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Altered interoceptive–exteroceptive profile in Generalized Anxiety Disorder: Evidence from bayesian psychophysics and metacognitive modeling

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ABSTRACT

Generalized Anxiety Disorder (GAD) is believed to involve impaired processing of external information and excessive focus on internal bodily signals. However, comparative evidence on exteroceptive and interoceptive performance within a common experimental framework remains limited. In the present study, individuals with GAD ($n = 31$) and healthy controls (HC; $n = 31$) completed a heart rate discrimination (HRD) task, combined with Bayesian psychophysical modeling and signal detection theory–based metacognitive indices. At the first-order level, we estimated an HRD threshold parameter (α), indexing systematic tendency in cardiac judgments, and a precision parameter (β; lower β indicates greater precision), indexing the sharpness or uncertainty of those judgments. At the second-order level, we estimated metacognitive sensitivity (meta-d′), reflecting how well confidence tracked first-order task performance. We also included exploratory self-report measures of bodily awareness and bodily appraisal using the Body Awareness Questionnaire and the Body Sensations Interpretation Questionnaire. In the HC group, participants showed a relative exteroceptive advantage within the HRD framework, reflected in lower β and higher meta-d′ in the exteroceptive condition than in the interoceptive condition. By contrast, this within-group exteroceptive advantage was not observed in GAD. Relative to HC participants, individuals with GAD showed greater precision in HRD-based cardiac judgments (lower β) and reduced exteroceptive metacognitive sensitivity (lower meta-d′), whereas no group differences emerged for α or the exploratory self-report measures. Taken together, these findings suggest an altered interoceptive–exteroceptive performance profile in GAD, characterized by greater precision in cardiac judgments alongside weaker exteroceptive metacognitive monitoring. These results may help refine theoretical accounts of internal–external information processing in anxiety and inform future computational approaches to assessment in GAD.

1. Introduction

Generalized Anxiety Disorder (GAD) is one of the most common anxiety disorders, characterized by persistent and excessive worry, along with an inability to control anxiety in response to everyday events (Ruscio et al., 2017). Epidemiological studies indicate that the lifetime prevalence of GAD in the general population ranges from 4.2% to 12.7% (Kessler et al., 2005). GAD significantly impairs individuals' quality of life and is often comorbid with other disorders such as depression and panic disorder (Ruscio et al., 2017). From a pathological perspective, the core features of GAD are believed to involve excessive worry and heightened sensitivity to uncertainty. Patients struggle to control these worries, often accompanied by significant physical symptoms and functional impairment (Dugas et al., 2007). This persistent state of hypervigilance is not only manifested in an exaggerated focus on external environmental threats but also extends to abnormal perception of internal physiological signals (Paulus & Stein, 2010). While traditional research has often treated these external and internal processes

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separately, an integrative perspective is essential to understand how the brain prioritizes and monitors sensory information across the internal-external divide.

Cognitive models of GAD have primarily emphasized abnormalities in the processing of external information, especially deficits in attentional control, inhibitory regulation, and the monitoring of potentially threatening environmental cues (Eysenck et al., 2007; Hirsch & Mathews, 2012). Consistent with this view, anxious individuals often show less efficient performance on tasks that require inhibition or externally oriented control (Breuer et al., 2024; Hallion et al., 2017; Houghton et al., 2020). Wells' metacognitive account likewise highlights persistent monitoring of external events and their possible negative consequences as a key feature of GAD (Wells, 2010). Although these models are important for understanding external threat monitoring, they do not fully explain the bodily symptoms and persistent sense of internal alarm that are equally characteristic of the disorder.

Interoceptive models provide an important complementary perspective. Interoception refers to the sensing, interpretation, and integration of internal physiological signals, including those arising from the cardiovascular, respiratory, gastrointestinal, and autonomic systems (Craig, 2003; Khalsa et al., 2018). Beyond its role in physiological homeostasis, interoception is increasingly recognized as central to emotional experience, self-regulation, decision-making, and self-related processing (Craig, 2009). Contemporary accounts further emphasize that interoception is not a unitary construct, but comprises multiple related yet dissociable dimensions (Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022). Self-report measures capture distinct facets of bodily experience and belief. For example, the Body Awareness Questionnaire (BAQ) indexed subjective awareness of everyday, non-emotional bodily processes, whereas the Body Sensations Interpretation Questionnaire (BSIQ) indexed threat-related interpretations of ambiguous bodily sensations (Desmedt et al., 2022; Vancleef & Peters, 2008). Behavioral tasks capture task-based interoceptive performance, reflecting how individuals judge, discriminate, or estimate internal bodily signals (Hickman et al., 2020). A further distinction concerns metacognitive monitoring, namely the extent to which individuals can evaluate the likely correctness or reliability of their own interoceptive judgments (Garfinkel et al., 2015; Suksasilp & Garfinkel, 2022). This multidimensional perspective is especially important in anxiety research, because subjective body awareness, threat-related interpretation of bodily sensations, task-based discrimination performance, and metacognitive monitoring may not vary in parallel.

