

Interoceptive Breathing Perceptions with Anxiety

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Research Article

Keywords: Anxiety, Interoception, Sensitivity, Inspiratory Resistance, Hypercapnia

Posted Date: October 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10992030/v1>

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Additional Declarations: No competing interests reported.

Interoceptive Breathing Perceptions with Anxiety

Type of manuscript: Original article

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10/09/26

Abstract

Background

Interoception (i.e. the sensing, processing, and evaluation of signals originating from within the body) has emerged as a key process linked to anxiety, sharing both neural and physiological substrates. The current project examined how anxiety is related to subjective measures of sensitivity towards two different interoceptive breathing modalities, inspiratory resistance and hypercapnia (elevated carbon dioxide; CO₂), across a spectrum of anxiety levels.

Methods

Participants (n = 75) completed self-report measures of anxiety and related variables before undergoing two breathing perception tasks involving graded increases in inspiratory resistance (10, 20, 30 cmH₂O/L/s) and hypercapnia (2%, 4%, 6% CO₂). Perceptual responses (sensory via breathlessness ratings and affect via anxiety ratings) at each step were recorded using visual analogue scales. Data were analysed in STATA using linear mixed effects regression models to assess the variance associated with anxiety status, stimulus level, and their interaction. Additional exploratory correlation analyses were also performed between the perceptual, physiological and anxiety-related measures.

Results

Primary analyses indicated that anxiety was associated with increased overall affective ratings (resistance: $\beta = 3.83$, $p < 0.05$; CO₂: $\beta = 3.28$, $p < 0.05$) but not sensory ratings. However, anxiety did not influence participants' sensitivity to changes in stimulus intensity (i.e. slope) for either inspiratory resistance or hypercapnia. Additionally, anxiety did not relate to ventilatory responses during either stimulus. Exploratory analyses revealed additional correlations including lower self-efficacy relating to altered ventilation during both tasks.

Conclusions

Overall, these findings suggest that anxiety is primarily associated with increased overall affective perceptions of breathing-related interoceptive signals but does not alter the sensory ratings nor ventilatory responses. This dissociation highlights potential markers for anxiety vulnerability and may inform the development of targeted interventions that focus on specifically modifying affective responses to bodily sensations.

Keywords: Anxiety, Interoception, Sensitivity, Inspiratory Resistance, Hypercapnia

Abbreviations: Anxiety Disorder (AD); Centre of Epidemiological Studies Depression scale (CESD); Carbon Dioxide (CO₂); General Anxiety Disorder 7-item scale (GAD-7); Global Physical Activity Questionnaire (GPAQ); General Self-Efficacy scale (GSE); Minute ventilation (VE); Multidimensional Assessment of Interoceptive Awareness (MAIA); Oxygen (O₂); Principal Component Analysis (PCA); Respiratory rate (RR); Spielberger's State-Trait Anxiety Inventory (STAI); Tidal volume (TV)

Statements and Declarations

- Funding: This study was supported by the Rutherford Discovery Fellowship awarded to OK Harrison.
- Ethics: The current study was reviewed by the University of Otago Human Ethics Committee (reference H24/0193) in accordance with UOHEC guidelines and complies with the Declaration of Helsinki. This included a peer review of the study protocol by two external authorities before being reviewed and subsequently authorised by the board of ethics at the University of Otago.
- Consent to Participate: All participants signed informed consent prior to data collection.
- Consent for Publication: Not applicable.
- Author contributions: Project planning was completed by RNC and OH. Custom building of hypercapnic and resistance delivery devices was undertaken by JPC and TE. All data were collected by RNC. The manuscript was drafted by RNC and edited by all authors.
- Competing interests: Not applicable.
- Dual publications: Not applicable.
- Authorship: All authors on this project have read and understand the submission guidelines. All authors agree with the contents and have given their explicit permission to submit this article.
- Third-party material: Not applicable.
- Data availability: Analyses for this study were conducted using Stata 18, with reproducible code documented and retained for review. A time-stamped analysis plan that details all planned analyses and research questions was uploaded to a GitHub repository (<https://github.com/IMAGEotago/RC-Sensitivity-AnalysisPlan>).

Introduction

Anxiety is a fundamental biological mechanism that can become disordered when responses occur frequently and impair normal functioning. The ability to accurately identify and recognise the bodily changes associated with anxiety has been shown to attenuate emotional reactivity and improve symptom perception [1, 2]. Notably, recent research has implicated a role for impaired interoception (the sensing, interpretation, integration, and representation of signals originating from within the body) in the development and maintenance of anxiety [3, 4]. Such impairments may exacerbate symptoms and contribute to the persistence of anxious states.

Changes in breathing – a particularly salient and readily modifiable interoceptive signal – can be both a consequence and a driver of anxiety [3]. Breathing has multiple sensory input channels, including the detection of blood carbon dioxide (CO₂) (and less potently oxygen; O₂) as well as more mechanical aspects such as resistance to breathing (induced via increased breathing effort and/or external resistances) [5]. Early evidence has suggested that sensitivity towards these sensory inputs may be differentially related to anxiety, with heightened responses to elevated blood CO₂ (i.e. hypercapnia) [6-9] yet possibly blunted responses to breathing effort [10-13]. However, these have yet to be systematically tested in the same participants across a range of anxiety levels, to determine if these differences are in opposition and directly related to level of anxiety. Investigating individual differences in interoceptive sensitivity to breathing-related sensations may help identify physiological markers of heightened anxiety at both subclinical and clinical levels, providing a window into anxiety across the population as well as avenues for treatments that target the bodily experience of anxiety.

Interoceptive Sensitivity

Interoception refers to the perception of the internal state of the body and encompasses numerous sensory modalities, including the processing of information from cardiac, respiratory, gastrointestinal and immune sources (to name a few) [14, 15]. Respiration is unique among interoceptive avenues as breathing can be voluntarily controlled and consciously monitored [16], unlike heart rate, for example, which is almost completely automatic [17].

Importantly, altered interoceptive sensitivity has been suggested to play a key role in the aetiology and maintenance of anxiety states and disorders [14, 18]. The term 'interoceptive sensitivity' is widely used in the literature to describe generally how well a person can detect, access, or respond to signals from inside their body. However, the term is used inconsistently across studies and can refer to multiple facets of interoception, including metrics such as sensitivity to incoming signals as well as high-order affective and evaluative processes [11, 19].

While many respiratory studies examine interoceptive sensitivity by stimulus detection [11, 20, 21] or physiological changes to respiratory stimuli (such as altered respiratory rate or tidal volume) [6-8], there are other measures which are less explored. For example, sensory evaluation (e.g. perceived dyspnoea) and affective appraisal (e.g. feelings of anxiety) of respiratory stimuli are underrepresented and often report mixed results in anxiety-focused studies [8, 22-24]. In this context, visual analogue scales are a useful tool for independent assessment of perceived dyspnoea and affective responses to respiratory stimuli. This sensory-affect dissociation has been used in

both resistance and hypercapnia research, demonstrating that the perceived intensity of breathlessness and the anxiety associated with breathlessness are distinct from one another [23, 25, 26], indicating the engagement of partially separable interoceptive networks.

The current project builds on this framework to assess sensory sensitivity to incoming signals and the affective and evaluative processing of breathing-related interoception associated with anxiety. However, interoceptive signals related to breathing are themselves multimodal, most notably including the sensations of respiratory effort (a largely mechanoreceptive modality) and air hunger (a chemoceptive modality), which are both highly salient and measurable.

Respiratory Effort

Respiratory effort is a mechanoreceptive modality of breathing. It refers to the amount of force that is required by the muscular effector system to supply adequate airflow to maintain homeostasis [27, 28]. Increased respiratory effort is normal during and after heavy exertion, though it can also be induced by applying external load, sometimes referred to as breathing resistance.

Studies suggest that individuals with elevated anxiety may have reduced perception of breathing resistance compared to healthy individuals [13]. These findings are supported by various breathing-resistance studies which have found blunted interoceptive sensitivity towards stimulus detection [11, 20, 21] and either blunted or unchanged sensory evaluation [12, 22]. However, it remains unclear how interoceptive sensitivity to respiratory effort varies across the spectrum of anxiety severity. Furthermore, subjective components of interoceptive sensitivity are underrepresented compared to objective discrimination measures, and it is unclear how these alternate measures of respiratory interoception are modulated with anxiety.

Air Hunger

Air hunger is driven by signals from peripheral and central chemoreceptors in response to hypercapnia, hypoxia, and acidosis [29-31]. These altered states lead to a feeling of suffocation, characterized by an intense urge to breathe or “unsatisfied breathing” [29]. Interoceptive sensitivity to CO₂ is strongly implicated in anxiety, particularly in panic-related pathology. As such, individuals with elevated anxiety have repeatedly demonstrated increased chemosensitivity to CO₂, where various levels of CO₂ exposure can produce increased breathing rate [6, 7], heightened sensory evaluation [8, 23], and heightened negative affective valence [9, 23, 32, 33] in anxious groups (particularly in panic disorder) compared to healthy controls.

While hypersensitivity to hypercapnic stimuli has been consistently demonstrated in anxious populations, especially at low and clinically relevant CO₂ concentrations, the extent to which this sensitivity varies across the broader spectrum of anxiety has not been systematically examined. Furthermore, the relationship between anxiety and responses to varying levels of CO₂ has yet to be clearly established. Finally, while the air hunger and respiratory effort components of dyspnoea appear to be differently modulated by anxiety, these have not yet been examined within the same participants for direct comparison. Clarifying how anxiety relates to sensory and affective responses to air hunger, particularly in comparison with respiratory effort, can therefore help to elucidate mechanisms underlying interoceptive processing in anxiety.

The Present Study

Previous literature suggests that there may be opposing relationships between two different modalities of breathing interoception (respiratory effort and air hunger) and anxiety. Therefore, this study directly addresses this hypothesis by measuring both the sensory and affective components evoked by each stimulus in a group of individuals across a broad spectrum of anxiety. We also examine the ventilatory response and anxiety-related correlations as exploratory measures.

Methods

Participants

Participants were based in Dunedin, New Zealand and were recruited through the University of Otago. Participants were pre-screened through a customised questionnaire on Qualtrics to ensure they met the eligibility criteria. Participants were excluded from the study if they currently used nicotine or illicit drugs, had a history of excessive smoking or vaping, were pregnant or breastfeeding, had a history of cardiac or respiratory problems, history of a serious brain disease, brain injury, or brain surgery, history of a severe mental disorder (including psychosis), were an elite athlete, had consumed alcohol <24 hours prior to the session, or completed vigorous exercise <2 hours prior to the session. The final study sample comprised of 75 participants (62 female, 13 male) aged 18-45 years (mean = 21.4; SD = 2.89). The majority of participants were psychology undergraduate students in their first or second year of study. Throughout recruitment, ongoing monitoring of anxiety scores ensured the sample spread covered a sufficiently broad range (Appendix A). If scores deviated from this pattern, study enrolment was adjusted to target the missing range of individuals.

