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The influence of false interoceptive feedback on emotional state and balance responses to height-induced postural threat

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ABSTRACT

Postural threat elicits a robust emotional response (e.g., fear and anxiety about falling), with concomitant modifications in balance. Recent theoretical accounts propose that emotional responses to postural threats are manifested, in part, from the conscious monitoring and appraisal of bodily signals ('interoception'). Here, we empirically probe the role of interoception in shaping emotional responses to a postural threat by experimentally manipulating interoceptive cardiac feedback. Sixty young adults completed a single 60-s trial under the following conditions: Ground (no threat) without heart rate (HR) feedback, followed by Threat (standing on the edge of a raised surface), during which participants received either false heart rate feedback (either slow [n = 20] or fast [n = 20] HR feedback) or no feedback (n = 20). Participants provided with false fast HR feedback during postural threat felt more fearful, reported feeling less stable, and rated the task more difficult than participants who did not receive HR feedback, or those who received false slow HR feedback (Cohen's d effect size = 0.79 – 1.78). However, behavioural responses did not significantly differ across the three groups. When compared to the no HR feedback group, false slow HR feedback did not significantly affect emotional or behavioural responses to the postural threat. These observations provide the first experimental evidence for emerging theoretical accounts describing the role of interoception in the generation of emotional responses to postural threats.

1. Introduction

Fear and anxiety about falling are highly prevalent in older adults (Scheffer et al., 2008). These emotional states can lead to a range of negative outcomes, including disrupted balance performance and increased risk for falls (Ellmers et al., 2023a; Young & Williams, 2015). Although some level of fear and anxiety about falling may reflect a protective response to a perceived postural threat (Ellmers et al., 2022), many older adults will experience high levels of fear and anxiety in situations of comparatively low postural threat (Ellmers et al., 2023a; Delbaere et al., 2010). Such 'maladaptive' emotional response can lead to overly-cautious behaviour which may increase the likelihood of falling (Ellmers et al., 2023a, 2023b; Delbaere et al., 2010). Researchers have therefore sought to identify the mechanisms through which postural threats trigger an emotional response, as this may help identify the aberrant processes that lead to an individual experiencing maladaptive levels of fear and anxiety about falling.

It is firmly established that interoception (i.e., the perception of the internal state of our body [Craig, 2002]) is a core facet in shaping our emotional experiences (Critchley & Garfinkel, 2017; Seth & Friston, 2016). Recent work has built upon early theories linking physiological changes and emotion (e.g., James-Lange and related theories (Dewey, 1894)). Specifically, LeDoux's influential 'two-system' model proposes that fear and anxiety reflect the integration of internal awareness of brain and bodily (threat-related) signals with information about the external situation (LeDoux, 2013, 2014; LeDoux & Pine, 2016). Building on this theoretical understanding, a new conceptual framework proposed by Ellmers et al. (2022, 2023a) contends that emotional responses to postural threats are manifested, in part, from the conscious monitoring and appraisal of bodily signals (e.g., increased arousal, heart rate [HR], trembling or tense muscles etc.) when exposed to a postural threat. As Ellmers et al. (2022) write, "postural threats will trigger a series of subcortical (or, 'automatic') defensive responses that are then consciously interpreted and integrated with one's appraisal of the situational context […] If the situational context is appraised as being likely to cause harm, and the individual interprets the accompanying bodily signals to indicate that they are fearful (and/or anxious), then a conscious emotional response will be triggered" (p. 8). Although this

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stance is supported by indirect evidence (Ellmers et al., 2022), the direct role of interoception in the formation of emotional responses to postural threats has not yet been directly tested.

Supportive evidence for the importance of interoception in shaping emotional states more broadly is, however, highlighted by studies that use exogenous manipulations of interoceptive feedback. For instance, false fast HR feedback (i.e., providing false awareness of an exaggerated physiological response) has been found to alter the emotional salience of neutral faces (Gray et al., 2007), increase perceived physical effort during exercise (Iodice et al., 2019), and increase anxiety during stressful situations (Costa et al., 2016; 2019). The tight coupling between false feedback about interoception and emotions suggests that it might be possible to modulate emotional response to a postural threat by misleading people into believing that their HR is either fast or slow (Ellmers et al., 2022; 2023a). Such findings could be used to modify 'maladaptive' emotional responses to postural threats in older adults (Ellmers et al., 2023a, 2023b).

Using a false interoceptive feedback paradigm, we examined whether the presentation of false cardiac feedback could influence emotional states and balance control when exposed to a postural threat (raised support surface). We predicted that participants provided with slow HR feedback would feel less fearful when exposed to a postural threat, which would be accompanied by attenuated changes in threat-related balance control. In contrast, we expected that the fast HR feedback group would experience the opposite effect: an increase in fear and more pronounced changes in postural control (specifically, smaller amplitude and higher frequency postural adjustments, indicative of an enhanced threat-related 'postural stiffening' response [Adkin & Carpenter, 2018]) when exposed to a threat.

