals, Portland, OR, USA). Peak turning velocity was computed from the maximum angular displacement (degrees) at the end of the walkway as participants reversed direction to return to their starting position.

## Data analysis

We used the *fitlme* and *anova* (ANOVA; analysis of variance) functions in MATLAB to analyze linear mixed-effect regression models and type 3 tests for fixed effects, respectively. Separate fully factorial linear mixed-effect regressions (LMERs) were used to evaluate any effect of Age (continuous), Height (low vs. high, categorical), and Instructed Speed (self-selected vs. fast, categorical) on gait speed and peak turning velocity. Because step length and step width might be less sensitive to Age and Height effects when averaged across binary Instructed Speeds (i.e., normal vs fast), Speed for each trial was included as a continuous factor in LMERs models analyzing step length and step width across Age (continuous), Height (low vs high, categorical). All regression models included a fully crossed random effect of participant, participant within height, and participant within speed, that accounted for within-participant variance at each elevation and speed. In all models, we computed the continuous Age factor from reported birthdate and multiplied by 10 to examine effects in age per decade, rather than per year. We then mean-centered Age from the sample grand mean. Categorical Height and Speed factors were centered by contrast coding for ease of interpretation (Height: low = − 1, high = + 1; Speed: self-selected = − 1, fast = + 1). Therefore, the reported beta weights ($\beta$) and respective confidence intervals [CI] (see Supplementary Data) for categorical comparisons can be multiplied by two and interpreted as average mean differences. If needed, continuous speed factors were broken down and interpreted using gaits speed re-centered on the maximum and minimum gait speeds for each participant (i.e., so that other effects can be interpreted at an individual's fastest or slowest speed respectively).

We analyzed self-reported ratings using fully factorial LMERs to determine the effect of Age (continuous), Height (low vs. high, categorical), and Instructed Speed (self-selected vs. fast, categorical) on perceived anxiety, confidence, and mental effort, but no ratings exhibited a normal distribution of residuals in Q–Q plots and histograms. Although LMER is robust to violations of normality, we bootstrapped the values ($N = 1000$) to compare more robust confidence intervals in self-report ratings between low and high VR heights. The significance threshold for all statistical analyses was set at $\alpha = 0.05$.

## Results

### Demographics

Participant scores on balance and cognitive tests are included in Table 1. In addition to the range of ages represented (age range 18.9–71.1 years), participants had considerable variability in their trait (STAIT-T range 23–60) and state (STAI-S range 20–54) anxiety scores, and in their movement-specific anxiety scores (GSAP range: 11–30). Reports of physical activity (CHAMPS range 0–24.5), as well as clinical tests of dynamic gait (DGI stair climb time: 9.6–17.6 s) and physical function (SPPB chair stand time range 5.8–16.7 s), varied within the sample, although balance confidence was similar across individuals (ABC range: 90–100). Finally, tests of cognitive function (i.e., Stroop, TMT) demonstrated substantial variability (see Table 1).

**Table 1** Participant characteristics ($n = 24$)

| | Mean | SD | Range | |
|---|---|---|---|---|
| | | | Lower limit | Upper limit |
| Age (years) | 49.2 | 18.7 | 18.9 | 71.1 |
| Height (cm) | 170.3 | 14.6 | 125.0 | 193.5 |
| Mass (kg) | 88.3 | 23.2 | 54.9 | 145.0 |
| Leg length (mm) | 918 | 52 | 838 | 1060 |
| Gender (women/men) | 13 | 11 | – | – |
| Fallers (number) | 5 | – | – | – |
| STAI-T | 33 | 8 | 23 | 60 |
| STAI-S | 35 | 12 | 20 | 54 |
| ABC | 95 | 3 | 90 | 100 |
| GSAP | 15 | 5 | 11 | 30 |
| CHAMPS (h/week) | 10 | 8 | 0 | 24.5 |
| SPPB chair stand (s) | 10.5 | 2.8 | 5.8 | 16.7 |
| DGI stair time (s) | 13.2 | 2.2 | 9.6 | 17.6 |
| TUG (s) | 8.8 | 1.1 | 6.3 | 10.6 |
| Stroop Congruent | 79 | 14 | 50 | 105 |
| Stroop Incongruent | 53 | 14 | 32 | 80 |
| TMT-A (s) | 26.2 | 9.4 | 14.8 | 54.3 |
| TMT-B (s) | 60.9 | 22.1 | 28.6 | 128.0 |