Instruments

The hypercapnic system used a custom-built automated flow-controlled gas mixing device, such that specific, computer-controlled percentages of CO₂ could be delivered to the participant. The resistive system used a separate custom-built device that employed a variable-aperture valve, such that specific, computer-controlled levels of inspiratory resistance could be imposed by closing the aperture to different degrees. Stimuli were delivered to participants through a medical grade breathing mask with a single-use breathing filter, connected via a tubing system to the hypercapnia or resistance devices. Psychopy3 software was used with custom-written code to control the onset and duration of breathing task stimuli. The breathing tube was connected to a flowmeter incorporating a spirometer (ADInstruments; Dunedin, New Zealand) for the measurement of respiratory airflow and volume. The breathing filter also provided connectors for pressure and respiratory gas sampling lines, which were connected to a pressure transducer and bridge amplifier (ADInstruments) for inspiratory pressure readings, and to a gas analyser (ADInstruments) for respiratory gas analysis. Heart rate was measured using five electrocardiography sensors connected to a bioamp (ADInstruments). All front end measures were connected to a central Powerlab (ADInstruments), and LabChart 8 software (ADInstruments) was used to simultaneously measure all physiological traces.

Procedure and Timeline

Each session lasted up to 90 minutes, allowing for the completion of pre-screening and informed consent, a multidimensional questionnaire, 10 minutes of baseline physiological recordings, and two breathing perception tasks. Task instructions were standardized across participants to minimise experimenter bias. At the beginning of the session (following informed consent), participants were required to complete a multidimensional questionnaire to measure aspects relating to anxiety, depression, and interoception. The questionnaires included the General Anxiety Disorder assessment (GAD-7) [34], State Trait Anxiety Inventory (STAI) [35], Centre of Epidemiology Studies Short Depression Scale (CESD) [36], Multidimensional Assessment of Interoceptive Awareness (MAIA) [37], General Self-Efficacy scale (GSE) [38], and the Global Physical Activity Questionnaire (GPAQ) [39]. The GAD-7 and STAI (forms Y1; state anxiety and Y2; trait anxiety) were used as the key markers of anxiety. Participants were then fitted with an electrocardiogram and secure breathing mask, and instructed to sit quietly and breathe normally for the duration of the session. Ten minutes of baseline data were collected whilst the participant was at rest, and measures continued throughout both breathing tasks. Physiological measurements included flow (from which tidal volume and respiratory rate were calculated), pressure at the mouth, CO₂ and O₂ (from which breath-by-breath end-tidal values were identified), and heart rate.

During each breathing task, a visual cue (white circle on a dark grey screen) signalled the stimulus period to aid self-assessment (Figure 1). In the resistance task, three magnitudes of resistance were employed: 10, 20, 30 cmH₂O/L/s. Inspiratory resistive stimuli were administered for 60 seconds each followed by 180 seconds of rest, with each stimulus presented once in ascending order. For the hypercapnia task, three magnitudes of CO₂ were employed: 2, 4, 6%. CO₂ stimuli were administered for 180 seconds each followed by 180 seconds of rest, with each stimulus also presented once in ascending order. The increased duration of hypercapnic stimuli compared to resistance was to account for the time taken to reach a physiological steady state with hypercapnia [40, 41]. At the end of every stimulus period (resistance and CO₂ alike) whilst the stimulus remained present, participants completed a short assessment on the screen, measuring their perception of breathlessness and their coinciding anxiety state (Figure 1). For all individuals, the resistance task was completed prior to the CO₂ task to ensure no cross-contamination and residual influence of hypercapnia, with at least 5 minutes of rest between tasks.

Figure 1

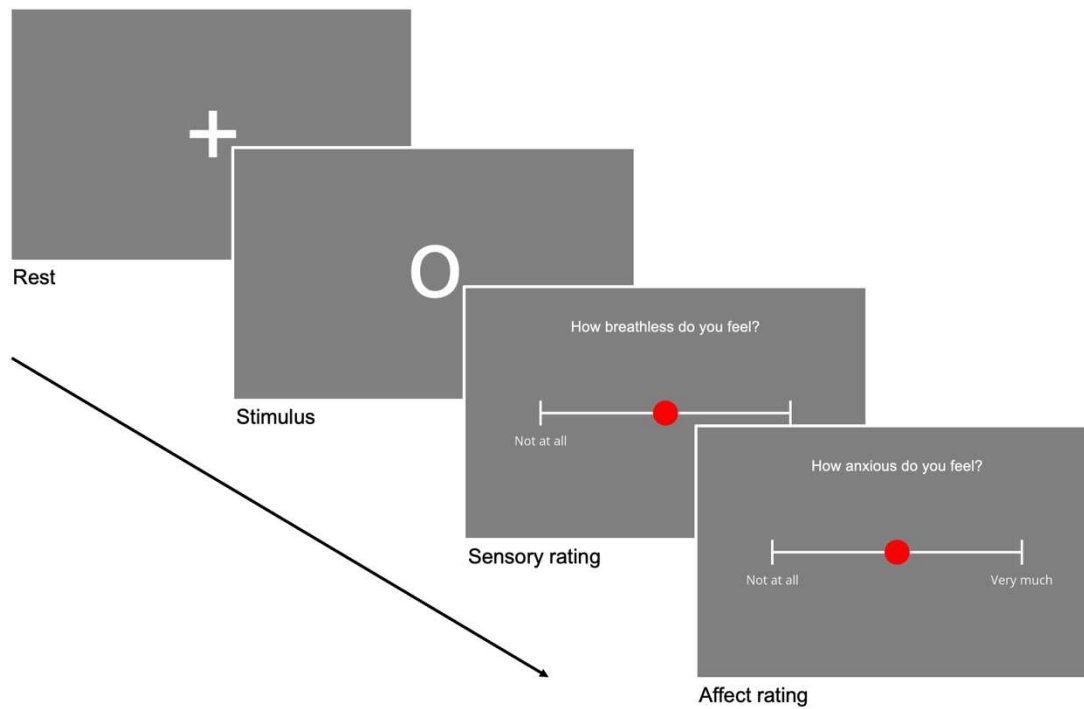


Fig.1 The image shows the sequence of screens displayed on the experimental computer during the Breathing Perception Tasks. The first two slides depict the visual cues for rest (+) and for the presence of a stimulus (o). The second two slides show two self-assessment questions paired with a visual analogue scale: “How breathless do you feel?” and “How anxious do you feel?”. On each scale, the pointer (red circle) position corresponds to a number from 0 (‘Not at all’) to 100 (‘Very much’).

Preprocessing

Questionnaires were scored according to their respective manuals. To obtain a general anxiety variable, a principal component analysis (PCA) was applied to derive a single composite anxiety score from the anxiety-related questionnaires (GAD-7, STAI-Y1, and STAI-Y2) that captures their shared variance.

Behavioural perception data obtained in PsychoPy 3 corresponded to the visual analogue scale position selected by participants following each stimulus for both breathlessness and anxiety ratings (on a 0-100 scale).

Physiological data were selected in Labchart 8, taking the average of the final 45 seconds for each resistive stimuli and the final 60 seconds for each gaseous stimuli. Respiratory rate (RR) was calculated as mean breaths per minute, tidal volume (TV) as mean expired volume of air per breath, end-tidal CO₂ as mean of the end-expiration peak values, and pressure as peak inspiratory pressure, corresponding to the maximum pressure generated during inhalation. Minute ventilation (VE) was calculated with Equation 1:

$$VE = TV \times RR \quad (1)$$

To corroborate valve position and account for any potential aperture drifts, Equation 2 was used to calculate airway resistance (R) from peak inspiratory pressure (P) and flow (Q):

$$R = \frac{P_{peak} - P_{plateau}}{Q} \quad (2)$$

Statistical Analyses

Primary perceptual analyses

The relationship between anxiety level and perceptual measures were examined using linear mixed-effects models in STATA (version 18). The two interoceptive measures (perceived breathlessness and anxiety) were analysed with individuals' stimulus level (calculated resistance or end-tidal CO₂) with three levels, anxiety PCA scores, and their interaction as fixed effects. Random intercepts and slopes were included to account for repeated measures within each participant. Model assumptions were evaluated using residual diagnostics. Finally, post-hoc linear regressions were conducted to better understand how anxiety relates to the magnitude of perception at each stimulus level separately. As such, twelve additional separate linear regression models were conducted. Each model regressed either sensory or affect ratings at a single stimulus level (low, medium, or high) on participants' PCA-derived anxiety scores. All models used anxiety scores as the sole predictor and were estimated using ordinary least squares regression.

Ventilatory analyses

To assess whether any influences of anxiety were constrained to perceptual responses only, additional analyses were conducted to assess the influence of anxiety scores on the ventilatory responses to each stimulus. Matched linear mixed-effects models were again used for three ventilatory measures (RR, TV and VE). For each outcome, fixed effects included stimulus level, anxiety PCA scores, and their interaction. Random intercepts and slopes for each stimulus were included at the participant level to account for repeated measures. Model assumptions were evaluated using residual diagnostics.

Exploratory analyses

An exploratory Pearson's correlation analysis was used to map the relationship between perceptual variables for each stimulus type, ventilatory responses, and additional aspects of potential anxiety-related measures. Variables included: age, sex, GAD-7, STAI-Y1, STAI-Y2, GPAQ, MAIA, CESD, GSE, anxiety PCA, perceptual slopes (sensory and affect) for both resistance and CO₂, and ventilation slopes for RR, TV, and VE. Additionally, to measure the overall sensitivity to resistance and CO₂, the average perceptual ratings of breathlessness and anxiety as well as ventilation measures across all stimulus levels were calculated and added to the correlation matrix. To account for multiple comparisons across the correlation matrix, p values were adjusted using the Benjamini-Hochberg false discovery rate procedure [42]. Statistical significance was determined using a false discovery rate-adjusted $q < 0.05$.

Results

Principal Component Analysis

For the PCA, the first principal component (PC1) explained 80.1% of the total variance (eigenvalue = 2.40). Component loadings demonstrated substantial contribution from all three questionnaires: GAD-7 (PC1 loading = 0.582), STAI-Y2 (PC1 loading = 0.586), and STAI-Y1 (PC1 loading = 0.563), supporting the use of PC1 as an overall anxiety score in subsequent analyses (Appendix B).