2. Methods

2.1. Participants and sample size estimation

Power analysis (G*Power, v3.1.9.4) showed that for a repeated measures ANOVA a minimum of 42 participants ($n = 14$ per group) would be required to be able to detect a significant within-between interaction of medium effect size (assuming 1-β = 80 %, α = 0.05, Cohen's f = 0.25 [standardized medium effect size], three groups, and two within-subject conditions). Whilst previous research has reported a large effect size of false HR feedback effects on state anxiety (Costa et al., 2016), we chose a more conservative medium effect size estimate because the relatively low number of investigations will inherently increase the uncertainty of the true population estimate.

Following baseline assessment (no threat condition), 60 healthy young adult participants were randomly assigned to one of three groups: (i) slow HR feedback ($n = 20$), (ii) fast HR feedback ($n = 20$), or (iii) no HR feedback ($n = 20$) (Table 1). All participants initially completed a health screening questionnaire to assess eligibility for the study. Inclusion criteria were age between 18 and 40 years. Exclusion criteria were self-reported history of psychiatric, neurological, cardiovascular or pulmonary diseases, orthopaedic pathology or musculoskeletal dysfunctions. Potential participants were invited to volunteer in a research study that examined the "physiological responses to postural threat". Interested participants were told that at some point during their session, they may "hear their heart rate as it was recorded". Participants provided written, informed consent prior to data collection. The experimental procedures were carried out in accordance with the standards outlined in the declaration of Helsinki (1964) and the study received approval by the institutional ethics committee (Application ID: P144640).

Table 1
Mean and SD participant characteristics.

	Slow HR feedback (*n*=20)	Fast HR feedback (*n*=20)	No HR feedback (*n*=20)
Women (*n*)	7	7	5
Age (years)	21.3 ± 2.7	21.5 ± 2.6	25.9 ± 6.2
Stature (m)	1.73 ± 0.11	1.75 ± 0.11	1.73 ± 0.16
Mass (kg)	73.2 ± 14.9	78.2 ± 19.8	76.6 ± 19.0
STAI-T	38.6 ± 8.2	38.2 ± 9.4	38.4 ± 8.7
MAIA-Noticing	3.10 ± 0.77	2.95 ± 0.91	3.13 ± 0.86
MAIA-Listening	1.95 ± 0.60	1.94 ± 0.65	2.03 ± 0.66

MAIA; Multidimensional Assessment of Interoceptive Awareness, STAI-T; State Trait Anxiety Inventory

2.2. Questionnaires

During the visit, we first assessed participants interoceptive sensibility (belief in interoceptive abilities [Garfinkel et al., 2015]) using the Multidimensional Assessment of Interoceptive Awareness (MAIA) to ensure parity between experimental groups (Calì et al., 2015; Mehling et al., 2012). The MAIA is composed of 32 items on a 6-points Likert scale, in which the participant has to rate "how often each statement applies to you generally in daily life," with ordinal responses coded from 0 ("never") to 5 ("always"). For the purpose of the present study, we focussed on the Noticing (awareness of uncomfortable, comfortable, and neutral body sensations) and Body Listening (active listening to the body for insight) MAIA subscales, which relate directly to bodily processes (Iodice et al., 2019). The score for each subscale is calculated by averaging the scores of its individual items, and can range from 0–5, with greater scores indicating greater self-reported interoception sensibility. Given the association between trait anxiety and interoception (Büttiker et al., 2021; Mallorquí-Bagué et al., 2016), we also assessed trait anxiety using Spielberger's State Trait Anxiety Inventory (STAI-T) (Spielberger, 1983). STAI-T scores are commonly classified as "no or low anxiety" (20−37), "moderate anxiety" (38−44), and "high anxiety" (45−80). See Table 1 for all baseline assessments.

2.3. Procedures

This study was conducted as a randomised controlled trial, using a three (feedback) × two (condition) way mixed-model design, with feedback (slow, fast and no HR feedback) as a between-subject factor and condition ('Ground' [i.e. no threat] and 'Threat') as a within-subject factor. Participants completed a single 60-s trial under the following conditions: Ground (no threat) without HR feedback followed by Threat (0.8 m raised surface), during which participants received either false heart rate feedback (slow and fast HR feedback groups) or no feedback (no HR feedback group) (Fig. 1). During the Threat condition, the 5 cm

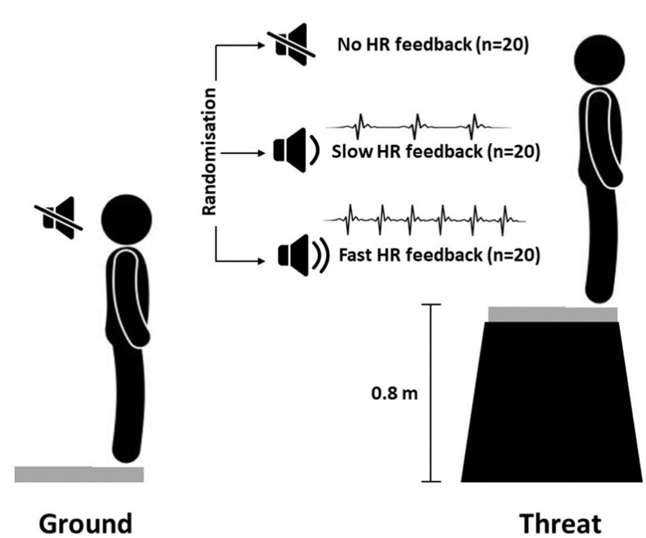

Fig. 1. Study schematic.