Note: Fallers = number of participants reporting a fall in the previous 6 months. ABC = Activities Balance Confidence Scale; STAI-T/S = State-Trait Anxiety Inventory; GSAP = Gait Specific Attentional Profile; CHAMPS = Comprehensive High-Level Activity Mobility Predictor; $SPPB_{CS}$ = chair stand time; $DGI_{Stair}$ = stair climb time; TUG = Timed Up and Go Test; $Stroop_{Con}$ = Stroop Test Congruent; $Stroop_{Inc}$ = Stroop Test Incongruent; TMT-A/B = Trails Making Test A and B; SD = standard deviation; cm = centimeters; kg = kilograms; mm = millimeters; s = seconds; h/week = hours per week of moderate to intense physical activity

### Spatiotemporal gait outcomes

The analysis of gait speed indicated significant main effects for Height ($\beta$ [CI] = − 0.09 [− 0.12, − 0.05], $p < 0.001$), Instructed Speed ($\beta$ [CI] = 0.14 [0.11, 0.17], $p < 0.001$), and a small, but significant effect of Age ($\beta$ [CI] = − 0.04 [− 0.08, − 0.00], $p = 0.048$). A three-way interaction effect between Age, Height, and Instructed Speed ($\beta$ [CI] = 0.01 [0.00, 0.01], $p = 0.011$) was explored further. At low elevation the effect of Age × Speed was not significant ($\beta$ [CI] = − 0.00 [− 0.01, 0.00], $p = 0.391$). At high elevation, the effect of Age × Speed was significant ($\beta$ [CI] = 0.01 [0.00, 0.02], $p = 0.015$). Exploring this interaction further showed at high elevation and self-selected speeds, the effect of Age was significant ($\beta$ [CI] = − 0.05 [− 0.09, − 0.01], $p = 0.024$); relatively older adults walked ~ 10 m/s slower than their younger peers at high heights and self-selected speeds. At high elevation and fast speeds, the effect of Age was no longer significant ($\beta$ [CI] = − 0.01 [− 0.07, − 0.05], $p = 0.844$). The results support gait speed increased from self-selected to fast walking by approximately 0.26 m/s, supporting participants walked faster when instructed to do so. From low to high VR height, gait speed decreased approximately 0.18 m/s, surpassing a clinically meaningful decline in walking speed of 0.13 m/s (Perera et al. 2006). The significant interaction showed that age effects on walking were only detected at self-selected speeds, since both groups increased gait speed similarly during fast walking conditions.

The analysis of step length revealed main effects of Height ($\beta$ [CI] = −0.04 [−0.07, −0.02], $p < 0.001$), and Speed (continuous; $\beta$ [CI] = 0.28 [0.25, 0.30], $p < 0.001$), but no significant effect of Age ($\beta$ [CI] = −0.00 [−0.03, −0.01], $p = 0.327$). Interaction effects were superseded by a three-way effect between Age, Height, and Speed, ($\beta$ [CI] = 0.02 [0.01, 0.03], $p = 0.002$) (Fig. 2). Exploring the interaction by