Breathing Perceptions

Resistance stimuli

For both perceptual rating outcomes, resistance intensity had a significant positive effect (sensory: $\beta = 0.53$, $p < 0.001$, 95% CI [0.41, 0.65]; affect: $\beta = 0.21$, $p < 0.005$, 95% CI [0.07, 0.35]), confirming that increasing resistance was perceived as both more intense and more emotionally aversive. Participants' perceptions of breathlessness were greater than their feelings of anxiety towards resistance, reflected by a larger standardized coefficient for the sensory component (0.53) relative to affect (0.21). Notably, anxiety did not significantly predict overall sensory ratings ($\beta = 1.33$, $p = 0.481$, 95% CI [-2.37, 5.04]). However, anxiety significantly predicted overall affect ratings ($\beta = 3.83$, $p < 0.05$, 95% CI [0.21, 7.43]), indicating that while participants perceived breathlessness independent of anxiety levels, individuals with higher anxiety experienced greater feelings of affective distress towards resistance (Figure 2). Contrary to the hypothesis, there was no significant interaction between anxiety and resistance for either outcome (sensory: $\beta = 0.002$, $p = 0.945$, 95% CI [-0.070, 0.076; affect: $\beta = 0.006$, $p = 0.902$, 95% CI [-0.083, 0.094]), indicating that anxiety did not modulate sensitivity to increasing respiratory effort (i.e. slope of the regression), either in terms of breathlessness or in feelings of anxiety elicited.

Figure 2

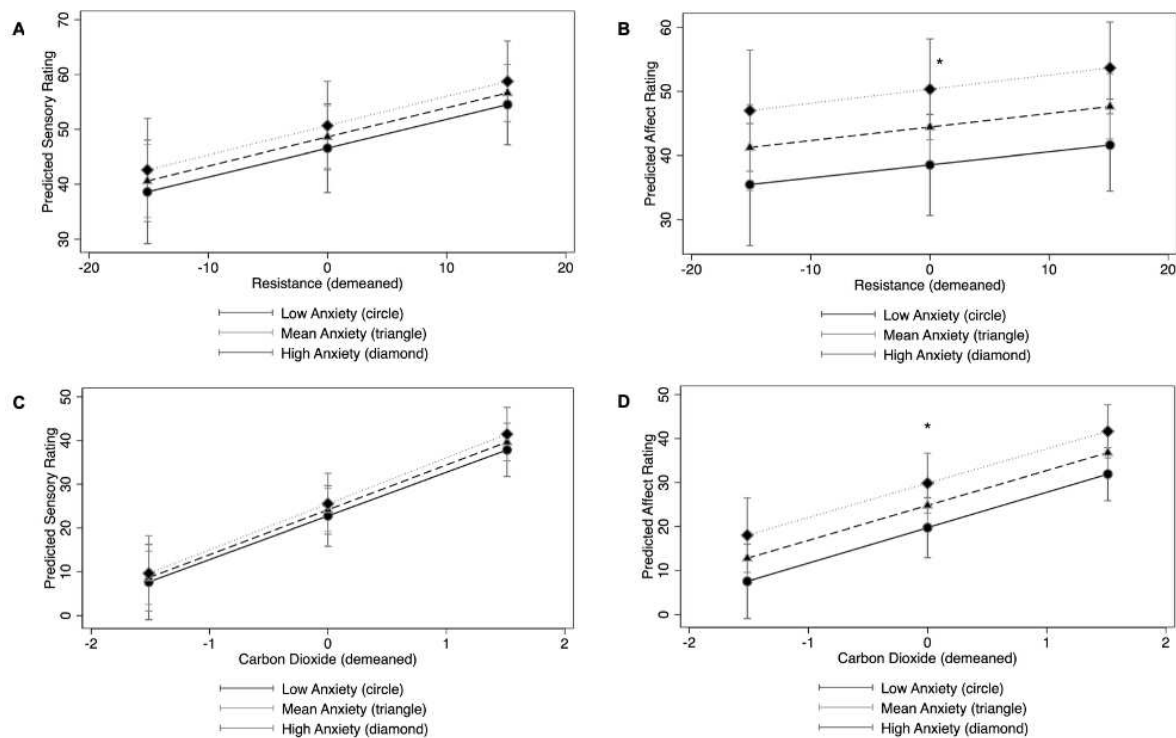


Fig.2 The effect of anxiety on predicted breathing perceptions across increasing stimulus strengths. Anxiety is grouped into low (mean – 1 SD), mean, and high (mean + 1 SD) anxiety to aid interpretation. (a) Sensory ratings towards resistance are unchanged for all anxiety levels; (b) affect ratings towards resistance significantly increase with increasing anxiety score; (c) sensory ratings towards CO₂ are unchanged for all anxiety levels; (d) affect ratings towards CO₂ significantly increase with increasing anxiety score. $n = 75$; * $p < 0.05$, 95% CI.

CO₂ stimuli

For both perceptual rating outcomes, CO₂ intensity had a significant positive effect (sensory: $\beta = 10.25$, $p < 0.001$, 95% CI [8.96, 11.53]; affect: $\beta = 7.93$, $p < 0.001$, 95% CI [6.63, 9.22]), confirming that increasing CO₂ levels were perceived as both more intense and more emotionally aversive. Unlike resistance, both perceived breathlessness ($\beta = 10.25$) and anxiety ($\beta = 7.93$) towards CO₂ were experienced to a similar degree. Similar to resistance, anxiety did not predict overall sensory ratings ($\beta = 0.90$, $p = 0.577$, 95% CI [-2.28, 4.09]) but significantly predicted overall affect ratings towards CO₂ ($\beta = 3.28$, $p < 0.05$, 95% CI [0.15, 6.40]) (Figure 2). This indicates that anxiety consistently amplified perceived anxiety, but not perceived breathlessness, across stimulus types. No significant interaction was found between anxiety and CO₂ for either outcome (sensory: $\beta = 0.18$, $p = 0.676$, 95% CI [-0.65, 1.00]; affect: $\beta = -0.08$, $p = 0.849$, 95% CI [-0.92, 0.75]), indicating that anxiety did not modulate sensitivity to changes in CO₂ levels (i.e. regression slopes). For all regression values, refer to Appendix C.

Model diagnostics

Random-effects estimates revealed substantial individual differences, supporting the use of mixed-effects models. Large standard deviations for random slopes (resistance: sensory SD = 23.3 and affect SD = 22.8; CO₂: sensory SD = 19.0 and affect SD = 19.0), along with high intraclass correlations (all ICCs > 0.76), indicate considerable

between-participant variability in baseline ratings. Conditional R^2 values indicated that over 82% of variance was explained by the models, largely attributable to random effects, while marginal R^2 values showed that fixed effects accounted for approximately 7–9% of the variance for resistance models and 26–33% for CO_2 models. Diagnostic checks indicated acceptable residual skewness (resistance: -0.6 to -0.8 ; CO_2 : -0.17 to -0.31), reasonable kurtosis (resistance: 4.66 to 5.05 ; CO_2 : 3.84 to 3.99), and approximate homoscedasticity (Appendix D). Furthermore, fewer than 1% of observations were identified as extreme outliers, supporting data quality and result reliability.

Stimulus Strength-Specific Models

To further explore the perceptual findings, a post-hoc exploratory analysis examined the effects of anxiety at individual stimulus strengths with twelve simple linear regressions (2 perceptual ratings $\times$ 3 intensities $\times$ 2 stimulus types). Anxiety did not significantly predict intensity ratings at any resistance or CO_2 level (all $p > 0.241$). In contrast, anxiety significantly predicted affect ratings at both low and high stimulus levels for resistance (low: $\beta = 4.28$, $p = 0.026$; high: $\beta = 4.45$, $p = 0.013$) and CO_2 (low: $\beta = 3.58$, $p = 0.019$; high: $\beta = 3.37$, $p = 0.049$), with weaker effects at medium levels (resistance: $\beta = 3.34$, $p = 0.086$; CO_2 : $\beta = 2.52$, $p = 0.150$) (Figure 3).

Figure 3

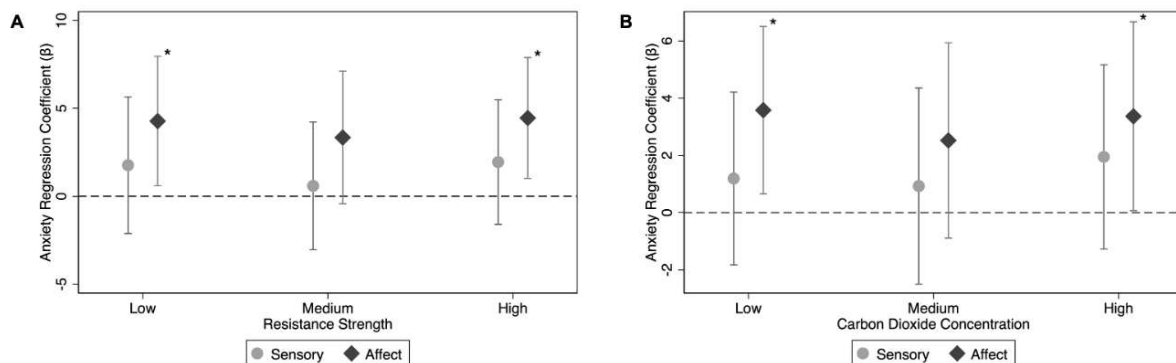


Fig.3 Coefficient plot showing the effects of each stimulus at low (resistance ~ 10 $\text{cmH}_2\text{O/L/s}$; $\text{CO}_2 \sim 2\%$), medium (resistance ~ 20 $\text{cmH}_2\text{O/L/s}$; $\text{CO}_2 \sim 4\%$) and high (resistance ~ 30 $\text{cmH}_2\text{O/L/s}$; $\text{CO}_2 \sim 6\%$) levels. Sensory ratings are denoted by light grey circles and affect ratings by dark grey diamonds. (a) Anxiety significantly predicts overall affect ratings at low and high resistance strengths, and weakly at medium strength; (b) anxiety significantly predicts overall affect ratings at low and high CO_2 levels, and weakly at a medium level. $n = 75$; * $p < 0.05$, error bars indicate 95% confidence intervals.

Ventilation

Three measures of ventilation (RR, TV, and VE) were additionally measured against stimulus level, anxiety, and their interaction. Increasing resistance significantly reduced RR ($\beta = -0.11$, $p < 0.005$, 95% CI $[-0.19, -0.04]$) and increased TV ($\beta = 0.003$, $p < 0.001$, 95% CI $[0.001, 0.004]$), with VE unchanged overall ($\beta = -0.10$, $p = 0.109$, 95% CI $[-0.23, 0.02]$). Increasing CO_2 significantly increased all three measures (RR: $\beta = 1.37$, $p < 0.001$, 95% CI $[0.85, 1.89]$; TV: $\beta = 0.16$, $p < 0.001$, 95% CI $[0.14, 0.18]$; and VE: $\beta = 4.97$, $p < 0.001$, 95% CI $[3.79, 6.14]$). However, neither anxiety nor the interaction regressor significantly predicted the ventilatory response for either stimulus

(Appendix E). Predicted values were generated and plotted to aid interpretation (Figure 4).