high force platform was placed on a podium measuring 50 cm long, 50 cm wide and 75 cm high, raising participants 0.8 m above the laboratory floor (Fig. 1). Participants ascended the platform via three steps. For both trials, participants stood in a bipedal position with the feet together and the toes touching the anterior edge of the force platform (AMTI, AccuGait, Watertown, MA; dimensions 50 × 50 × 5 cm). During the no threat Ground condition, the investigators were blind to treatment allocation. Immediately following the no threat Ground condition, participants were randomly assigned to either a slow HR feedback, fast HR feedback or no HR feedback. The randomisation process was completed using Research Randomizer, a program published on a publicly accessible official website (https://www.randomizer.org/). After the completion of trait questionnaires (see 2.2), but before experimental conditions, participants performed a 30-s practice trial at ground level. Consistent with the Ground experimental trial, practice trials were performed without HR feedback. To maximise the emotional response to the postural threat, practice trials were not performed in the Threat condition.

2.4. Interoceptive manipulation

Participants randomised to the HR feedback groups were informed that starting 5 s before the recording for the Threat condition commenced, they would hear their HR and that auditory feedback would continue throughout the following 60 s trial. As a cover story, participants were informed that auditory HR feedback was necessary for the investigator to count the number of heart beats in a minute. The frequency of heart beats was 60 beats·min^{-1} and 160 beats·min^{-1} for the slow and fast HR feedback groups, respectively. These frequencies were derived from prior pilot testing which revealed that these were the most believable. We used pre-recorded Korotkoff sounds played through a portable speaker to provide the strongest possible valence component of the interoceptive feedback. Participants in the no HR feedback group underwent the same procedure but did not receive HR feedback. During all trials, participants were asked to stand quietly while gazing at a black circle (10 cm diameter) 3 m away from the force platform (adjusted to individual eye level), with the hands clasped in front of the body (Johnson et al., 2023). To maximise the postural threat, all trials were completed without a safety harness and participants were barefoot. Heart rate was continually monitored (Polar Electro, Oy, Finland) throughout the experimental conditions.

2.5. Effectiveness of interoceptive manipulation

The effectiveness of the manipulation procedures (feedback groups only) was assessed during a debrief immediately after the Threat trial, at which point the true purpose of the experiment was revealed. Participants were asked to respond on a visual analogue scale (VAS) "how much did you believe the HR feedback you received" (from 0, 'did not believe at all' to 10, 'completely believed') (Russell et al., 2022). We also asked participants to respond on a VAS, "how much did you believe the HR feedback influenced your performance" (from 0, 'no influence' to 10, 'high influence'). One male participant in the fast HR feedback group scored 'zero' for the belief question. As confidence in the validity of the feedback represents a central requirement in false intercoeptive feedback trials, we excluded this participant from further analyses (as per previous false interoceptive literature [Ehlers et al., 2021]). As such, 19 participants remained in the fast HR feedback group (mean±SD age = 21.4 ± 2.6 years, stature = 1.74 ± 0.11 m, mass = 77.1 ± 19.7 kg).

2.6. Emotional and self-reported outcomes

Immediately prior to each trial (i.e., while standing in position), participants rated how confident they were that they could maintain their balance using a VAS from 0 ("not at all confident") to 10 ("completely confident") (Huffman et al., 2009; Cleworth & Carpenter, 2016; Zaback et al., 2016). Immediately following each trial, participants rated the level of fear of falling they experienced during the trial itself from 0 ("not fearful at all") to 10 ("extremely fearful") (Davies et al., 2009; Huffman et al., 2009; Cleworth et al., 2023). We also asked participants to rate how difficult it was to maintain balance during the task from 0 ("not difficult at all") to 10 ("maximal difficulty"). Participants were then asked to rate their degree of instability during the trial using a 0 – 10 VAS, where 0 corresponded to being "completely steady" and 10 "so unsteady that I would fall". Finally, participants completed a 4-item questionnaire that assessed the degree to which they directed conscious attention towards monitoring and controlling their balance: (i) "I am always trying to think about my balance when I am doing this task", (ii) "I am aware of the way my mind and body works when I am doing this task", (iii) "I am self-conscious about the way I look when I am doing this task", (iv) "I am concerned about my style of moving when I am doing this task"; 1 = strongly disagree; 6 = strongly agree) (Ellmers and Young, 2018; Ellmers et al., 2021). The sum of the four conscious balance processing questions (range, 4 – 24) were used in the subsequent analyses, with greater scores reflecting greater conscious processing of balance.