Prior research suggests that GAD is associated with altered processing of bodily signals. For example, Andor et al. (2008) found that individuals with GAD were more accurate in detecting brief autonomic arousal and were more likely to interpret such sensations as evidence that worry was uncontrollable or dangerous. In pharmacological challenge studies, female patients with GAD showed faster heart rate responses, stronger anxiety reactions, and more acute subjective experiences during low-dose isoproterenol perturbation (Teed et al., 2022). Related work also reported larger heart-evoked-potential changes and stronger cardiopulmonary sensations in GAD under autonomic stimulation (Verdonk et al., 2024). Together, these findings suggest heightened salience of internal physiological signals in GAD, particularly under conditions of bodily perturbation. Importantly, heightened task-based sensitivity to bodily signals does not necessarily imply better metacognitive monitoring of those signals, as first-order cardiac judgments and second-order confidence calibration may vary independently in anxiety.

Recent predictive-processing accounts offer a useful framework for understanding why interoceptive dimensions may diverge. Within this view, interoceptive experience is not a passive readout of bodily signals, but an inferential process in which predictions about bodily states are constrained by ascending visceral input (Barrett & Simmons, 2015; Seth, 2013). On this account, interoceptive judgments may depend on the integration of prior beliefs and current bodily evidence, weighted by their relative precision (Ainley et al., 2016). This perspective is especially relevant to anxiety, where altered weighting of internal evidence or prior expectations may shape how bodily signals are judged, interpreted, and monitored.

From this perspective, cognitive/exteroceptive and interoceptive accounts of GAD need not be treated as competing explanations. Rather, both external and internal signals contribute to belief updating, body regulation, and adaptive behavior under uncertainty (Petzschner et al., 2021; Pezzulo et al., 2015). The key question, therefore, is not whether GAD is defined by external or internal processing alone, but whether the relative balance between these channels is altered. In the present study, we adopt this integrative perspective and test whether GAD is associated with an altered interoceptive–exteroceptive task profile, reflected in the relative weighting and monitoring of cardiac judgments and matched auditory judgments within the same psychophysical framework.

This framework also motivates our use of the Heart Rate Discrimination (HRD) task. Unlike heartbeat counting and related tracking/tapping tasks, which rely on uncontrolled endogenous signals and are strongly shaped by subjective beliefs about heart rate (Ring et al., 2015; Ring & Brener, 2018), the HRD estimates trial-wise cardiac judgments using dynamically titrated auditory stimuli referenced to each participant's current heart rate (Legrand et al., 2022). We treated the HRD as a psychophysical task that quantifies bias, precision, and metacognitive sensitivity in task-based cardiac judgments about current heart rate. Within this framework, these judgments reflect momentary estimates of cardiac state that may be shaped jointly by subjective beliefs, bodily inputs, and decision processes (Legrand et al., 2022). The threshold parameter α indexes bias in heart-rate estimation, the slope parameter β indexes cardiac judgment precision (with smaller values indicating greater precision), and meta-d' indexes metacognitive sensitivity, namely how well confidence tracks the first-order task performance. The exteroceptive condition served as a matched auditory temporal judgment control condition, allowing us to compare relative profiles of cardiac and auditory judgments within a common task architecture. Additionally, we included two self-report measures that indexed distinct facets of bodily experience and belief: the Body Awareness Questionnaire (BAQ), which captures subjective awareness of everyday bodily processes, and the Body Sensations Interpretation Questionnaire (BSIQ), which captures threat-related interpretations of ambiguous bodily sensations. These measures were included to characterize self-reported bodily awareness and bodily appraisal in GAD alongside task-based psychophysical indices.

Based on the above, we formulated two primary hypotheses and two secondary exploratory questions. First, within the HRD framework, healthy controls were expected to show a relative exteroceptive advantage, reflected in greater judgment precision (lower β) and higher metacognitive sensitivity (higher meta-d') for matched auditory judgments than for cardiac judgments. Second, we expected this relative exteroceptive advantage to be reduced in GAD, reflected in relatively enhanced cardiac-judgment precision and/or reduced exteroceptive metacognitive sensitivity. In addition, we examined group differences in the threshold parameter α as a secondary exploratory question. Because α indexes systematic over- or underestimation of one's own heart rate, and the available literature does not provide a sufficiently specific basis for a directional prediction regarding group differences in this parameter, we treated α as a secondary exploratory outcome. We also explored whether group differences would emerge in self-reported bodily awareness and bodily appraisal, as indexed by the BAQ and BSIQ.