Figure 4

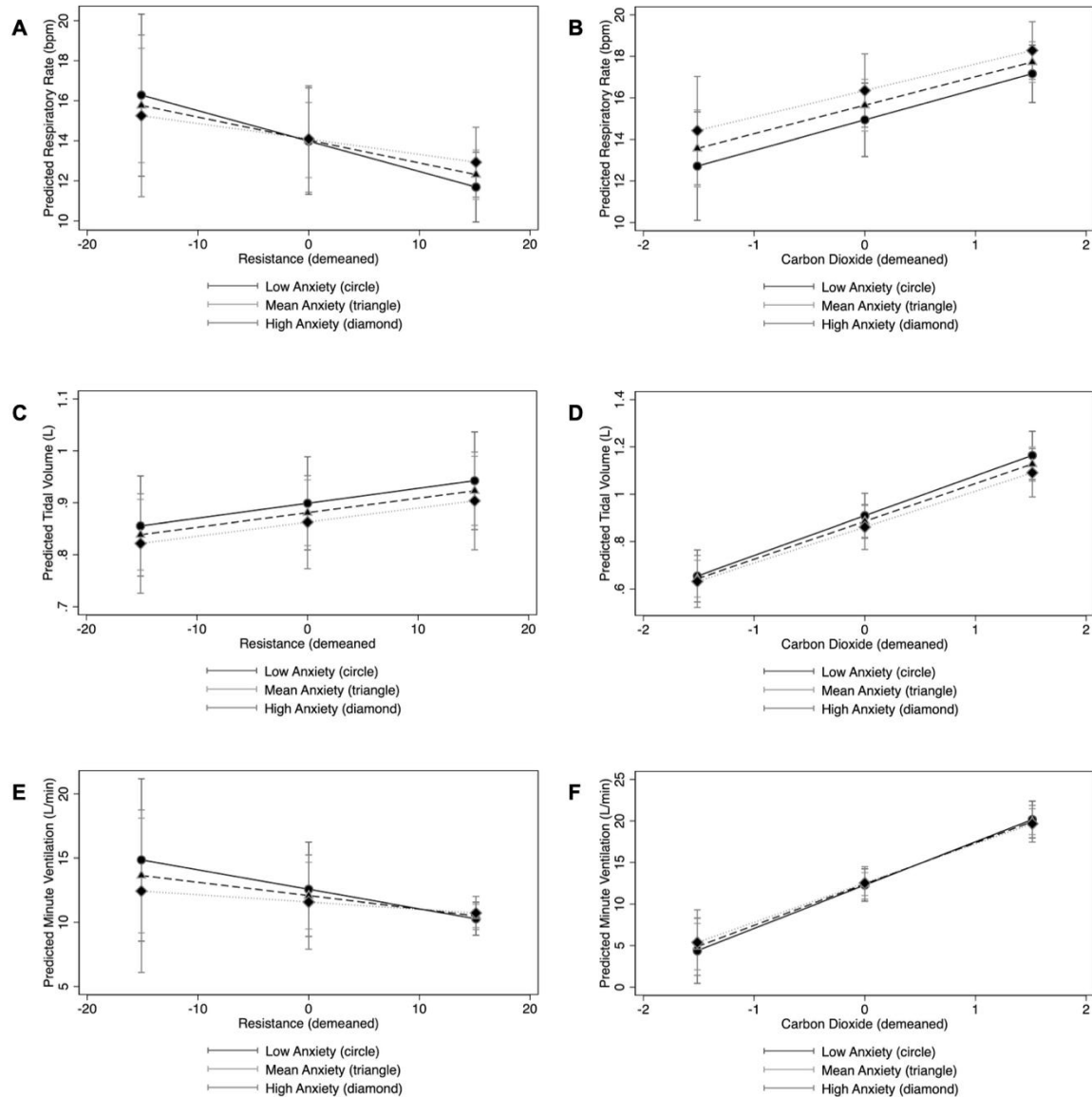


Fig.4 Predicted values for ventilatory measures in response to increasing stimulus strength. Anxiety is grouped into low (mean – 1 SD; circle), medium (mean; triangle), and high (mean + 1 SD; diamond) anxiety, to aid interpretation. (a) As resistance increases, RR decreases; (b) as CO₂ increases, RR increases; (c) As resistance increases, TV increases; (d) As CO₂ increases, TV increases; (e) As resistance increases, VE is unchanged; (f) As CO₂ increases, VE increases. $n = 75$; ns $p \geq 0.05$, error bars indicate 95% CI.

Model diagnostics

Random slope standard deviations were modest for TV (resistance = 0.25, CO₂ = 0.25), but larger for RR (resistance = 7.77, CO₂ = 4.02) and VE (resistance = 11.30, CO₂ = 1.23). High intraclass correlations for resistance measures (all ICCs > 0.77) indicate substantial between-participant variability, whereas CO₂ models showed considerable between-participant variability for RR (ICC > 0.72) and more moderate

variability for the remaining measures (ICCs < 0.53). Conditional R^2 values indicated that the full models (fixed and random effects combined) explained 77–96% of the variance in resistance and 62–84% in CO_2 models. Marginal R^2 values indicated that fixed effects alone accounted for only 2–11% of the variance, suggesting that participant-level differences contributed substantially to model fit.

Exploratory Correlations

Exploratory pairwise correlation analyses were conducted between perceptual measures (mean ratings and sensitivity slopes), ventilatory responses (means and slopes), and questionnaire measures. Statistical significance was determined using Benjamini-Hochberg false discovery rate correction ($q < 0.05$) (Appendix F). All raw r and p values have also been reported for exploratory purposes (Appendix G). As expected, anxiety measures were strongly intercorrelated ($r > 0.669$, $q < 0.001$) and were also associated with depression ($r > 0.635$, $q < 0.001$), general self-efficacy ($r < -0.290$, $q < 0.023$), and sex ($r < 0.228$, $q < 0.047$). Mean perceptual ratings were positively associated with perceptual sensitivity slopes ($r > 0.454$, $q < 0.001$), with this pattern evident both within and across resistance and hypercapnia measures (Figure 5). Ventilatory variables were also strongly intercorrelated across modalities. General self-efficacy was associated with reduced hypercapnia RR slopes ($r < -0.298$, $q < 0.044$) and increased resistance TV means ($r > 0.294$, $q < 0.047$) (Figure 6).

Figure 5

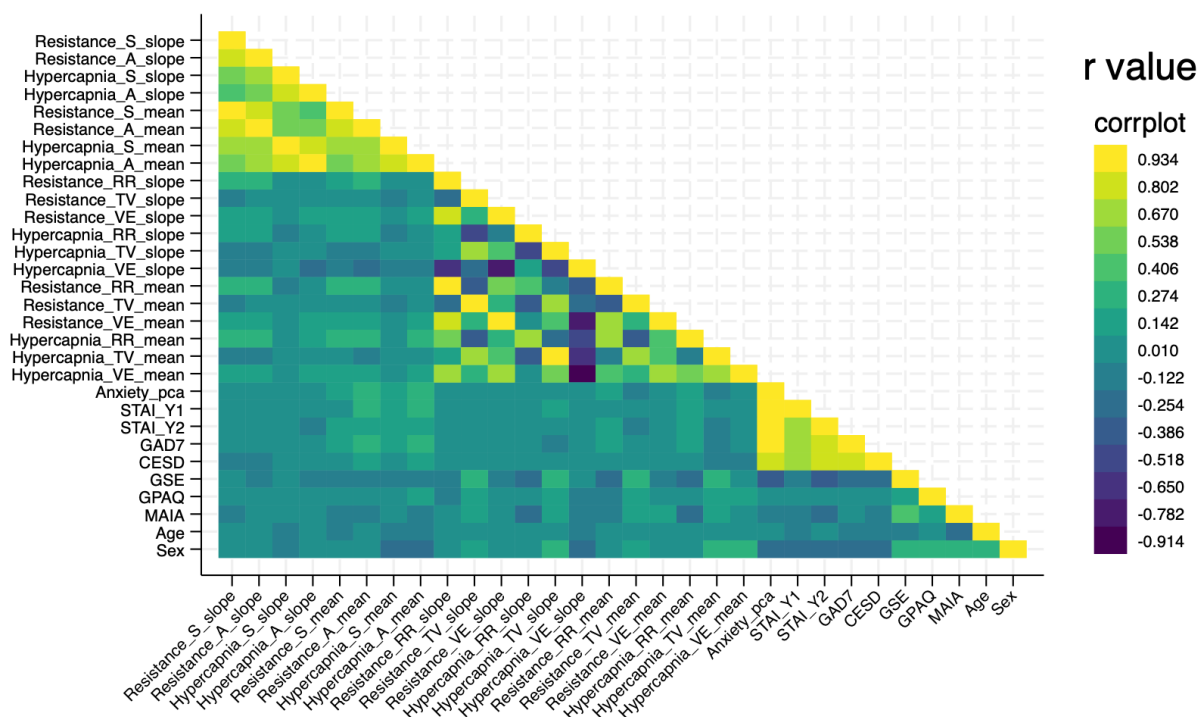


Fig 5. Pearson's correlation heat plot with perceptual, ventilatory, and questionnaire measures for both resistance and hypercapnia. S = sensory measure; A = affect measure. Prominent within-domain correlations are observed for perceptual, ventilatory and anxiety measures. The male sex regressor is

associated with lower anxiety and CESD scores and higher GSE, GPAQ, and MAIA. $n = 75$; refer to Appendix F for r and p values.