2.7. Behavioural (postural control) outcomes

Ground reaction force data were sampled at 100 Hz (Netforce, AMTI, Watertown, MA) and low-pass filtered (5 Hz) offline with a bidirectional, second-order Butterworth filter. We assessed the amplitude and frequency of postural adjustments by calculating the root mean square (RMS) and mean power frequency (MPF; mean frequency in power spectrum after fast Fourier transformation) (Carpenter et al., 1999; 2006; Ellmers et al., 2021; Zaback et al., 2019) of the centre of pressure (COP). Given that the postural threat (platform edge) was anterior to participants, all analyses were confined to the anterior-posterior (AP) direction, as per previous postural threat work (Adkin & Carpenter, 2018; Ellmers et al., 2021; Zaback et al., 2019). The RMS was calculated to determine the amplitude of COP adjustments (with respect to the COP mean position). The MPF and RMS were derived following removal of the bias value from the signal. MPF has been viewed as an indirect index of ankle stiffness—typically, the higher the frequency of postural sway, the higher the stiffness around the ankle joint (Warnica et al., 2014). Together, a higher frequency, coupled with reduced amplitude, of COP displacements is thought to reflect a 'postural stiffening' response when standing at height (Adkin & Carpenter, 2018).

2.8. Statistical analyses

Data were analysed using SPSS version 25.0 (IBM Inc., Chicago, IL). For all analyses, normality (Shapiro–Wilk Test) and homogeneity of variance/sphericity (Mauchly Test) were performed and confirmed prior to parametric analyses. To examine differences in subjective and objective responses, a series of two-way mixed model analysis of variance (ANOVA) were undertaken (with Bonferroni correction) to test for the within-subject effects of Condition (× 2 [Ground vs. Threat]) and between subject effects of Group (× 3 [no HR feedback vs. slow HR feedback vs. fast HR feedback]). The effectiveness of belief manipulation was assessed using an independent t-test (slow HR feedback vs. fast HR feedback). Where significant interactions or main effects were detected, post hoc analyses using Bonferroni-adjusted α determined the location of any differences. For ANOVA, effect sizes are reported as partial eta-squared value ($\eta 2$). The alpha value was a priori set at $p < 0.05$ for all tests.

3. Results

3.1. Effectiveness of interoceptive manipulation

There was no difference in the degree of perceived belief that the intervention influenced performance between the slow HR feedback (4.2 ± 2.4, range 1 – 8) and fast HR feedback (4.2 ± 2.2, range 1 – 8) ($p = .946$) groups. However, participants in the slow HR feedback group (8.2 ± 1.5, range 5 – 10) reported greater belief in the information that they received compared to the fast HR feedback group (4.8 ± 2.4, range 1 – 8) ($p < .001$, d=1.70). Note, results presented hereafter for the fast HR feedback group are for $n = 19$, after one participant was excluded from the analysis (as reported above).

3.2. Emotional and self-reported outcomes

Table 2 illustrates the mean ± standard deviation (SD) for all variables.

3.2.1. Balance confidence

There was a significant main effect of condition ($F_{(1,56)}$= 108.87, $p < .001$, $\eta_p^2 = .660$), with participants reporting lower confidence during Threat compared to the Ground condition. There was neither a significant main effect of group ($F_{(1,56)}$= 1.02, $p = .37$, $\eta_p^2 = .035$), nor an interaction between the two ($F_{(2,56)}$= .19, $p = .82$, $\eta_p^2 = .007$) (Fig. 2A).

3.2.2. Fear of falling

There was a significant main effect of both condition ($F_{(1,56)}$= 138.27, $p < .001$, $\eta_p^2 = .712$) and group ($F_{(2,56)}$= 12.48, $p < .001$, $\eta_p^2 = .308$), as well as a significant interaction between the two, with respect to fear ($F_{(2,56)}$= 20.25, $p < .001$, $\eta_p^2 = .420$). Post-hoc tests revealed a significant increase in fear from Ground to Threat with slow (d=1.38), fast (d=2.78) and no HR feedback (d=0.99; all three groups $p < .001$). However, fear was significantly greater during Threat in the fast HR feedback group compared to both the slow HR feedback ($p < .001$, d=1.78) and no HR feedback ($p < .001$, d=1.39) groups (Fig. 2B).

3.2.3. Perceived difficulty

There was a significant main effect of both condition ($F_{(1,56)}$= 37.99, $p < .001$, $\eta_p^2 = .404$) and group ($F_{(2,56)}$= 8.67, $p < 001$, $\eta_p^2 = .237$), as well as a significant interaction between the two, with respect to perceived difficulty ($F_{(2,56)}$= 10.90, $p < .001$, $\eta_p^2 = .280$). Post-hoc tests revealed a significant increase in perceived difficulty from Ground to Threat in the fast HR feedback group only ($p < .001$, d=1.85). Correspondingly, perceived task difficulty during Threat was greater in the fast HR feedback group compared to both the slow HR feedback ($p < .001$, d=1.50) and no HR feedback ($p < .001$, d=1.26) groups (Fig. 2C).