2. Methods

2.1. Participants

We used G*Power 3.1 to conduct an a priori sample-size estimation (Faul et al., 2009). Because the primary aim of the study concerned group differences in the relative interoceptive–exteroceptive profile of

HRD performance, sample-size planning was anchored on the Group ×Condition interaction in a 2 (Group: GAD vs. HC) × 2 (Condition: interoception vs. exteroception) mixed ANOVA. As the main analyses were ultimately performed using linear mixed-effects models, this ANOVA-based calculation should be understood as an approximate planning approach. In the absence of closely matched prior estimates for this interaction, we followed conventional benchmarks and powered for a medium interaction, f = 0.25 (Cohen, 1988). With α = 0.05 and 1 −β = 0.80, the resulting calculation indicated a total sample of N = 34 (17 per group). A total of 62 participants were recruited for this study, including 31 individuals in the GAD group and 31 individuals in the HC group. Questionnaire analyses (BAQ and BSIQ) were treated as secondary exploratory analyses rather than as primary power-planning targets. To clarify the sensitivity of the final sample for these secondary analyses, we conducted a post hoc sensitivity analysis in G*Power 3.1. This indicated that, with n = 31 per group, α = .05, and 1 −β = .80, the study was powered to detect independent-group effects of approximately d = 0.72. Accordingly, smaller questionnaire effects might not have been detected. Participants in the GAD group were diagnosed through structured clinical interviews using the Mini-International Neuropsychiatric Interview (MINI) (Sheehan et al., 1998) and met the DSM-5 diagnostic criteria for GAD. Additionally, they had a score greater than 10 on the GAD-7 scale (Spitzer et al., 2006), indicating clinically significant levels of anxiety (Teed et al., 2022). Healthy controls had no current or past psychiatric diagnosis. To obtain a relatively clinically homogeneous GAD sample, current or past psychiatric disorders other than GAD were exclusionary in the GAD group, including depressive disorders, panic disorder, bipolar disorder, psychotic disorders, substance use disorders, and obsessive-compulsive disorder. For both groups, participants were also excluded if they met any of the following self-reported criteria: current psychotropic medication use or ongoing psychological therapy; history of serious neurological disorder or brain injury (e.g., epilepsy, stroke, traumatic brain injury); serious cardiovascular, metabolic, or endocrine disorder; pregnancy or breastfeeding; auditory or visual impairment; or other physiological factors that could interfere with task performance. The GAD group consisted of 7 males, with ages ranging from 19 to 31 years. Participants in the HC group did not meet the diagnostic criteria for any mental disorder according to DSM-5, and had GAD-7 scores below 5, indicating low levels of anxiety symptoms. This group included 12 males, with ages also ranging from 19 to 31 years. The distribution of sex did not differ significantly between groups, $\chi^2(1, N = 62) = 1.90, p = .17$. Participants reported both sex assigned at birth and current gender identity. In this sample, these were concordant for all participants; no participants reported a gender-diverse identity. Prior to the experiment, all participants signed an informed consent form, and no participants dropped out of the study. The research protocol was approved by the Ethics Committee of the Department of Psychology, Nanjing University.

2.2. Measures

2.2.1. Body Awareness Questionnaire (BAQ)

The BAQ was used to assess subjective awareness of everyday, non-emotional bodily processes. The total score was used as an index of self-reported bodily awareness (Desmedt et al., 2022; Shields et al., 1989). The BAQ comprises 18 items indexing subjective awareness of non-emotional bodily processes, including sensitivity to bodily rhythms and cycles, recognition of incipient illness, and anticipation of bodily reactions. Example items include: “I can always tell when I bump myself whether or not it will become a bruise”, “I know in advance when I'm getting the flu”, and “I am aware of a cycle in my activity level throughout the day”. Participants were asked to respond to statements on a scale from 1 (‘not at all true about me’) to 7 (‘very true about me’). The total score was used as the index of interoceptive sensibility. Internal consistency in the present sample was good (Cronbach's α =.83).

2.2.2. Body Sensations Interpretation Questionnaire (BSIQ)

The BSIQ was used to assess threat-related interpretation of ambiguous bodily experiences, while noting that the questionnaire also includes broader general and social scenarios. The instrument was originally developed by Clark et al. (1997) and has demonstrated good psychometric properties (Vancleef & Peters, 2008). It comprises 27 scenarios spanning four domains: panic-related bodily sensations, other bodily symptoms, social events, and general events. Each scenario describes an everyday yet ambiguous bodily or social experience (e.g., “You notice that your heart is beating quickly and pounding. Why??”) and offers three possible explanations—one threatening/negative (e.g., “Because there is something wrong with your heart.”) and two relatively neutral alternatives (e.g., “Because you have been physically active.”; “Because you are feeling excited.”). For each explanation, participants provide a likelihood rating from 0 (“not at all likely”) to 100 (“very likely”). The threat/negative explanation rating for each item is taken as the threat-interpretation bias score. This measure captures the tendency to interpret common, ambiguous bodily sensations as threatening or pathological. Internal consistency in the present sample was excellent (Cronbach's α =.91).

2.2.3. Heartbeat Discrimination Task (HRD)

To assess task-based cardiac judgment bias, precision, and metacognitive sensitivity, we implemented the HRD following the psychophysical approach of Legrand et al. (2022). The task yields estimates of the systematic bias between perceived and actual heart rate (threshold α) and the precision of these judgments (slope β), and confidence-based metacognitive sensitivity (meta-d′). Prior to the main task, participants completed a practice block (5 interoception and 5 exteroception trials) with immediate feedback to familiarize them with the procedure. The main task comprised 120 trials (60 interoception, 60 exteroception) presented in randomized order, with short breaks after every 30 trials. Feedback was provided only during practice to familiarize participants with the task requirements; no trial-by-trial feedback was provided during the main task and both groups and both conditions underwent the same practice procedure. Total duration was approximately 30 min.