Figure 6

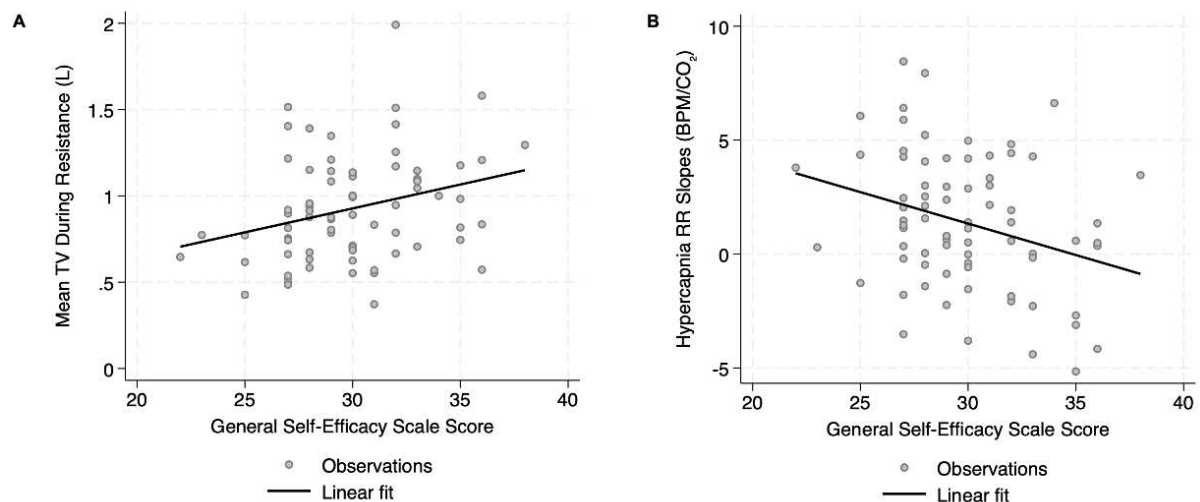


Fig 6. Scatter plots showing statistically significant associations with General Self-Efficacy Scale (GSE) scores. (a) Higher GSE scores are associated with increased overall tidal volume during the resistance task; (b) Higher GSE scores are associated with a smaller slope (interaction effect) between anxiety and respiratory rate during hypercapnia. $n = 75$; * $q < 0.05$.

Discussion

Increased Overall Affective Sensitivity with Anxiety

Higher levels of anxiety were associated with greater anxious distress during hypercapnia. Whilst previous research has linked hypercapnia sensitivity to anxiety, this has primarily been examined through categorical group comparisons between clinical anxiety (most often panic disorder) and healthy controls [7-9]. Although categorical approaches are useful for studying clinically diagnosed ADs, by treating anxiety as a continuum, the present findings show that heightened affective responses to hypercapnia are evident across the broader spectrum of anxiety severity, including at sub-clinical levels [11, 43]. Importantly, individuals with higher anxiety reported a greater affective response despite experiencing similar levels of breathlessness as those with lower anxiety. This dissociation suggests that anxiety may amplify the negative affective appraisal of hypercapnic signals without altering sensory evaluation. Consistent with this, a growing body of research proposes that mismatches between interoceptive input and subjective experience contribute to elevated anxiety states [3, 44].

Similarly, higher anxiety levels were associated with greater anxious distress during inspiratory resistance, despite no corresponding increase in perceived breathlessness. As with hypercapnia, this suggests that heightened affective

responses to respiratory stimuli occur across the anxiety spectrum, including at subclinical levels, and may help identify individuals at risk of developing ADs. Notably, previous studies investigating inspiratory resistance have primarily examined stimulus detection or discrimination thresholds, whereas the present study assessed subjective sensory and affective evaluation. Our findings suggest that anxiety is associated with preserved sensory perception but heightened negative affective appraisal of respiratory sensations. This pattern may reflect the hierarchical organisation of interoception, with different paradigms capturing distinct processing stages. Consistent with this interpretation, mismatches between sensory processing and the subjective experience of dyspnoea may contribute to heightened anxiety states [3].

The marked dissociation between sensory and affective responses observed in the present study supports a functional and neuroanatomical distinction between these aspects of respiratory interoception. Although closely related, sensory evaluation processes (e.g. “How breathless am I?”) and affective-motivational processes (e.g. “How distressing is this?”), appear to retain a degree of functional independence and are processed within partially separable neural circuits [18, 45, 46]. Consistent with this, affective aspects of interoception are often more salient than sensory aspects [25, 26] and neuroimaging studies suggest that anxiety preferentially influences affective processing of respiratory sensations rather than earlier sensory stages [24]. Together, this pattern indicates that altered interoception in anxiety may arise primarily from changes in affective processing, or from mismatches between sensory input and affective interpretation, ultimately contributing to heightened distress.

Finally, the anxiety-related increase in distress appeared strongest at the lowest and highest levels of hypercapnia and inspiratory resistance, with weaker effects at moderate intensities. One possibility is this pattern reflects heightened catastrophic interpretation of mild respiratory discomfort and amplified threat responses to severe respiratory challenges, with more normative responses to moderate stimulation. However, because the effects at medium intensities trended towards significant, this weak U-shaped pattern may more likely reflect sampling variability rather than meaningful differences across stimulus levels [3, 44].

Sensitivity to Increasing Resistance and Carbon Dioxide

Anxiety did not appear to modulate sensitivity slopes to increasing magnitudes of resistance or hypercapnia, despite being associated with increased overall perception. This pattern suggests that while anxiety may produce a baseline elevation in anxious distress, the rate at which distress increases with stimulus magnitude remains similar regardless of anxiety level. Although few studies have directly examined this relationship, Livermore and colleagues determined that dyspnoea ratings increased linearly as resistive load increased for both healthy and panic disorder patients with a respiratory disease [12], consistent with the current findings. This may indicate that mean ratings may be more useful than slopes to identify anxiety-related changes in future studies.

Random effects revealed substantial individual differences in baseline perceptual responses, indicating variability in how participants evaluated respiratory stimuli. However, these differences in slopes were not related to anxiety and likely reflect stable physiological variability across individuals, including biomechanical factors such as respiratory muscle strength, lung parenchymal elasticity, body weight, posture, and individual respiratory demands [47-50]. Importantly, our ventilatory mixed-effects

analyses indicated no association between anxiety and differences in RR, TV, or VE, suggesting anxiety-related effects on affective breathing perceptions are not associated with concurrent differences in breathing behaviour. Instead, anxiety appears to independently modulate the affective appraisal of respiratory inputs. Despite baseline variability, our experimental manipulations of resistance and hypercapnia reliably modulated perceptual ratings within individuals, indicating robust stimulus effects independent of anxiety and respiratory physiology.

Exploratory Correlations

Exploratory pairwise correlation analyses provided additional insight into broader relationships between anxiety, respiratory perception, physiological responses, and other related measures. The strong correlations between perceptual means and perceptual sensitivity slopes indicate that participants who experienced greater overall breathlessness or affective distress during the tasks also tended to show larger increases in ratings as stimulus intensity increased. These relationships were also observed across stimulus types, suggesting a general phenotype for heightened respiratory interoceptive responsiveness rather than stimulus-specific effects, despite only mean affect scores relating to general anxiety levels. Additionally, lower general self-efficacy was associated with differential ventilatory responses to the respiratory challenges, with lower respiratory rate change across hypercapnia levels and larger mean tidal volumes with inspiratory resistance. This is consistent with previous work demonstrating that breathing and posture are related to self-efficacy [51, 52], whereby those with higher self-efficacy may be more able to control respiratory rate and depth responses. Although these findings were exploratory and do not establish causality, they identify several relationships that may warrant further investigation in future studies.

Limitations

The present study has several limitations. First, our findings may not generalise to individuals with respiratory illnesses, as this group was excluded to reduce potential confounding effects. The inspiratory resistance task was always completed before the hypercapnia task to avoid carryover effects, as elevated CO₂ levels can persist for longer than the time allotted [53]. Stimulus–response measurements were not repeated due to potential habituation effects that can attenuate dyspnoea and anxiety responses [44, 54]. Finally, interoceptive processing is known to be influenced by top-down predictions and prior experience [55], which may have contributed to individual differences beyond anxiety severity.

Practical Implications and Future Directions

Our findings contribute to understanding anxiety-related interoceptive processing. Results suggest that affective responses to breathing sensations strongly increase with anxiety, supporting the idea that affective sensitivity towards bodily signals may represent a risk factor for ADs and serve as a useful intermediate phenotype for AD development in future research [56]. Importantly, elevated anxiety that does not meet clinical thresholds may still be associated with altered affective appraisal, highlighting the value of studying anxiety along a continuum in identifying potential vulnerability markers. This aligns with evidence that suggests biases in interpreting bodily sensations may emerge prior to the onset of clinically significant anxiety [11, 49]. Affective components of interoception appear to be more readily modifiable than sensory components and may therefore be a useful target for intervention [57, 58].

Cognitive behavioural therapy can reduce maladaptive interpretations of bodily sensations, and interoceptive exposure may further help reduce sensitivity to respiratory stimuli such as resistance and CO₂ [14, 59, 60], supporting more individualised treatment strategies focused on reappraising bodily signals.

Conclusion

Our results revealed that increasing anxiety was associated with consistently elevated affective responses to both resistance and hypercapnia stimuli. However, anxiety did not relate to the change in perceptual response relative to increasing levels of either stimulus, contrary to our hypothesis. In the context of existing literature, the present findings facilitate understanding of the relationship between specific aspects of interoception and anxiety severity, identify potential markers for the development of ADs, and may help to inform individualised interventions for anxiety which target interoceptive processing.

Appendices

Appendix A: Distribution of Anxiety Questionnaires

Figure 6

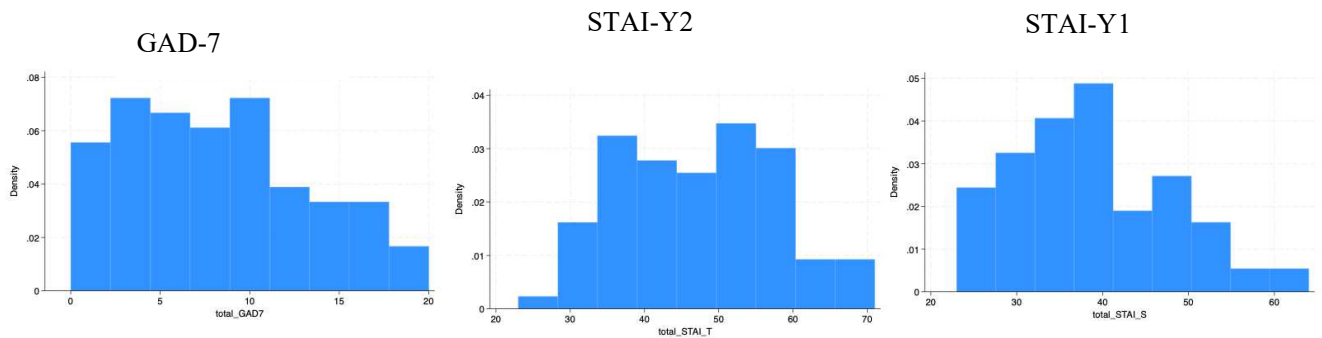


Fig.6 Histograms demonstrate the approximate normal distribution of anxiety questionnaires: GAD-7 (general anxiety disorder), STAI-Y2 (trait anxiety), and STAI-Y1 (state anxiety) respectively. n = 75.