3.2.4. Perceived instability

There was a significant main effect of both condition ($F_{(1,56)}$= 48.88, $p < .001$, $\eta_p^2 = .466$) and group ($F_{(2,56)}$= 4.77, $p = 012$, $\eta_p^2 = .145$), as well as a significant interaction between the two, with respect to perceived instability ($F_{(2,56)}$= 4.97, $p < .001$, $\eta_p^2 = .151$). Post-hoc tests revealed a significant increase in perceived instability from Ground to Threat for all three groups (slow d=1.13, fast d=1.64, no HR feedback d=0.85; all three groups $p < .001$). However, the fast HR feedback group felt significantly more unstable during Threat, compared to both the slow HR feedback ($p = .020$, d=0.79) and no HR feedback ($p = .004$, d=1.01) groups (Fig. 2B).

3.2.5. Conscious movement processing

There was a significant main effect of condition ($F_{(1,56)}$= 87.24, $p < .001$, $\eta_p^2 = .609$), with participants reporting greater conscious movement processing during Threat compared to Ground. There was neither a significant main effect of group ($F_{(2,56)}$= 1.26, $p = .29$, $\eta_p^2 = .043$), nor an interaction between the two ($F_{(2,56)}$= 1.88, $p = .16$, $\eta_p^2 = .063$) (Fig. 2E).

3.2.6. Heart rate (HR)

With respect to HR, there was a significant main effect of condition ($F_{(1,56)}$= 15.45, $p < .001$, $\eta_p^2 = .216$), with a greater HR frequency during Threat compared to Ground. There was neither a significant main effect of group ($F_{(2,56)}$= .03, $p = .97$, $\eta_p^2 = .001$), nor an interaction between the two ($F_{(2,56)}$= .56, $p = .58$, $\eta_p^2 = .019$) (Fig. 2F).

3.3. Behavioural (postural control) outcomes

3.3.1. COP amplitude (RMS)

There was a significant main effect of condition ($F_{(1,56)}$= 13.53, $p < .001$, $\eta_p^2 = .195$), with lower RMS during Threat compared to Ground. There was neither a significant main effect of group ($F_{(2,56)}$= .74, $p = .48$, $\eta_p^2 = .026$), nor an interaction between the two ($F_{(2,56)}$= .58, $p = .56$, $\eta_p^2 = .020$) (Fig. 3A).

3.3.2. COP frequency (MPF)

There was a significant main effect of condition ($F_{(1,56)}$= 15.09, $p < .001$, $\eta_p^2 = .212$), with a greater MPF during Threat compared to Ground. There was neither a significant main effect of group ($F_{(2,56)}$= .51, $p = .61$, $\eta_p^2 = .018$), nor an interaction between the two ($F_{(2,56)}$= .01, $p = .99$, $\eta_p^2 = .001$) (Fig. 3B).

4. Discussion

Recent theoretical advancements posit fear and anxiety as resulting from the monitoring and appraisal of the physiological response to a threat; and the integration of this with the interpretation about the likelihood of the threat causing harm (LeDoux, 2013, 2014; LeDoux & Pine, 2016; Ellmers et al., 2022; 2023a). To empirically probe the role of interoception in the generation of fear of falling, the present study tested whether manipulating the appraisal of the physiological threat response (via false HR feedback) could influence emotional and behavioural responses when exposed to a postural threat. In support of our hypothesis, participants provided with false fast HR feedback during postural threat felt more fearful, reported to feeling less stable, and rated the task more

Table 2
Mean ± SD for all outcome measures.

	No HR feedback (n = 20)		Slow HR feedback (n = 20)		Fast HR feedback (n = 19)	
	Ground	Threat	Ground	Threat	Ground	Threat
Emotional outcomes						
Balance confidence (0-10)	9.3 ± 0.9	7.3 ± 0.9	9.1 ± 1.2	7.1 ± 1.6	8.8. ± 1.0	7.0 ± 1.0
Fear of falling (0-10)	0.5 ± 0.6	1.6 ± 1.5	0.3 ± 0.4	1.4 ± 1.0	0.5 ± 0.5	3.7 ± 1.6
Perceived difficulty (0-10)	0.9 ± 1.2	1.4 ± 1.6	0.9 ± 0.7	1.4 ± 1.0	1.1 ± 0.7	3.4 ± 1.6
Perceived instability (0-10)	1.4 ± 1.0	2.2 ± 0.9	1.3 ± 0.9	2.5 ± 1.2	1.3 ± 0.6	3.7 ± 2.0
Conscious processing (4-24)	10.9 ± 3.1	13.8 ± 3.7	11.2 ± 3.7	16.1 ± 3.0	11.5 ± 3.7	15.9 ± 3.3
Mean HR (beats·min^{-1})	83 ± 12	87 ± 14	84 ± 8	86 ± 10	84 ± 14	87 ± 12
Postural control outcomes						
COP-RMS (mm)	4.90 ± 1.84	4.30 ± 1.14	4.86 ± 1.08	4.07 ± 0.84	4.88 ± 1.50	3.66 ± 0.66
COP-MPF (Hz)	0.20 ± 0.10	0.30 ± 0.19	0.20 ± 0.08	0.30 ± 0.17	0.23 ± 0.10	0.33 ± 0.20

Table 3
Main and interaction effects of the repeated measures mixed-modal ANOVA for all outcome measures.