In the interoception condition, each trial included: (1) a 5-s cardiac focusing period during which participants attended to their heartbeat without responding, while a finger clip photoplethysmograph recorded heart rate in real time; (2) a judgment period in which a sequence of five pure tones (440 Hz, 200 ms) was presented at a tempo offset (Δ-BPM) relative to the participant's current heart rate; participants judged whether the tone sequence was “faster” or “slower” than their heartbeat; and (3) a confidence rating, provided on a 0 (completely unsure) to 100 (completely certain) visual analog scale. The slider's starting position was jittered around the midpoint to reduce default-choice bias. In the exteroception condition, participants compared two sequential tone sequences (440 Hz, 200 ms) and judged whether the second was faster or slower than the first; timing and response procedures matched the interoception condition.

All trials used a two-interval forced-choice (2-IFC) design, with an adaptive Bayesian staircase (Psi method) employed to adjust Δ-BPM on each trial. This method efficiently sampled the psychometric function, converging on the point of subjective equality (PSE) and slope (precision). The Psi method, implemented using the Systole Python package (Legrand & Allen, 2022), was applied consistently across both interoceptive and exteroceptive conditions, ensuring comparable stimulus presentation. Specifically, the α parameter, reflecting response bias, ranged from [-50.5, 50.5] BPM, while the β parameter, indicating sensitivity to heart rate changes, ranged from [0.1, 25]. The precision for both α and β was set at 1 BPM and 0.1, respectively, with a lapse rate of 0.02. Catch trials were interleaved with standard trials to assess response consistency. The maximum response window was set to 8 s, and trials advanced automatically if no response was recorded. The mean proportion of valid trials was 99.0% for GAD–Extero, 98.1% for GAD–Intero, 97.8% for HC–Extero, and 96.3% for HC–Intero. These invalid trials were due to response timeouts. Participants were seated at rest in a quiet room and instructed to minimize movement to reduce motion artifacts in pulse recordings.

2.2.4. Physiological recordings

In line with Legrand et al. (2022), pulsatile signals were recorded during the HRD using a Nonin 3012LP Xpod USB oximeter with a Nonin 8000SM "softclip" fingertip sensor (Nonin Medical, USA). Data acquisition was interfaced via the Systole Python package (v0.1.3; Legrand & Allen, 2022), which streamed photoplethysmography at 75 Hz in real time. To ensure reliable heart rate estimation, the raw PPG signal underwent several preprocessing steps. First, the signal was resampled from 75 Hz to 1000 Hz. Clipping artefacts were corrected using cubic spline interpolation, and the processed signal was then squared and rolling-window normalized. Systolic peaks were detected for heart rate estimation.

In the present study, signal quality control was handled primarily at the data-acquisition stage: interbeat intervals were continuously monitored, and when the derived heart rate fell outside the predefined plausibility range (<40 or >120 bpm), participants were instructed to remain still, and the trial was restarted. Each trial could be repeated up to five times before being discarded. The experimenter remained present throughout testing to monitor the recording and remind participants to minimize movement when necessary. These measures helped maintain signal quality and minimize noise, ensuring accurate heart rate estimation. Under this procedure, no trials or participants were ultimately excluded due to poor physiological recordings.

2.3. Analytic method

2.3.1. Bayesian modeling of psychometric functions

We fit a Bayesian psychophysical model to responses in the HRD to obtain stable, interpretable indices of performance. Specifically, the model linked binary choices ("faster" vs. "slower") to the tempo offset between the auditory sequence and the participant's current heart rate (Δ-BPM), yielding two core parameters: the threshold (α) and the slope (β). The threshold α indexes the systematic bias in heart-rate estimation—i.e., the difference between the participant's subjectively inferred heart rate and the objectively recorded heart rate. Values closer to zero indicate more accurate estimation; negative values reflect underestimation and positive values overestimation. The slope β captures precision (or uncertainty) of cardiac judgments: smaller β values correspond to a steeper psychometric function, higher discriminability, and lower decision noise, whereas larger β values indicate greater uncertainty. Modeling followed the algorithmic specifications and prior settings described by Legrand, and Nikolova, Correa, et al. (2022). In this study, R-hat values for α and β were all below 1.004, and effective sample sizes for both parameters were sufficiently large (mean ESS = 4865.96–5167.23 for α, 4517.68–4812.06 for β). Model fit was assessed using weighted RMSE, with values ranging from 0.272 to 0.305 across conditions.

2.3.2. Signal-theoretic modeling of metacognition

To quantify metacognitive ability in the HRD, we applied a signal detection theory (SDT)–based computational approach. Within this framework, meta-d′ indexes metacognitive sensitivity, i.e., how closely confidence tracks task performance. Conceptually, meta-d′ is derived from the Type-2 (metacognitive) ROC, which compares the proportion of high-confidence ratings on correct trials (Type-2 "hits") to the proportion of high-confidence ratings on incorrect trials (Type-2 "false alarms"), thereby capturing the degree to which confidence discriminates correct from incorrect decisions (Fleming & Lau, 2014). Higher meta-d′ values indicate stronger alignment between confidence and first-order task performance and thus better metacognitive performance. Estimation procedures and implementation details followed Legrand et al. (2022).