Appendix B: PCA Results

Table 1 PCA results

Variable	PC1	PC2	h^2
GAD7	0.582	-0.463	0.553
STAI-T	0.586	-0.331	0.453
STAI-S	0.563	0.822	0.993
Metric			Total
Eigenvalue	2.404	0.348	2.752
Variance (%)	80.1	11.6	91.7

Appendix C: Primary Regression Results

Table 2 Multiple Liner Regressions fixed effects for all four models

Model	Fixed Effect	Coefficient	SE	P value	95% CI (L, U)
1 (Resistance x sensory)	Resistance	0.530	0.059	0.000**	0.41, 0.65
	Anxiety PCA	1.333	1.891	0.481	-2.37, 5.04
	Interaction	0.003	0.037	0.945	-0.07, 0.08
	Constant	48.626	2.908	0.000	42.93, 54.33
2 (Resistance x affect)	Resistance	0.212	0.071	0.003**	0.07, 0.35
	Anxiety PCA	3.821	1.842	0.038*	0.21, 7.43
	Interaction	0.006	0.045	0.902	-0.08, 0.09
	Constant	44.447	2.834	0.000	38.89, 50.00
3 (CO ₂ x sensory)	CO ₂	10.256	0.654	0.000**	8.96, 11.53
	Anxiety PCA	0.904	1.623	0.577	-2.28, 4.09
	Interaction	0.179	0.421	0.676	-0.65, 1.00
	Constant	24.146	2.501	0.000	19.24, 29.05
4 (CO ₂ x affect)	CO ₂	7.929	0.661	0.000**	6.63, 9.22
	Anxiety PCA	3.276	1.600	0.04*	0.15, 6.40
	Interaction	-0.081	0.426	0.849	-0.92, 0.75
	Constant	24.784	2.458	0.000	19.97, 29.60

Table 3 Multiple linear regression mixed effects for all four models

Model	Intercept SD	Slope SD	Residual SD	ICC	Marginal R ²	Conditional R ²	Effect Size
1	0.213	23.3	11.3	0.811	0.0934	0.829	0.00395
2	0.406	22.8	10.7	0.821	0.0691	0.834	0.00852
3	3.93	19.0	10.6	0.762	0.335	0.847	0.272
4	4.35	19.0	9.64	0.796	0.262	0.855	-0.125

Table 4 Effects of anxiety on stimulus perception at each individual level of stimulus

Model	Stimulus	Coefficient	SE	p	95% CI
1	Low resist	1.77	1.98	0.376	-2.18, 5.72
	Med resist	0.59	1.85	0.750	-3.12, 4.29
	High resist	1.94	1.81	0.286	-1.66, 5.55
2	Low resist	4.28	1.88	0.026*	0.53, 8.02
	Med resist	3.34	1.93	0.086	-0.50, 7.18
	High resist	4.45	1.75	0.013*	0.96, 7.94
3	Low CO ₂	1.19	1.54	0.439	-1.88, 4.27
	Med CO ₂	0.93	1.75	0.596	-2.56, 4.41
	High CO ₂	1.95	1.64	0.241	-1.33, 5.22
4	Low CO ₂	3.58	1.49	0.019*	0.60, 6.56
	Med CO ₂	2.52	1.74	0.150	-0.94, 5.99
	High CO ₂	3.37	1.68	0.049*	0.01, 6.72

Appendix D: Mixed Effects Residual Diagnostics

Figure 7

Resistance Sensory Diagnostics

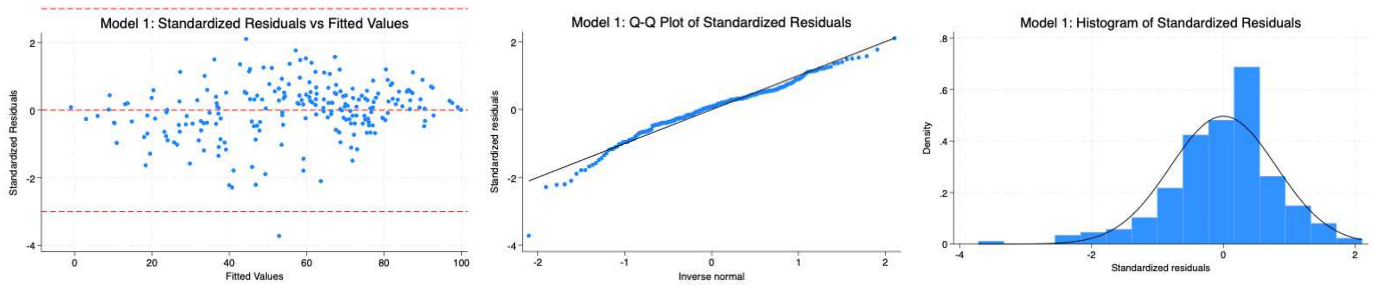


Figure 8

Resistance Affective Diagnostics

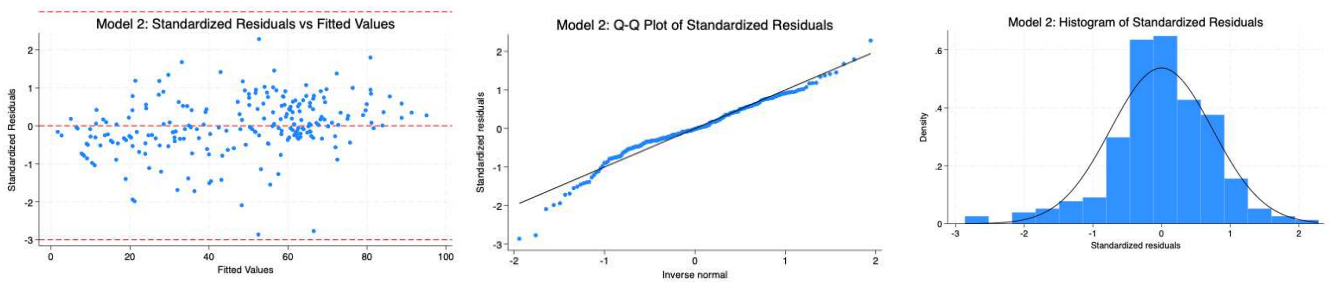


Figure 9

Hypercapnia Sensory Diagnostics

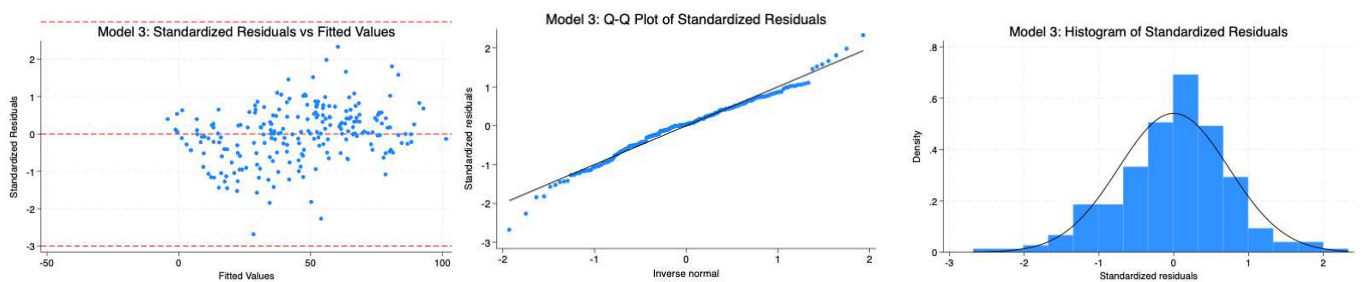
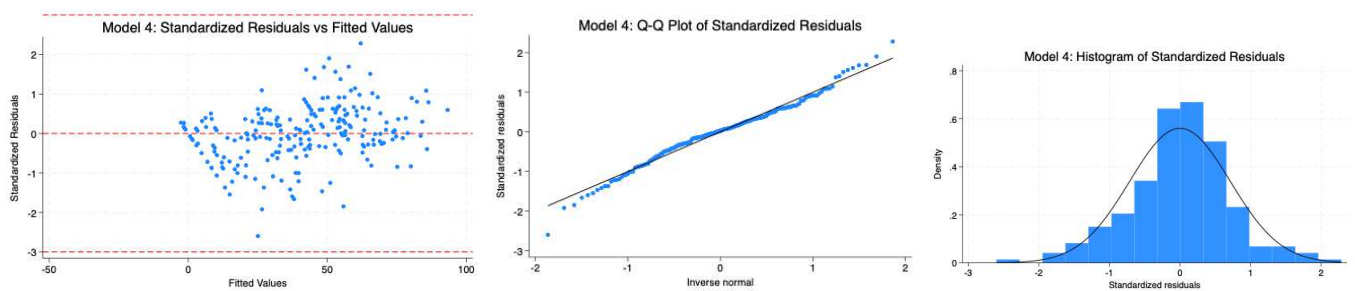


Figure 10

Hypercapnia Affective Diagnostics



Appendix E: Ventilatory Results

Table 5 Ventilatory Multiple Liner Regressions fixed effects for all six models

Model	Fixed Effect	Coefficient	SE	P value	95% CI (L, U)
A (Resistance~RR)	Resistance	-0.114	0.039	0.003**	-0.19, -0.04
	Anxiety PCA	0.033	0.621	0.957	-1.19, 1.25
	Interaction	0.024	0.025	0.331	-0.02, 0.07
	Constant	14.039	0.956	0.000	12.2, 15.9
B (Resistance~TV)	Resistance	0.003	0.0008	0.0003**	0.001, 0.004
	Anxiety PCA	-0.012	0.021	0.575	-0.05, 0.03
	Interaction	0.000	0.0005	0.909	-0.001, 0.00
	Constant	0.881	0.032	0.000	0.82, 0.94
C (Resistance~VE)	Resistance	-0.104	0.0648	0.109	-0.23, 0.023
	Anxiety PCA	-0.321	0.859	0.708	-2.0, 1.4
	Interaction	0.031	0.0420	0.462	-0.051, 0.11
	Constant	12.1	1.322	0.000	9.5, 15
D (CO ₂ ~RR)	CO ₂	1.373	0.266	0.000***	0.85, 1.9
	Anxiety PCA	0.457	0.413	0.269	-0.35, 1.3
	Interaction	-0.0627	0.172	0.715	-0.40, 0.27
	Constant	15.6	0.637	0.000	14, 17
E (CO ₂ ~TV)	CO ₂	0.160	0.0114	0.000***	0.14, 0.18
	Anxiety PCA	-0.0156	0.0221	0.482	-0.059, 0.028
	Interaction	-0.00542	0.00733	0.459	-0.020,
	Constant	0.885	0.0341	0.000	0.0089 0.82, 0.95
F (CO ₂ ~VE)	CO ₂	4.97	0.600	0.000***	3.8, 6.1
	Anxiety PCA	0.0791	0.458	0.863	-0.82, 0.98
	Interaction	-0.159	-0.411	0.681	-0.92, 0.60
	Constant	12.4	17.5	0.000	11, 14