	Condition		Group		Condition × group	
	$F_{(1,56)}$	p (η_p^2)	$F_{(2,56)}$	p (η_p^2)	$F_{(2,56)}$	p (η_p^2)
Emotional outcomes						
Balance confidence	108.87	.001 (0.660)	1.02	.37 (0.035)	0.19	.82 (0.007)
Fear of falling	138.27	.001 (0.712)	12.48	.001 (0.308)	20.25	.001 (0.420)
Task difficulty	37.99	.001 (0.404)	8.67	.001 (0.237)	10.90	.001 (0.280)
Perceived instability	48.88	.001 (0.466)	4.77	.012 (0.145)	4.97	.001 (0.151)
Conscious processing	87.24	.001 (0.609)	1.26	.29 (0.043)	1.88	.16 (0.063)
Mean HR	15.45	.001 (0.216)	0.03	.97 (0.001)	0.56	.58 (0.019)
Postural control outcomes						
COP-RMS	13.53	.001 (0.195)	0.74	.48 (0.026)	0.58	.56 (0.020)
COP-MPF	15.09	.001 (0.212)	0.51	.61 (0.018)	0.01	.99 (0.001)

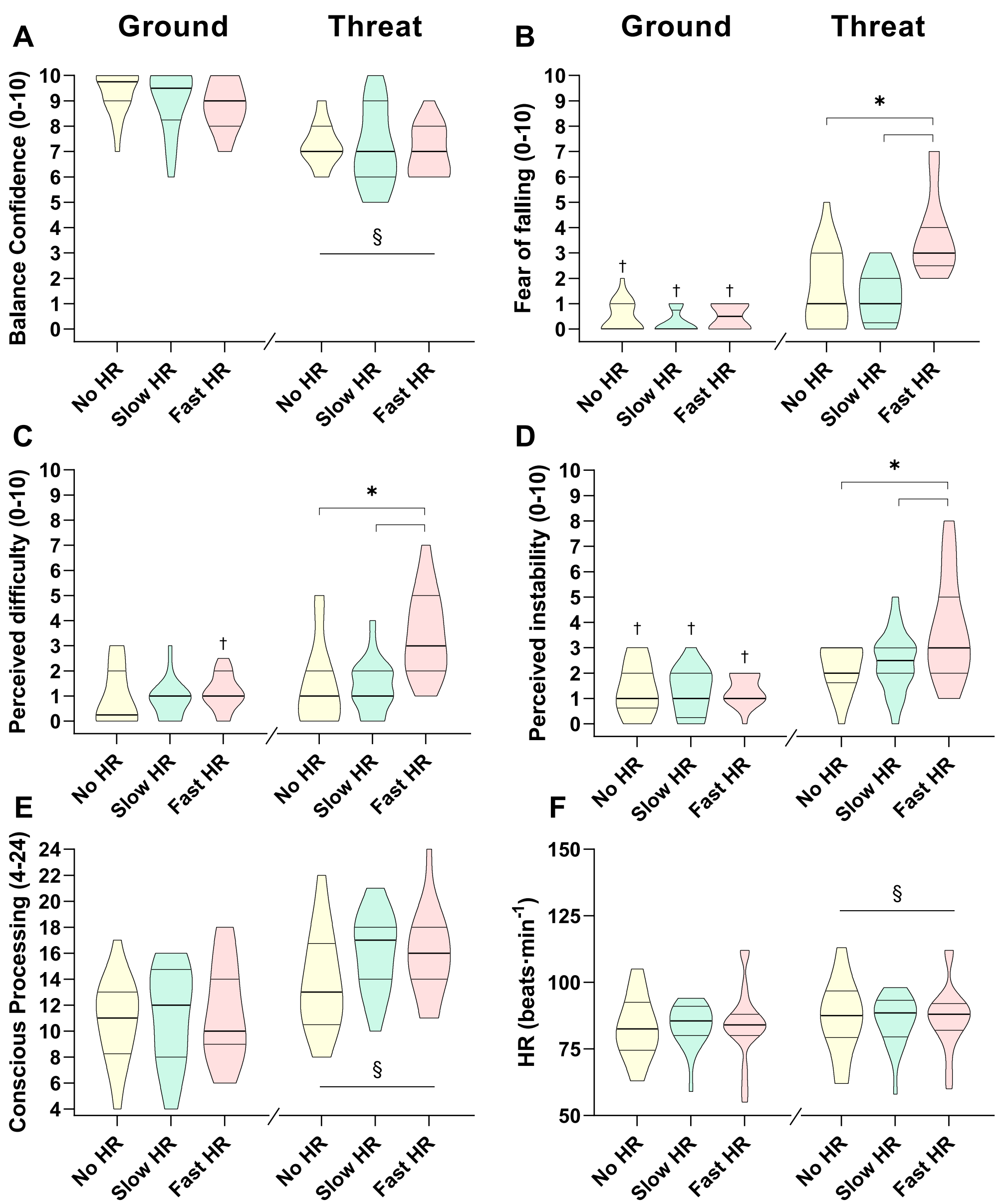

Fig. 2. Violin plots showing illustrating emotional responses between Ground and Threat, in the slow HR feedback, fast HR feedback and no HR feedback control group. Each violin represents the median (centre line), 25th% (bottom of the violin) and 75th% (top of the violin) percentile. *Statistically significantly different to the fast HR feedback group ($p < .05$). †Statistically significantly different to the Threat condition. §Statistically significant main effect of condition ($p < .05$).

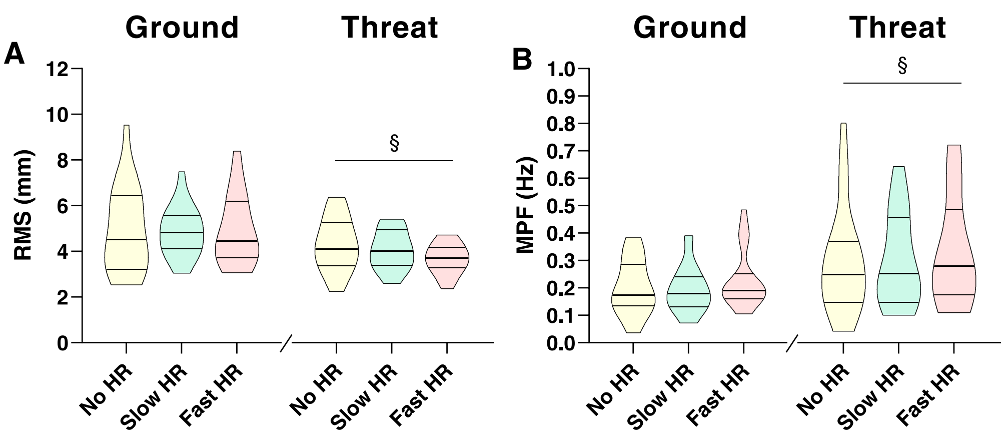

Fig. 3. Violin plots showing illustrating postural control outcomes between Ground and Threat conditions in the slow HR feedback, fast HR feedback and no HR feedback control group. Each violin represents the median (centre line), 25th% (bottom of the violin) and 75th% (top of the violin) percentile. §Statistically significant main effect of condition ($p < .05$).

difficult than participants who did not receive HR feedback, or those who received slow HR feedback. However, contrary to expectation, and despite significant maladaptation of the emotional response to threat in the fast HR feedback group, the behavioural response did not significantly differ across the groups. Further, the slow HR feedback did not affect emotional or behavioural responses to the postural threat (when compared to the no HR feedback group) – with the differences restricted to the fast HR group. Nonetheless, these observations provide direct experimental support for emerging theoretical accounts describing the role of interoception in the generation of emotional responses to postural threats (Ellmers et al., 2022, 2023a).