2.3.3. Statistical analysis

All analyses were conducted in R 4.5.0. Parameters estimated from the Bayesian psychophysical model (perceptual threshold α and slope β), as well as metacognitive sensitivity (meta-d′) derived under the SDT framework were analyzed using linear mixed-effects models. For each outcome, Group (GAD vs. HC), Condition (interoception vs. exteroception), and their interaction were entered as fixed effects, and participant was included as a random intercept to account for repeated observations within individuals. Prior to model fitting, assumptions relevant to repeated-measures analyses were examined. Homogeneity of variance across the Group × Condition cells was assessed using Levene's tests. For outcomes showing evidence of heterogeneity of variance, models were specified to allow residual variances to differ across Group × Condition cells. For outcomes without evidence of heterogeneity, standard models were retained. Effect sizes for fixed effects in the mixed models were indexed using R^2-type estimates that reflect the unique variance attributable to each fixed effect after controlling for the other fixed effects in the model. When a significant Group × Condition interaction was observed, we conducted simple-effects analyses to clarify the pattern of effects. To control for multiple testing, p values from post hoc comparisons were adjusted using the false discovery rate (FDR) procedure. Between-group differences in interoceptive sensibility (BAQ total score) and interpretation bias (BSIQ threat-interpretation score) were tested with independent-samples *t*-tests (GAD vs. HC). Statistical significance was set at $p < .05$. Data and analysis code are available at https://osf.io/wcnd8.

3. Results

3.1. Interoceptive sensibility (BAQ)

To compare interoceptive sensibility between groups, we conducted an independent-samples *t*-test with Welch's correction on BAQ total scores. The GAD group (M = 87.0, SD = 11.8) scored lower than the HC group (M = 90.8, SD = 16.9), but the difference was not significant, $t(53.60) = -1.02$, $p = .314$, Cohen's d = −0.26, 95% CI [−0.76, 0.24]. See Fig. 1.

3.2. Interoceptive threat-interpretation bias (BSIQ)

Between-group differences in threat-interpretation bias were tested with an independent-samples *t*-test using Welch's correction on BSIQ scores. The GAD group (M = 703, SD = 304) did not differ significantly

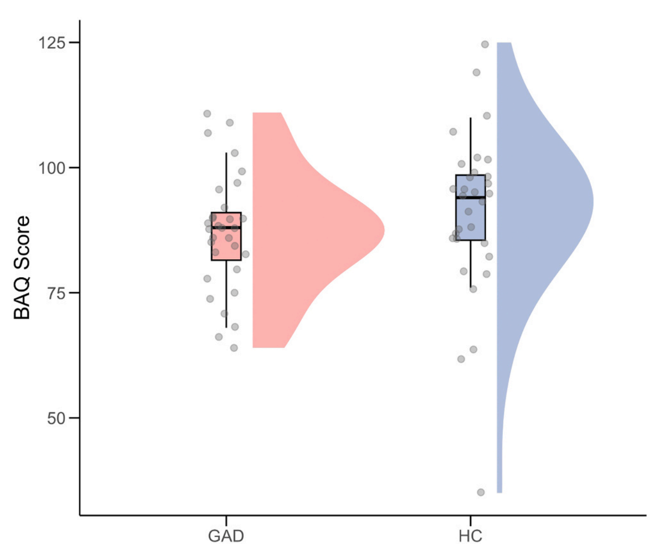

Fig. 1. Group differences in interoceptive sensibility as measured by the Body Awareness Questionnaire (BAQ).

from the HC group (M = 550, SD = 358), t(58.46) = 1.81, p = .076, Cohen's d = 0.46, 95% CI [−0.05, 0.96]. See Fig. 2.

3.3. Bayesian psychophysics parameters α and β

For the threshold (α), Levene's test indicated heterogeneity of variance across the Group × Condition cells, F(3, 120) = 12.37, $p < .001$; therefore, the data were analyzed using a linear mixed-effects model with a heteroskedastic residual structure. The model revealed a significant main effect of Condition, F(1, 60) = 36.37, $p < .001$, partial R^2 = .315, 95% CI [.194,.443], indicating more negative thresholds in the interoception condition (GAD: M = −6.04, SD = 8.73; HC: M = −9.50, SD = 9.73) than in the exteroception condition (GAD: M = −0.55, SD = 3.71; HC: M = −0.81, SD = 2.60). The main effect of Group was not significant, F(1, 60) = 2.00, p = .163, partial R^2 = .031, 95% CI [.000,.117], and the Group × Condition interaction was also not significant, F(1, 60) = 1.86, p = .178, partial R^2 = .023, 95% CI [.000,.103]. See Fig. 3.