*** p < 0.001

Table 6 Ventilatory Multiple linear regression mixed effects for all six models

Model	Intercept SD	Slope SD	Residual SD	ICC	Marginal R ²	Conditional R ²	Effect Size
A	0.00311	0.254	0.138	0.772	0.250	0.777	-0.00008
B	0.300	7.77	3.40	0.839	0.0481	0.847	0.0376
C	0.552	11.3	2.21	0.963	0.0220	0.964	0.0477
D	0.0775	0.251	0.157	0.720	0.392	0.841	-0.00837
E	1.78	4.02	3.82	0.526	0.120	0.621	-0.0968
F	4.64	1.23	6.05	0.0398	0.487	0.685	-0.246

Appendix F: Correlation Analyses - Multiple Comparisons Corrected

Table 7 Perceptual correlations (1-8) with all variables – FDR corrected q values

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Res_S_slope								
(2) Res_A_slope	0.000*							
(3) CO ₂ _S_slope	0.000*	0.000*						
(4) CO ₂ _A_slope	0.000*	0.000*	0.000*					
(5) Res_S_mean	0.000*	0.000*	0.000*	0.000*				
(6) Res_A_mean	0.000*	0.000*	0.000*	0.000*	0.000*			
(7) CO ₂ _S_mean	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*		
(8) CO ₂ _A_mean	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	
(9) Res_RR_slope	0.221	0.157	1.000	0.912	0.255	0.129	1.000	0.912
(10) Res_TV_slope	0.888	1.000	1.000	0.974	1.000	1.000	0.931	1.000
(11) Res_VE_slope	0.590	0.441	1.000	0.677	0.541	0.431	1.000	0.677
(12) CO ₂ _RR_slope	0.684	0.705	0.435	1.000	0.684	0.705	0.445	1.000
(13) CO ₂ _TV_slope	0.677	0.697	1.000	1.000	0.863	0.930	1.000	0.978
(14) CO ₂ _VE_slope	0.526	0.328	0.974	0.271	0.445	0.277	0.892	0.315
(15) Res_RR_mean	0.187	0.168	0.960	1.000	0.200	0.093	1.000	1.000
(16) Res_TV_mean	0.850	1.000	1.000	0.978	1.000	0.978	0.878	1.000
(17) Res_VE_mean	0.506	0.349	1.000	0.860	0.353	0.353	1.000	0.807
(18) CO ₂ _RR_mean	0.105	0.073	1.000	0.334	0.095	0.038*	0.979	0.187
(19) CO ₂ _TV_mean	0.877	0.903	1.000	0.978	0.974	0.931	1.000	1.000
(20) CO ₂ _VE_mean	0.558	0.400	1.000	0.353	0.446	0.336	1.000	0.400
(21) Anxiety_PCA	1.000	1.000	1.000	1.000	0.778	0.079	0.705	0.121
(22) STAI_Y1	1.000	1.000	0.979	0.967	0.960	0.159	0.684	0.111
(23) STAI_Y2	1.000	1.000	1.000	0.863	0.815	0.235	0.752	0.340
(24) GAD7	1.000	0.978	1.000	1.000	0.705	0.056	0.884	0.147
(25) CESD	0.778	0.892	1.000	1.000	1.000	0.446	1.000	0.261
(26) GSE	0.967	0.930	0.978	0.778	0.922	0.315	0.763	0.445
(27) GPAQ	0.974	1.000	1.000	0.978	0.979	1.000	1.000	0.863
(28) MAIA	0.922	1.000	0.892	0.973	0.930	0.941	0.979	0.686
(29) Age	0.978	1.000	0.803	1.000	0.937	1.000	0.735	0.948
(30) Sex	1.000	0.931	0.677	0.978	0.978	1.000	0.140	0.264

* q < 0.05

Table 8 Ventilatory correlations (9-20) with ventilation and questionnaire variables – FDR corrected q values

Variables	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
(9) Res_RR_slope												
(10) Res_TV_slope	0.242											
(11) Res_VE_slope	0.000*	0.105										
(12) CO ₂ _RR_slope	0.257	0.000*	0.647									
(13) CO ₂ _TV_slope	0.510	0.000*	0.001*	0.000*								
(14) CO ₂ _VE_slope	0.000*	0.033*	0.000*	0.686	0.000*							
(15) Res_RR_mean	0.000*	0.000*	0.000*	0.002*	0.834	0.001*						
(16) Res_TV_mean	0.238	0.000*	0.128	0.000*	0.000*	0.044*	0.000*					
(17) Res_VE_mean	0.000*	0.044*	0.000*	1.000	0.001*	0.000*	0.000*	0.047*				
(18) CO ₂ _RR_mean	0.000*	0.018*	0.024*	0.000*	0.139	0.000*	0.000*	0.015*	0.005*			
(19) CO ₂ _TV_mean	0.528	0.000*	0.001*	0.000*	0.000*	0.000*	0.849	0.000*	0.001*	0.315		
(20) CO ₂ _VE_mean	0.000*	0.051	0.000*	1.000	0.000*	0.000*	0.000	0.058	0.000*	0.000*	0.000*	
(21) Anxiety_PCA	1.000	1.000	1.000	1.000	1.000	1.000	0.778	0.960	1.000	0.684	0.686	1.000
(22) STAI_Y1	1.000	0.970	1.000	1.000	0.877	1.000	0.973	1.000	1.000	0.877	0.978	1.000
(23) STAI_Y2	1.000	0.978	1.000	1.000	1.000	1.000	0.747	0.747	1.000	0.783	0.634	0.974
(24) GAD7	1.000	1.000	1.000	0.979	0.892	1.000	0.748	0.973	1.000	0.591	0.580	1.000
(25) CESD	1.000	1.000	1.000	1.000	1.000	0.978	0.978	1.000	1.000	0.892	0.677	0.912
(26) GSE	0.400	0.088	0.840	0.044*	0.222	0.979	0.147	0.047*	0.931	0.053	0.116	1.000
(27) GPAQ	0.706	0.445	1.000	1.000	0.634	0.602	0.370	0.541	0.974	1.000	0.334	0.575
(28) MAIA	1.000	0.315	1.000	0.053	0.684	0.803	0.930	0.271	0.877	0.238	0.598	0.974
(29) Age	0.960	1.000	1.000	0.974	1.000	0.922	0.974	1.000	1.000	0.966	1.000	0.941
(30) Sex	1.000	0.487	1.000	1.000	0.187	0.222	1.000	0.445	1.000	1.000	0.025*	0.140

* q < 0.0

Table 9 Questionnaire correlations (21-30) – FDR corrected q values

Variables	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
(21) Anxiety_PCA										
(22) STAI_Y1	0.000*									
(23) STAI_Y2	0.000*	0.000*								
(24) GAD7	0.000*	0.000*	0.000*							
(25) CESD	0.000*	0.000*	0.000*	0.000*						
(26) GSE	0.022*	0.315	0.002*	0.051	0.067					
(27) GPAQ	0.933	1.000	0.912	0.950	1.000	0.758				
(28) MAIA	0.682	0.912	0.187	1.000	0.930	0.000*	0.621			
(29) Age	0.973	0.922	1.000	0.752	0.892	0.334	0.978	0.029*		
(30) Sex	0.040*	0.168	0.047*	0.053	0.051	0.142	0.175	0.186	0.016*	