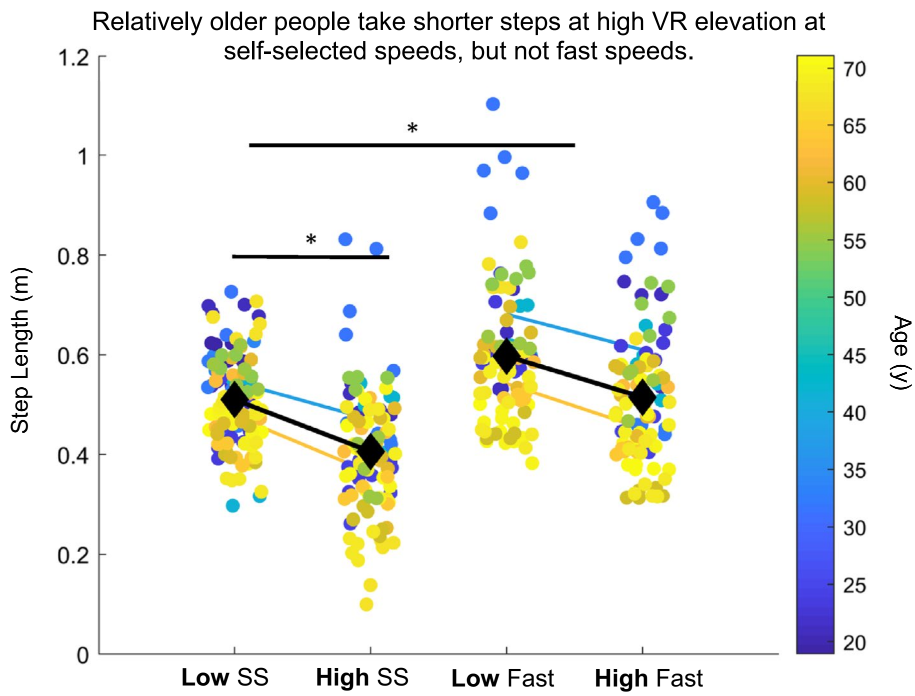


**Fig. 2** The median step length for each participant during each trial at low and high VR elevation and at self-selected (SS) and fastest comfortable (Fast) speeds (i.e., participants colored by age, mapping youngest to oldest from blue to yellow; see right bar). Black diamonds indicate condition means, black lines illustrate the slope of the change in step length across conditions. Post-hoc tests of the Age × Speed × Height interaction are indicated by asterisks reflecting significant condition effects ($p < 0.001$) and colored lines (age mapping split into median younger (blue line) and older (orange line) values) illustrating Age effects are detected in changes to step length from low to high heights at self-selected speeds, but not fast speeds (Table 2)

**Table 2** Full LMER model regression: step length

| Fixed effects | DoF | *F* | *p* | *β* | 95% confidence | |
|---|---|---|---|---|---|---|
| | | | | | Lower limit | Upper limit |
| Intercept | **1, 607** | **66.56** | **< 0.001** | **0.30** | **0.23** | **0.38** |
| Age | **1, 607** | **3.89** | **0.049** | **− 0.04** | **− 0.08** | **0.00** |
| Height | **1, 607** | **6.06** | **0.014** | **− 0.02** | **− 0.04** | **0.00** |
| Speed | **1, 607** | **49.87** | **< 0.001** | **0.28** | **0.20** | **0.36** |
| Age × Height | **1, 607** | **11.70** | **< 0.001** | **− 0.02** | **− 0.03** | **− 0.01** |
| Age × Speed | 1, 607 | 1.21 | 0.273 | 0.02 | − 0.02 | 0.07 |
| Height × Speed | **1, 607** | **0.72** | **< 0.001** | **0.00** | **− 0.02** | **0.02** |
| Height × Age × Speed | **1, 607** | **10.01** | **0.002** | **0.02** | **0.01** | **0.03** |

| Random effects | *β* | 95% confidence | |
|---|---|---|---|
| | | Lower limit | Upper limit |
| Intercept (std) | 0.17 | 0.13 | 0.23 |
| Speed (corr) | − 0.88 | − 0.95 | − 0.75 |
| Speed (std) | 0.18 | 0.13 | 0.25 |
| Group | 0.05 | 0.05 | 0.05 |