For the slope (β), Levene's test did not indicate significant heterogeneity of variance across the Group × Condition cells, F(3, 120) = 2.63, p = .054; therefore, the data were analyzed using a standard linear mixed-effects model. The model revealed a significant main effect of Condition, F(1, 60) = 18.96, $p < .001$, partial R^2 = .105, 95% CI [.026,.223], with higher β values in the interoception condition (GAD: M = 2.09, SD = 0.32; HC: M = 2.44, SD = 0.63) than in the exteroception condition (GAD: M = 2.01, SD = 0.35; HC: M = 1.96, SD = 0.30). This main effect was qualified by a significant Group × Condition interaction, F(1, 60) = 9.84, p = .003, partial R^2 = .058, 95% CI [.005,.159], whereas the main effect of Group was not significant, F(1, 60) = 3.04, p = .086, partial R^2 = .033, 95% CI [.000,.120]. Simple-effects tests showed that in the interoception condition, β was significantly lower in the GAD group than in the HC group, p = .008, Cohen's d = −0.71, 95% CI [−1.23, −0.19], whereas in the exteroception condition the groups did not differ, p = .540, Cohen's d = 0.15, 95% CI [−0.34, 0.66]. Within-group comparisons indicated that in the HC group β was higher in interoception than exteroception, $p < .001$, Cohen's d = −1.37, 95% CI [−1.92, −0.80], whereas in the GAD group β did not differ between conditions, p = .393, Cohen's d = −0.22, 95% CI [−0.73, 0.29]. See Fig. 4.

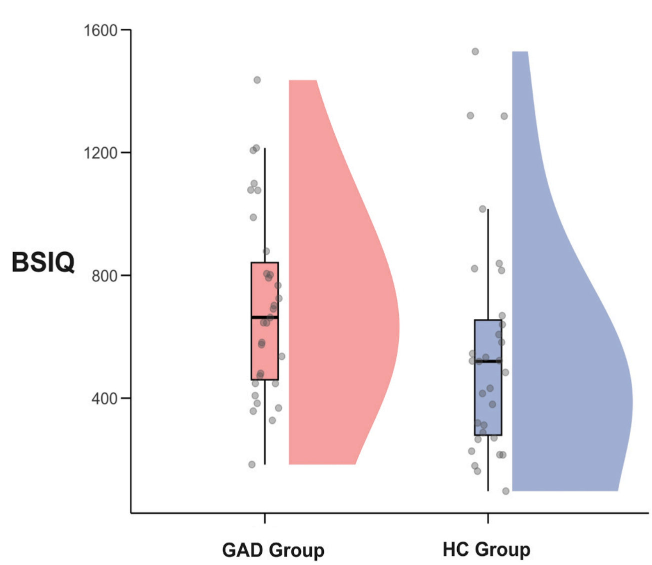

Fig. 2. Group differences in threat-related interoceptive interpretation bias as measured by the Body Sensations Interpretation Questionnaire (BSIQ).

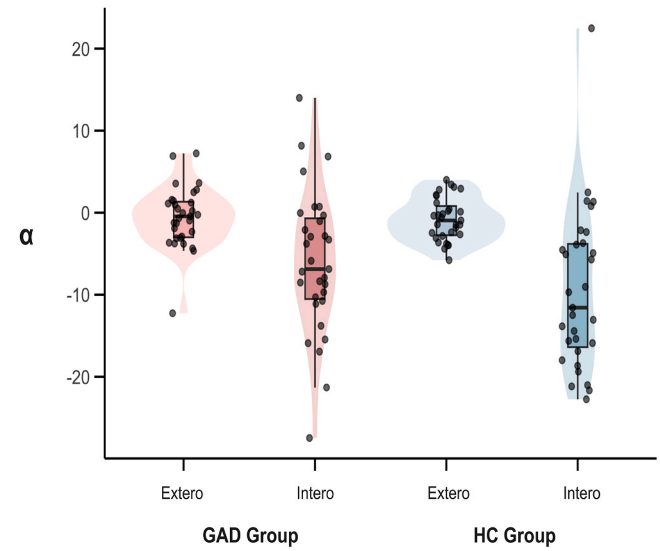

Fig. 3. Group Differences in Interoceptive and Exteroceptive Thresholds(α) Revealed by Bayesian Modeling.

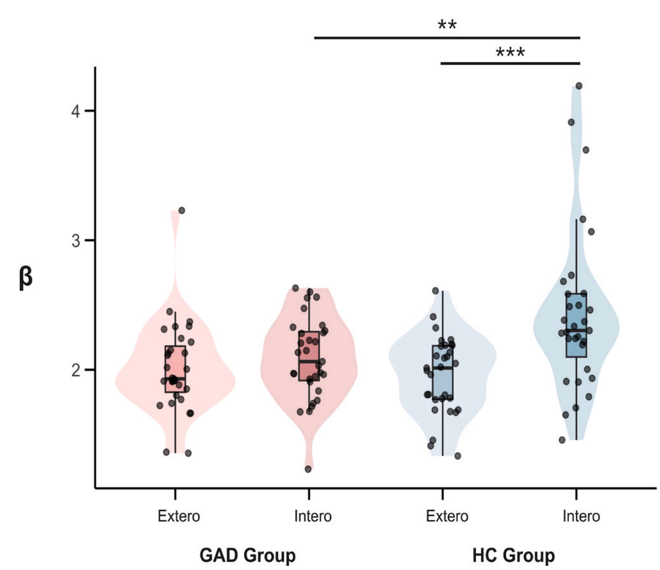

Fig. 4. Group Differences in Interoceptive and Exteroceptive Slopes(β) Revealed by Bayesian Modeling. Lower β values indicate greater precision.