4.1. *Influence of false interoceptive feedback on emotional responses to postural threat*

The present study provides the first experimental support for theoretical accounts describing the role that interoception plays in the formulation of emotional responses to postural threat (Ellmers et al., 2022). Ellmers et al., (2022, 2023a) previously hypothesised that fear of falling occurs as a direct result of an individual interpreting their bodily response to a threatening scenario (e.g., racing heartbeat, tense muscles, etc.), and then integrating this with their appraisal of the situational context. The present results provide strong evidence for such notion. Specifically, they reveal that individuals who receive interoceptive feedback indicating increased physiological arousal (i.e., faster HR) during conditions of postural threat will experience a stronger, more fearful emotional response. These individuals will then also perceive the postural task to be more difficult and experience a ‘distorted’ perception of postural instability, whereby they perceive their balance to be more unstable than it actually is (Ellmers et al., 2021). The present findings further reinforce the role that top-down processes play in both interoception and the subsequent formulation of the resulting emotional responses (Barrett & Simmons, 2015).

Contrary to both our expectations and previous research (Ehlers et al., 2021), false interoceptive feedback designed to imply low physiological arousal (i.e., slow HR feedback) did not reduce the emotional response to a postural threat. One possible interpretation for this finding could be the relatively ‘low’ threat posed by the postural threat manipulation used in the present research (raised surface height of 0.8 m vs. the 3.2 m used in previous research [Zaback et al., 2019; 2021]); with fear of falling only increasing to 1.6 out of 10 (from 0.5) for the no HR feedback group. Thus, a floor effect may have prevented the slow HR feedback group from reporting reduced emotional responses. Greater postural threat (i.e., increased surface heights or threat of a genuine perturbation to balance [K Johnson et al., 2019]) may therefore be necessary to ascertain whether slow HR feedback procedures can alter the emotional salience to a postural threat.