* q < 0.05

Appendix G: Correlation Analyses Raw Values

Table 10 Perceptual correlations with all variables – raw r and p values

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Res_S_slope	1.000							
(2) Res_A_slope	0.861* (0.000)	1.000						
(3) CO ₂ _S_slope	0.555* (0.000)	0.614* (0.000)	1.000					
(4) CO ₂ _A_slope	0.454* (0.000)	0.600* (0.000)	0.817* (0.000)	1.000				
(5) Res_S_mean	0.984* (0.000)	0.845* (0.000)	0.539* (0.000)	0.456* (0.000)	1.000			
(6) Res_A_mean	0.814* (0.000)	0.947* (0.000)	0.580* (0.000)	0.591* (0.000)	0.831* (0.000)	1.000		
(7) CO ₂ _S_mean	0.625* (0.000)	0.615* (0.000)	0.937* (0.000)	0.774* (0.000)	0.629* (0.000)	0.609* (0.000)	1.000	
(8) CO ₂ _A_mean	0.535* (0.000)	0.613* (0.000)	0.741* (0.000)	0.898* (0.000)	0.567* (0.000)	0.673* (0.000)	0.807* (0.000)	1.000
(9) Res_RR_slope	0.211 (0.070)	0.232* (0.045)	-0.023 (0.842)	0.071 (0.546)	0.201 (0.084)	0.244* (0.035)	-0.002 (0.985)	0.071 (0.547)
(10) Res_TV_slope	-0.078 (0.508)	-0.015 (0.900)	-0.025 (0.829)	0.049 (0.674)	-0.025 (0.830)	-0.026 (0.826)	-0.065 (0.581)	0.036 (0.760)
(11) Res_VE_slope	0.132 (0.258)	0.158 (0.174)	0.015 (0.900)	0.118 (0.313)	0.140 (0.231)	0.161 (0.169)	0.023 (0.846)	0.118 (0.314)
(12) CO ₂ _RR_slope	0.116 (0.324)	0.109 (0.350)	-0.160 (0.171)	-0.016 (0.892)	0.115 (0.325)	0.110 (0.346)	-0.157 (0.179)	-0.016 (0.890)
(13) CO ₂ _TV_slope	-0.118 (0.314)	-0.112 (0.340)	-0.004 (0.972)	0.013 (0.912)	-0.083 (0.480)	-0.065 (0.577)	-0.010 (0.932)	0.048 (0.685)
(14) CO ₂ _VE_slope	-0.143 (0.221)	-0.182 (0.118)	-0.051 (0.662)	-0.196 (0.093)	-0.156 (0.181)	-0.194 (0.095)	-0.075 (0.523)	-0.186 (0.109)
(15) Res_RR_mean	0.220 (0.058)	0.227* (0.050)	-0.057 (0.624)	0.004 (0.972)	0.216 (0.062)	0.261* (0.024)	-0.019 (0.870)	0.033 (0.779)
(16) Res_TV_mean	-0.086 (0.465)	-0.021 (0.861)	-0.033 (0.779)	0.045 (0.704)	-0.033 (0.781)	-0.045 (0.699)	-0.079 (0.498)	0.014 (0.903)
(17) Res_VE_mean	0.146 (0.210)	0.176 (0.130)	-0.028 (0.810)	0.084 (0.473)	0.175 (0.134)	0.175 (0.133)	-0.015 (0.897)	0.092 (0.432)
(18) CO ₂ _RR_mean	0.254* (0.028)	0.272* (0.018)	-0.004 (0.973)	0.180 (0.122)	0.260* (0.024)	0.304* (0.008)	0.042 (0.724)	0.221 (0.057)
(19) CO ₂ _TV_mean	-0.080 (0.496)	-0.073 (0.532)	-0.018 (0.877)	0.044 (0.710)	-0.050 (0.668)	-0.064 (0.584)	-0.027 (0.815)	0.019 (0.874)
(20) CO ₂ _VE_mean	0.137 (0.240)	0.166 (0.154)	0.015 (0.902)	0.175 (0.133)	0.155 (0.183)	0.179 (0.124)	0.032 (0.788)	0.166 (0.155)
(21) Anxiety_PCA	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)	0.097 (0.409)	0.269* (0.020)	0.110 (0.349)	0.247* (0.033)
(22) STAI_Y1	-0.024 (0.840)	-0.016 (0.890)	0.042 (0.720)	0.056 (0.636)	0.058 (0.620)	0.231* (0.046)	0.115 (0.326)	0.252* (0.029)
(23) STAI_Y2	0.008 (0.944)	-0.028 (0.811)	-0.024 (0.837)	-0.083 (0.480)	0.091 (0.438)	0.206 (0.076)	0.102 (0.385)	0.178 (0.126)
(24) GAD7	0.015 (0.901)	0.044 (0.708)	-0.016 (0.889)	0.030 (0.801)	0.110 (0.347)	0.284* (0.013)	0.078 (0.504)	0.235* (0.042)
(25) CESD	-0.097 (0.410)	-0.077 (0.514)	-0.035 (0.769)	-0.003 (0.982)	-0.001 (0.992)	0.155 (0.183)	0.033 (0.776)	0.199 (0.088)
(26) GSE	-0.055 (0.638)	-0.066 (0.574)	-0.044 (0.705)	-0.097 (0.408)	-0.068 (0.560)	-0.185 (0.112)	-0.100 (0.395)	-0.156 (0.180)
(27) GPAQ	-0.049 (0.674)	-0.037 (0.752)	-0.027 (0.819)	0.044 (0.706)	-0.042 (0.723)	0.004 (0.976)	-0.007 (0.953)	0.084 (0.476)
(28) MAIA	-0.068 (0.562)	0.016 (0.893)	0.075 (0.521)	-0.053 (0.653)	-0.066 (0.575)	-0.061 (0.601)	-0.041 (0.725)	-0.114 (0.332)
(29) Age	-0.045 (0.700)	0.028 (0.811)	-0.093 (0.428)	-0.003 (0.981)	-0.063 (0.594)	0.027 (0.820)	-0.105 (0.368)	-0.060 (0.608)
(30) Sex	-0.005 (0.965)	0.064 (0.584)	-0.119 (0.311)	-0.044 (0.707)	-0.047 (0.689)	-0.003 (0.982)	-0.238* (0.039)	-0.198 (0.089)

Note. For each pairwise correlation the top number represents the R coefficient, and the bottom number represents the P value. * p < 0.05

Table 11 Ventilatory correlations with all ventilation and questionnaire variables – raw r and p values

Variables	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
(9) Res_RR_slope	1.000											
(10) Res_TV_slope	-0.204 (0.080)	1.000										
(11) Res_VE_slope	0.828* (0.000)	0.255* (0.027)	1.000									
(12) CO ₂ _RR_slope	0.200 (0.086)	-0.462* (0.000)	-0.123 (0.293)	1.000								
(13) CO ₂ _TV_slope	0.145 (0.213)	0.619* (0.000)	0.425* (0.000)	-0.552* (0.000)	1.000							
(14) CO ₂ _VE_slope	-0.609* (0.000)	-0.310* (0.007)	-0.723* (0.000)	0.113 (0.333)	-0.581* (0.000)	1.000						
(15) Res_RR_mean	0.904* (0.000)	-0.446* (0.000)	0.550* (0.000)	0.395* (0.000)	-0.088 (0.450)	-0.429* (0.000)	1.000					
(16) Res_TV_mean	-0.205 (0.078)	0.996* (0.000)	0.244* (0.035)	-0.451* (0.000)	0.615* (0.000)	-0.297* (0.010)	-0.447* (0.000)	1.000				
(17) Res_VE_mean	0.835* (0.000)	0.298* (0.010)	0.949* (0.000)	-0.037 (0.755)	0.424* (0.000)	-0.733* (0.000)	0.633* (0.000)	0.294* (0.010)	1.000			
(18) CO ₂ _RR_mean	0.552* (0.000)	-0.332* (0.004)	0.322* (0.005)	0.677* (0.000)	-0.240* (0.038)	-0.505* (0.000)	0.640* (0.000)	-0.340* (0.003)	0.372* (0.001)	1.000		
(19) CO ₂ _TV_mean	0.142 (0.223)	0.649* (0.000)	0.412* (0.000)	-0.445* (0.000)	0.935* (0.000)	-0.657* (0.000)	-0.086 (0.462)	0.652* (0.000)	0.429* (0.000)	-0.185 (0.112)	1.000	
(20) CO ₂ _VE_mean	0.606* (0.000)	0.290* (0.012)	0.692* (0.000)	0.015 (0.898)	0.590* (0.000)	-0.980* (0.000)	0.440* (0.000)	0.282* (0.014)	0.721* (0.000)	0.549* (0.000)	0.677* (0.000)	1.000
(21) Anxiety_PCA	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)	0.097 (0.407)	-0.057 (0.627)	0.016 (0.892)	0.115 (0.327)	-0.114 (0.330)	-0.032 (0.783)
(22) STAI_Y1	-0.024 (0.837)	0.055 (0.642)	-0.012 (0.918)	-0.016 (0.892)	0.080 (0.496)	-0.017 (0.887)	0.053 (0.649)	0.005 (0.967)	0.005 (0.969)	0.080 (0.496)	-0.045 (0.699)	-0.008 (0.948)
(23) STAI_Y2	0.016 (0.890)	-0.047 (0.687)	0.010 (0.935)	-0.027 (0.818)	-0.001 (0.991)	0.020 (0.867)	0.104 (0.377)	-0.103 (0.378)	0.007 (0.954)	0.096 (0.414)	-0.125 (0.285)	-0.051 (0.665)
(24) GAD7	0.007 (0.952)	-0.005 (0.965)	0.002 (0.986)	0.043 (0.717)	-0.076 (0.517)	-0.004 (0.976)	0.103 (0.380)	-0.053 (0.653)	0.031 (0.791)	0.132 (0.260)	-0.134 (0.252)	-0.027 (0.816)
(25) CESD	-0.021 (0.860)	0.013 (0.910)	0.000 (1.000)	-0.022 (0.850)	0.003 (0.982)	0.046 (0.697)	0.047 (0.690)	-0.028 (0.810)	0.002 (0.986)	0.075 (0.520)	-0.119 (0.309)	-0.071 (0.543)
(26) GSE	-0.166 (0.155)	0.264* (0.022)	-0.087 (0.456)	-0.298* (0.009)	0.210 (0.071)	-0.042 (0.720)	-0.235* (0.042)	0.294* (0.011)	-0.064 (0.587)	-0.288* (0.012)	0.250* (0.031)	0.014 (0.905)
(27) GPAQ	-0.109 (0.352)	0.157 (0.177)	-0.013 (0.914)	-0.003 (0.983)	0.125 (0.286)	-0.130 (0.267)	-0.172 (0.141)	0.140 (0.231)	-0.050 (0.672)	0.013 (0.909)	0.180 (0.122)	0.135 (0.249)
(28) MAIA	-0.038 (0.746)	0.186 (0.111)	0.029 (0.806)	-0.286* (0.013)	0.116 (0.321)	-0.093 (0.428)	-0.067 (0.570)	0.196 (0.092)	0.080 (0.495)	-0.205 (0.078)	0.131 (0.264)	0.051 (0.664)
(29) Age	0.058 (0.624)	0.021 (0.858)	0.007 (0.951)	0.051 (0.663)	-0.011 (0.926)	-0.069 (0.559)	0.050 (0.670)	0.018 (0.879)	-0.003 (0.981)	0.056 (0.633)	0.000 (0.998)	0.061 (0.601)
(30) Sex	0.018 (0.877)	0.149 (0.201)	-0.013 (0.914)	-0.005 (0.964)	0.220 (0.058)	-0.210 (0.071)	0.000 (0.999)	0.156 (0.181)	0.017 (0.884)	-0.030 (0.800)	0.321* (0.005)	0.239* (0.039)

Note. For each pairwise correlation the top number represents the R coefficient, and the bottom number represents the P value. * p < 0.05

Table 12 Questionnaire correlations – raw r and p values

Variables	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
(21) Anxiety_PCA	1.000									
(22) STAI_Y1	0.873* (0.000)	1.000								
(23) STAI_Y2	0.909* (0.000)	0.685* (0.000)	1.000							
(24) GAD7	0.903* (0.000)	0.669* (0.000)	0.751* (0.000)	1.000						
(25) CESD	0.852* (0.000)	0.635* (0.000)	0.819* (0.000)	0.832* (0.000)	1.000					
(26) GSE	-0.325* (0.004)	-0.185 (0.111)	-0.395* (0.000)	-0.290* (0.012)	-0.276* (0.016)	1.000				
(27) GPAQ	0.063 (0.590)	0.038 (0.749)	0.072 (0.539)	0.060 (0.612)	0.024 (0.839)	0.101 (0.390)	1.000			
(28) MAIA	-0.117 (0.318)	-0.071 (0.547)	-0.221 (0.057)	-0.021 (0.861)	-0.066 (0.572)	0.449* (0.000)	0.127 (0.277)	1.000		
(29) Age	-0.054 (0.647)	-0.069 (0.555)	0.025 (0.829)	-0.102 (0.385)	-0.076 (0.518)	-0.181 (0.121)	-0.046 (0.693)	-0.315* (0.006)	1.000	
(30) Sex	-0.302* (0.009)	-0.228* (0.050)	-0.294* (0.010)	-0.287* (0.013)	-0.290* (0.012)	0.238* (0.040)	0.225 (0.052)	0.222 (0.056)	0.338* (0.003)	1.000

Note. For each pairwise correlation the top number represents the R coefficient, and the bottom number represents the P value. * p < 0.05

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