3.4. Interoceptive and exteroceptive metacognitive sensitivity (SDT parameter meta-d′)

For meta-d′, Levene's test indicated heterogeneity of variance across the Group × Condition cells, F(3, 120) = 3.87, p = .011; therefore, the data were analyzed using a linear mixed-effects model with a heteroskedastic residual structure. The model revealed a significant main effect of Condition, F(1, 60) = 18.71, $p < .001$, partial R^2 = .148, 95% CI [.052,.273], indicating higher meta-d′ in the exteroception condition (GAD: M = 1.21, SD = 0.50; HC: M = 1.52, SD = 0.43) than in the interoception condition (GAD: M = 1.01, SD = 0.90; HC: M = 0.70, SD = 0.80). This main effect was qualified by a significant Group × Condition interaction, F(1, 60) = 6.86, p = .011, partial R^2 = .060, 95% CI [.005,.162], whereas the main effect of Group was not significant, F(1, 60) < 0.001, p = .998, partial R^2 < .001, 95% CI [.000,.041]. To clarify this interaction, simple-effects tests were conducted. Within groups, meta-d′ was higher for exteroception than interoception in the HC group ($p < .001$, Cohen's d = 1.27, 95% CI [0.71, 1.82]), whereas no condition difference was observed in the GAD group ($p = .232$, Cohen's d = 0.31, 95% CI [−0.20, 0.82]). Between groups, the HC group showed higher meta-d′ than the GAD group under exteroception ($p = .011$, Cohen's d = −0.67, 95% CI [−1.19, −0.15]), whereas no group difference was found under interoception ($p = .155$, Cohen's d = 0.37, 95% CI [−0.13, 0.88]). Together, these follow-up analyses suggest that the significant interaction was driven by an exteroceptive advantage in the HC group that was absent in the GAD group. See Fig. 5.

4. Discussion

In the present study, healthy controls showed a relative exteroceptive advantage within the HRD framework, reflected in greater auditory than cardiac precision and metacognitive sensitivity. In contrast, individuals with GAD showed greater precision in judgments about current heart rate and reduced exteroceptive metacognitive sensitivity, yielding an altered interoceptive–exteroceptive task profile. This pattern may reflect an altered relative profile of internal and external information processing during judgment and monitoring in GAD. Importantly, the present findings were not characterized by generalized group differences across all measures. Rather, the overall pattern suggests that group differences were selective, with no reliable group differences observed for BAQ, BSIQ, or thresholds (α), and group-related effects emerging mainly in parameters indexing precision and metacognitive sensitivity.

Our findings suggest that, in the present sample, healthy controls showed a relative exteroceptive advantage. Consistent with prior HRD work (Legrand et al., 2022), healthy controls showed greater auditory than cardiac precision, together with higher metacognitive sensitivity in the exteroceptive condition. This pattern may be consistent with the possibility that, under ordinary conditions, external information provides a more readily discriminable basis for judgment than internal bodily signals. Because visceral afferents are noisier and less readily sampled than external sensory inputs, reliance on interoceptive signals is more dependent on top-down prior knowledge and inferential constraints to stabilize uncertain internal information (Ainley et al., 2016; Allen et al., 2022). Within predictive accounts, interoception reflects a precision-weighted integration of priors and ascending signals; when sensory precision is low, the model adaptively up-weights priors to maintain a stable bodily self-representation (Allen & Friston, 2018; Barrett & Simmons, 2015; Seth, 2013). From the standpoint of ecological rationality, this asymmetry is functional: the external world is more volatile, less predictable, and richer in threat and opportunity than the relatively stable internal milieu (Todd & Gigerenzer, 2012). From this perspective, the observed asymmetry may reflect that external signals are often more readily discriminable than cardiac signals in this task context. Against this background, the present findings in GAD point to an altered interoceptive–exteroceptive profile, characterized by greater precision in judgments about current heart rate together with weaker metacognitive sensitivity in the matched exteroceptive condition. Thus, the GAD pattern may reflect not simply heightened bodily salience, but a distinct combination of stronger cardiac-judgment precision and reduced exteroceptive monitoring. A related pattern has been reported in HEP studies: in healthy controls, HEP amplitude is condition-dependent—larger with eyes closed (greater interoceptive input) than eyes open (greater exteroceptive input)—whereas this modulation is absent in GAD (Pang et al., 2019).