4.2. *Lack of influence of false interoceptive feedback on behavioural responses to postural threat*

Although interoceptive streams can clearly influence the way people feel, we did not observe any between-group differences in postural control during the Threat condition. This was contrary to our predictions. Rather, we observed a main effect of condition on postural control outcomes – with each group exhibiting concomitant decreases in amplitude (RMS) and increases in frequency (MPF) of COP. This pattern of results is in line with previous research exploring the role of postural threat on balance, and is believed to reflect a ‘postural stiffening’ strategy (Adkin & Carpenter, 2018).

Although it is well established that emotion can directly influence postural control (Adkin & Carpenter, 2018; Ellmers et al., 2022; Davis et al., 2009), some changes in balance that are observed when participants are fearful or anxious appear to relate more to the presence of the threat rather than the emotional response itself. For instance, previous work has reported that despite marked reductions in fear of falling following repeated exposure to a height-induced postural threat, COP amplitude (RMS) remained unchanged following habituation (Zaback et al., 2019; 2021). It is therefore perhaps not surprising that we failed to observe a clear behavioural effect of the false HR feedback (and the subsequently stronger emotional response) on the COP outcomes studied in the present work.

4.3. *Applied implications*

Although some level of fear of falling may be adaptive when balance is threatened, many older adults experience a level of fear and anxiety that exceeds their *actual* risk of falling (Delbaere et al., 2010; Ellmers et al., 2023), resulting in overly-cautious and maladaptive behaviours when balance is threatened (Delbaere et al., 2010; Ellmers et al., 2023a, 2023b). The present findings highlight the strong influence that the appraisal of the physiological response to a postural threat can exert over the resulting emotional response itself. Future work could therefore explore the efficacy of interventions designed to train interoceptive awareness in reducing emotional symptoms in older adults with high levels of fear and anxiety about falling. Such approaches have been shown to be effective in reducing symptoms in other anxiety-related disorders (Khoury et al., 2018). Additionally, this novel procedure of manipulating emotions via false interoceptive feedback may offer a promising approach to maximise threat responses in experimental studies (particularly in situations where physical height manipulations may be limited due to ethical concerns or environmental constraints) in a simple, flexible and fairly implicit way.

4.4. Limitations

A key limitation of the present work relates to the fact that the false HR feedback provided was not individualised (e.g., 150 % of individual resting HR). Consequently, the discrepancy between the false feedback was substantially greater for the fast (actual HR of 84 ± 13 [range = 55 – 112] bpm vs. 160 bpm feedback) compared to slow HR feedback group (actual HR of 86 ± 10 bpm [range = 58 – 98] vs. 60 bpm feedback received). This may account for the greater scepticism of the fast compared to slow HR group, with these individuals overall having lower belief in the accuracy of the feedback provided. Alternatively, the greater scepticism of the fast HR group may instead relate to between-group differences in interoception. For instance, we did not assess – and therefore control for – actual interoceptive *accuracy,* but only between-group differences in interoceptive sensibility (i.e., an individual's subjective *beliefs* about their accuracy in perceiving interoceptive signals [Garfinkel et al., 2015]). It is therefore possible that the fast HR group had greater interoceptive accuracy, meaning that they were better able to identify that the HR feedback provided was false. Future work should therefore seek to directly assess participants' perception of their heartrate, to determine if the manipulation was indeed successful in driving an inaccurate belief about interoception during the Threat condition. Another limitation relates to the possibility that the different auditory stimuli presented (slow vs. fast vs. no auditory stimuli) may have caused different levels of distraction across the three groups. Although we are unable to rule out this possibility, previous work has shown that distraction leads to clear changes in behaviour during conditions of postural threat (Johnson et al., 2020; Ellmers et al., 2021). As we observed a lack of between-group differences in behaviour during Threat in the current work, we therefore deem it unlikely that the results presented were affected by between-group differences in distraction. Future work should nonetheless explore the moderating effect that interoceptive accuracy exerts on the efficacy of false physiological feedback during postural threats, and provide false feedback that is individualised to each participant – perhaps presenting this prior to the start of the threat trial itself, to ensure between-group parity with respect to within-task distraction.

5. Conclusion

The present study represents the first investigation to examine whether manipulating the appraisal of the physiological threat response (via false HR feedback) can influence emotional and behavioural responses when exposed to a postural threat. Our results show that providing faster cardiac feedback during a threatening postural task can increase the fear response in healthy young adults. These observations provide novel experimental support for recent theoretical accounts describing the role that interoception plays in the formulation of emotional responses to postural threat (Ellmers et al., 2022, 2023a). The novel findings raise the intriguing notion of directly targeting interoception to address 'maladaptive' fear of falling in older adults (Ellmers et al., 2023a, 2023b).

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CRediT authorship contribution statement

Toby Ellmers: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Mathew Hill:** Conceptualization, Data curation, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing, Formal analysis. **Ellie Johnson:** Data curation, Investigation.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author(s) did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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