Note: Significant tests are bolded; Age = per decade, Speed = continuous factor; *DoF* = degrees of freedom; *F* = Type 2 ANOVA test *F* value; *p* = probability value for significance test; *β* = unstandardized beta weight breaking down the speed effects by recentering on minimum and maximum gait speeds showed that at low heights and at minimum speeds, there was no effect of Age on step length ($\beta$ [CI] = − 0.02 [− 0.06, 0.01], $p = 0.131$) while at low heights and at maximum speeds the effect of Age was significant ($\beta$ [CI] = − 0.04 [− 0.05, − 0.00], $p = 0.014$), showing relatively older people took shorter steps at their fastest speeds. At high heights and minimum speeds, the effect of Age was significant ($\beta$ [CI] = − 0.05 [− 0.08, − 0.02], $p = 0.001$), indicating relatively older adults take shorter steps to walk in anxiety-inducing settings, but this effect was not significant at maximum speeds ($\beta$ [CI] = − 0.02 [− 0.05, 0.01], $p = 0.227$) (Fig. 2). To ensure our effects on step length were not dependent on leg length, we examined step length normalized by each person's averaged left and right leg length, and report these results in our Supplementary Data (see Supplementary Data Table B). The results from the normalized step length data can be interpreted identically. We have chosen to include the analysis and visualization of the raw step length data for ease of interpretation.

The analysis of step width revealed a main effect of Speed (continuous; $\beta$ [CI] = − 0.05 [− 0.06, − 0.03], $p < 0.001$), but not Age (continuous; $\beta$ [CI] = 0.00 [− 0.01, 0.02], $p < 0.001$), and no other significant effects were detected (see Supplementary Data Table C) (all $p$'s > 0.281).

### Peak turning velocity

The results for peak turning velocity indicated significant main effects of Height ($\beta$ [CI] = − 16.83 [− 24.18, − 9.47], $p < 0.001$) and Instructed Speed (categorical; $\beta$ [CI] = 51.46 [42.23, 60.69], $p < 0.001$), but not Age ($\beta$ [CI] = − 8.41 [− 19.42, 2.59], $p = 0.133$) (Supplementary Data Table D). Peak turning velocity slowed down by about 32 degrees per second from low to high elevation and increased by about 100 degrees per second when individuals are instructed to turn at faster speeds. An Age × Instructed Speed interaction was detected ($\beta$ [CI] = − 6.12 [− 11.08, − 1.16], $p = 0.015$). Relatively older participants showed smaller increases in peak turning velocity when instructed to turn at their fastest comfortable pace compared to self-selected speed. Although the main effect of Age was not statistically significant ($p = 0.176$), in the sample peak turning speed decreased by about 16 degrees per second each decade, which may help to explain why the Age × Speed interaction effect was significant. No interaction effects with Height were detected or explored further (all $p$'s > 0.184).

### Self-reported ratings

The full LMER model analyzing self-reported outcomes showed no effects of Age (all $p > 0.388$), or Instructed Speed (all $p > 0.091$). A main effect of Height was detected for all four outcomes (worry: $\beta$ [CI] = 1.20 [1.200, 1.2004], $p < 0.001$, arousal: $\beta$ [CI] = 1.25 [1.259, 1.260], $p < 0.001$, confidence: $\beta$ [CI] = − 0.99 [− 0.990, − 0.991], $p < 0.001$, mental effort: $\beta$ [CI] = 11.40 [7.710, 15.010], $p < 0.001$). At high elevation (compared to low), participants reported greater worry (mean difference = 2.4, standard deviation = 2.1), perceptions of increased physiological arousal (mean difference = 2.6, standard deviation = 2.2), less confidence in their ability to perform the task (mean difference = − 2.1, standard deviation = 1.9), and exerted more mental effort on walking (mean difference = 23.9, standard deviation = 18.4) (see Supplementary Data Table D).

## Discussion

We examined age-related changes to gait when walking in an anxiety-inducing virtual environment (i.e., simulated walkway 15 m above ground), and challenged mobility-related anxiety by instructing participants to walk at their self-selected and fastest comfortable speed. We hypothesized that age would be associated with larger changes to gait performance in the anxiety-inducing setting (VR high elevation), and that those changes would be greater when participants walked at faster speeds. We predicted relatively older adults would take more conservative steps (e.g., slower gait speed, shorter and wider steps) to cope with height-related postural threat, especially at faster gait speeds.

In a healthy adult sample with a large age range (approximately 19–71 years old), participants walked at virtual elevation by decreasing gait speed and peak turning velocity while taking shorter steps. In contrast to our hypotheses, age did not ubiquitously impair gait performance from low to high virtual elevation or from self-selected to fast instructed speeds. There was a null effect of Age detected on step width at high elevation, and null Age effects were detected when participants walked at fast speeds and high elevation. The changes to gait speed and step length partially supported our hypotheses, evidenced by an Age × Height × Speed interaction effect, suggesting that relative age slowed gait speed and shortened step length at comfortable speeds, and that effect was larger in anxiety-inducing settings. However, performance at faster speeds did not support our predictions that Age effects would be exaggerated when participants were instructed to walk faster and the effect of Age disappeared at fast speeds. Self-reported responses support the effectiveness of the VR height illusion to elicit feelings of anxiety, as well as reducing confidence and increasing mental effort on the task. However, no age- or task-related differences were observed in measures of perception.

## Using VR to simulate anxiety-inducing settings

Our results broadly support the efficacy of manipulating anxiety using virtual height simulation. At high VR heights participants slowed their step speed, shortened their steps, and decreased their peak turning speed. Self-reported ratings supported our expectation that the height illusion would pose an increased balance threat leading to greater cognitive and somatic anxiety, less confidence in walking ability, and more mental effort dedicated to walking and turning at simulated high heights. The extent to which mobility was impaired from low to high elevation was generally at a clinically meaningful and detectable level. For example, the mean difference in peak turning velocity from low to high heights was ~ 34°/s and a difference of 6.62°/s in natural turns distinguishes non-fallers from recurrent fallers (Mancini et al. 2016).

Changes in postural control in the real-world are sensitive to visual input (Mayo et al. 2011), specifically changes in view of the horizon. Therefore it could be argued that the present changes in gait at simulated high heights may be a result of differences in visual input in VR, specifically the view of the horizon line at high versus low elevation (Mayo et al. 2011). However, the interactions between vestibular input (or a lack thereof) and visual flow in VR are not the same as physically lifting participants to a high elevation, making it difficult to draw conclusions from real-world manipulations. The VR illusion depends on visual feedback alone and the novelty of the present study is that we are able to detect anxiety-related changes to posture (Raffegeau et al. 2020b) and gait (Raffegeau et al. 2020a) without actually lifting participants to elevation. However, we are unable to replicate similar vestibular input as in the real-world to compare how visual flow interacts with vestibular feedback for balance control in VR. In the future, researchers should explore differences in visual sampling due to visual-vestibular interactions in real versus simulated high heights using eye tracking.

The only spatiotemporal outcome that was not statistically influenced by the height illusion was step width. Additionally, step width outcomes revealed no differences in step widths with older age, on average, contrary to previous reports of age-differences on gait (Aboutorabi et al. 2016). Past studies reporting age-effects on gait in anxiety-inducing setting challenged balance by narrowing the width of the walkway at high elevation, and therefore did not report step width as a primary outcome for comparison (Brown et al. 2002; Gage et al. 2003). However, some fail to detect age-related differences in controlling step width when hypothesized (Shkuratova and Taylor 2008). A lack of differences in step width as a result of anxiety-inducing VR settings might be related to the fixed width (40 cm) of the walkway limiting any range of step width on the path, despite demonstrating height-related effects on standing balance on a similar sized walkway (Raffegeau et al. 2020b). Matching the real-world path to the VR simulation enhanced the verisimilitude of the virtual height illusion, however, our path may have been narrow enough that participants avoided large changes in step width across conditions.

## Age-related changes in mobility outcomes

We predicted that age would ubiquitously affect gait performance at high elevation and at fast speeds, supporting that older adults tend to exhibit greater mobility-related anxiety within balance threatening environments. Our results only partially supported our predictions, as age-associated changes to gait performance were limited to gait speed and step length at self-selected speeds. The Age × Height × Speed interaction effect detected in step length suggests that age is associated with gait compensations that preserve stability in anxiety-inducing settings. Without changing step width, taking slower and shorter steps to walk at a high elevation demonstrates a balance strategy specific to relatively older participants at high VR heights. Taking shorter steps enhances balance control with more discrete steps that enable more rapid adjustments in case of an external perturbation (Hak et al. 2013). Taking slower and shorter steps increases time to take in visual information and adds to sensory input gathered from each step (Bruijn and Van Dieën 2018), which may be particularly important for balance control for relatively older adults who have reduced sensory acuity (Duran-Badillo et al. 2020). Models predicting head stability during older adult gait, key for stabilizing the visual platform, are predicted by sensorimotor function, self-reported fear of falling, and shorter step length (Latt et al. 2008), supporting that aspects of sensory function may drive the age-related adaptations to gait observed at high VR heights.

Our prediction that walking faster in settings that threaten balance would elicit greater age-related gait deficits was not supported. It appears that at any age, participants are more likely to increase cadence than take longer steps when increasing their walking speed at high VR elevation. Such a strategy might indicate that individuals have a greater risk tolerance for temporal, compared to spatial, changes to gait in balance threatening environment, perhaps as a means of increasing sensory input in a high-risk setting (Bruijn and Van Dieën 2018). But walking faster than normal presents a considerable challenge for those with mobility impairments (Callisaya et al. 2017), as well as individuals at risk of falling (Middleton et al. 2016) and may not be a viable strategy for more impaired older adults. Although fast walking presents a challenge for pre-mobility impaired older adults (Baudendistel et al. 2021; Raffegeau et al. 2022), instructing participants to walk at their fastest comfortable speed eliminated the effects of age in the present study. In the future, researchers should include more impaired older adults to test how impaired mobility would influence their speed in high-risk environments.

Although the simulated elevation in the current study was much farther from the ground (i.e., 15 m high) compared to real-world studies [e.g., 0.60 m high in Brown et al. (2002, 2006b)], we speculate that either younger adults in the virtual environment began to walk like older adults at high VR heights and at fast speeds, or that shifting focus to the external goal of walking faster benefitted older adult performance at high VR heights. Evidence quantifying age effects on walking at real-world high elevation partially agrees with our results. For instance, while no interactions with age were detected in gait performance due to elevation or walking constraint (narrow path walking, in this case), older adults decreased gait speed during constrained walking at high elevation as compared to young adults (~20% slower), and the effect was meaningful but it was not statistically significant (Brown et al. 2002). Age differences were significant between groups at the joint level of gait kinematics, but summative gait parameters were not substantively affected by age differences, lending support to our interpretation that older adults adapt summative gait performance metrics (e.g. speed and cadence) like younger adults in high-risk settings (Brown et al. 2002). While dual-task walking on an elevated walkway (i.e. walking while performing a concurrent reaction time task), age differences are only detected in concurrent reaction time responses at high heights (Gage et al. 2003). In accord with the present results, older adults adapted their walking performance during the dual-task and the height manipulation similar to young adults (Gage et al. 2003). Perhaps comparisons of age effects at high elevation only detect age-related differences during a more cognitively demanding mobility task like dual-task walking.

In the present study, relatively younger adults may have exhibited optimal performance by adopting shorter steps and increasing cadence to gain faster speeds at high VR heights, like their relatively older peers. Alternatively, older adults may have already been dedicating more cognitive resources to the walking task at high VR heights (Ellmers et al. 2020a), supported by the Age × Height × Speed effect on step length. When participants were instructed to increase their walking speed, they may have shifted focus to the external goal of walking faster, eliminating the effects of age on step length. Young healthy participants who shift their focus of attention from internal to external factors typically improve motor performance (Wulf 2007), attributed to added reliance on 'automatic control' processes. In contrast, instructions with internal focus degrades older adult gait targeting performance in anxiety-inducing (high elevation) settings (Ellmers and Young 2019). In the present study, instructions to focus externally on speed could counteract the internal monitoring and conscious movement processing older adults were using to compensate at high VR heights (Ellmers et al. 2019). Shifting their attention from an internal to an external focus (i.e., to walk faster) may have helped older adults compensate for their conscious movement processing, benefitting motor performance (Chiviacowsky et al. 2010). Evidence suggests that variation in instruction can influence self-selected gait speeds for healthy adults in laboratory settings (Brinkerhoff et al. 2022), warranting further exploration of the cognitive and motor implications of instructing participants to walk faster. We hope that in the future, researchers will investigate attention-related aspects of speed manipulations in mobility studies.

No statistical age differences were detected in self-reported measures of the perceived effects of the virtual height illusion. This finding is encouraging because it supports the claim that our resultant age differences (or lack thereof) in gait performance are not a result of age-related differences in using VR technology itself. Although our oldest participant was a healthy, active older adult, these results corroborate other evidence that immersive, head-mounted VR is well-tolerated in healthy older adults (Delgado and Der Ananian 2020), and it may be a viable tool to promote healthy aging in the future (e.g., by way of training under various environmental threats to stability). As age was not associated with many changes in motor performance from low to high VR elevation, we speculate that individual differences might contribute to associations (or lack thereof) our outcomes. However, we did not have sufficient sample size to statistically evaluate the influence of individual differences on these results. We hope future studies will build on this work to improve understanding of how demographic characteristics (e.g., cognitive acumen, physical activity) influence motor performance in anxiety-inducing settings.

## Limitations

Several limitations are worth acknowledging. First, the older adults that were recruited were very functional, and due to the region where our study was conducted, most of our sample was Caucasian, well-educated, and active. Second, our oldest older adult was 73 years, representing a relatively younger contingent of older adults. As a result, there was greater homogeneity in behavior across the sample than initially expected. We anticipate that larger anxiety-induced motor deficits would be detected among older-older adults (i.e., > 75 years), those with a substantive fear of falling and/or history of falls, or for individuals with trait anxiety and/or acrophobia. Third, we included data from one young adult (34 years) and four participants over 60 years of age who reported falling in the previous 6 months, thus some variation in our results may be a result of including five participants with a recent history of falls. Because of the relatively young and healthy nature of our sample, the researchers opted to include all participants that reported a fall, whether younger or older. Although we suggest that in future researchers should compare fallers and non-fallers, we were unable to recruit a large enough sample for this comparison. Fourth, and relatedly, it remains unclear if immersive VR could be used in more impaired older adults, particularly given that one older adult withdrew because of a severe panic response to the high elevation simulation. Perhaps longer acclimation periods and increased safety precautions could allow these methods to be replicated using individuals with significant mobility deficits and/or a fear of falling in future research. Finally, we acknowledge that caution must be taken when interpreting research findings based on the sample size reported. During the COVID-19 pandemic, attempts to enroll an additional 10 participants and/or conduct remote data collections were not successful. Research on age-related differences in gait and postural control on elevated walkways has typically recruited a wider disparity amongst younger (e.g., 20–30 years old) and older adult (e.g., 65–75 years old) groups (Brown et al. 2002, 2006a, b; Gage et al. 2003; Schaefer et al. 2015). However, by examining age effects continuously rather than drawing conclusions from between-group differences, the findings presented may better generalize to future research in larger and more diverse populations.

## Conclusions

We present findings supporting that aging is associated with specific gait changes to maintain balance in threatening settings. Our results indicate that healthy aging is associated with decreasing self-selected speed and taking shorter and more frequent steps in anxiety-inducing virtual environments, a strategy that enhances gait stability and sensorimotor input. However, age did not affect all aspects of gait performance under simulated balance threats, contrary to our expectations, demonstrated by a null effect of age while walking at faster speeds. Future work will address how age influences the performance of cognitively demanding tasks of daily living with added threats to balance. This study provides further evidence that VR can induce anxiety about mobility across the lifespan, and therefore, serves as a tool to investigate anxiety-related processes during mobility for those most vulnerable to falling.

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**Author contributions** All authors contributed to the experimental design and project conceptualization. Data collection and management was completed by MC and TER. BTE designed and updated the VR program throughout the duration of the study. TER and PCF were responsible for data processing, assisted by MC. Figures and tables were created by MC and TER. Statistical analyses were completed by TER and KRL. TER, MC, BF, WY, and AMW contributed to writing the first draft and TER managed the revisions. All authors approved of the final version.

**Data availability** The data and analysis from this project are available upon reasonable request.

## Declarations

**Conflict of interest** The authors report no conflict of interest. Material has been reviewed by the Walter Reed Army Institute of Research. There is no objection to its presentation and/or publication. The opinions or assertions contained herein are the private views of the author, and are not to be construed as official, or as reflecting true views of the Department of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in AR 70–25.

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