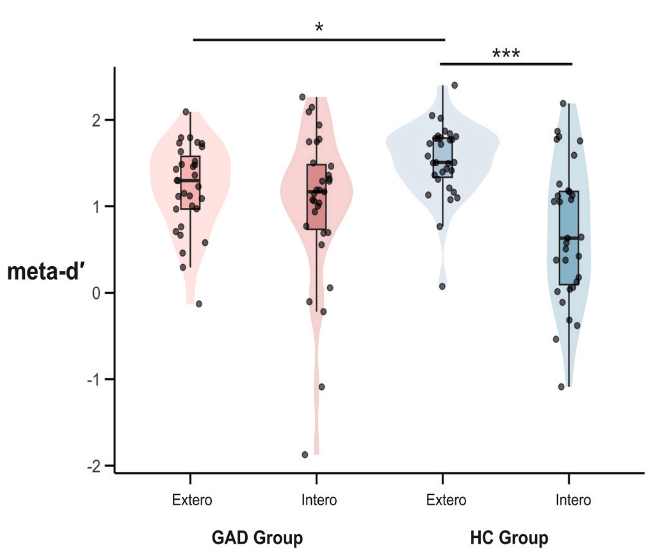

Fig. 5. Group Differences in Interoceptive and Exteroceptive meta-d′ Revealed by Signal theoretic modeling.

Individuals with GAD showed greater precision in HRD-based cardiac judgments together with reduced exteroceptive metacognition. Understanding how these alterations relate to one another may help clarify the broader information-processing profile of GAD. The observed increase in cardiac-judgment precision (lower β) is broadly consistent with prior work (Andor et al., 2008; Teed et al., 2022; Verdonk et al., 2024). One possible interpretation is that chronic threat monitoring and heightened intolerance of uncertainty are associated with altered processing of internal bodily information during cardiac judgments. Within predictive-coding accounts, this pattern may reflect stronger weighting of bodily signals, or a greater dependence on internal predictions under uncertainty, either of which could contribute to sustained vigilance toward bodily sensations and the persistence of worry (Paulus & Stein, 2010; Petzschner et al., 2017). From this perspective, the interoceptive pattern observed in GAD may be understood not simply as heightened bodily salience, but as a pattern consistent with greater reliance on internal bodily information during cardiac judgments.

Second, on the HRD metacognitive index (meta-d′), individuals with GAD showed significantly lower values than healthy controls in the exteroceptive condition, whereas no group difference emerged in the interoceptive condition. Here, metacognition refers to second-order monitoring of first-order judgments, indexed by the correspondence between confidence and task performance. Within inference-based accounts, such monitoring may play an important role in guiding behavioral adaptation under uncertainty, as beliefs about one's own performance can influence effort allocation and strategy adjustment (Petzschner et al., 2017). From this perspective, exteroceptive metacognition may support the effective evaluation of whether external information is sufficient for accurate judgment and action. The reduction of exteroceptive meta-d′ in GAD may therefore indicate less efficient monitoring of externally guided judgments, and may be relevant to the attentional/executive difficulties (Asfour et al., 2024) and decision-making problems (Teng et al., 2016) often reported in this disorder. More broadly, weaker exteroceptive metacognitive monitoring could potentially limit how effectively external information is used to update ongoing judgments, although this possibility remains speculative and requires direct testing.

We observed no between-group difference in the HRD threshold parameter (α), indicating that, relative to HC, GAD did not show a consistent tendency to overestimate or underestimate current heart rate. This null finding helps clarify that the group differences observed in the present study were more evident in performance-based indices of judgment precision and metacognitive monitoring than in response bias. This result should be interpreted cautiously, however, because variability in task engagement or familiarity with the temporal estimation demands of the HRD task may have reduced sensitivity to detect subtler between-group differences. Likewise, BAQ and BSIQ scores did not differ significantly between groups, suggesting limited correspondence between task-based and questionnaire-based indices. Rather than indexing the same construct, these measures may capture partly distinct aspects of bodily awareness, bodily appraisal, and judgments about current heart rate. Such divergence is also plausible at the neurobiological level:

performance on cardiac judgment tasks has been linked more closely to sensory and salience-related regions such as the insula and somatosensory cortices (Critchley & Harrison, 2013), whereas subjective interoceptive experience and self-report are thought to involve broader higher-order cortical processes, including prefrontal and posterior cingulate regions (Khalsa et al., 2018). Although the group difference in BSIQ scores did not reach significance, the small-to-moderate effect size (Cohen's d = 0.46, p = .076) may warrant further examination in larger samples, particularly given the broad content covered by this measure.

Our primary contribution is to offer an integrative framework for considering cognitive and interoceptive findings in anxiety together. The present results suggest that GAD is characterized by reduced exteroceptive metacognitive sensitivity alongside greater precision in HRD-based cardiac judgments. Taken together, these findings are consistent with an altered relative profile of internal and external information processing in GAD. This perspective moves beyond a simple exteroception–interoception dichotomy and highlights the value of examining judgment and monitoring across both internal and external channels in anxiety.

Several limitations warrant consideration. First, although the HRD allowed us to compare interoceptive and exteroceptive conditions within the same task, it did not simultaneously manipulate and measure both channels. Accordingly, the present findings should not be interpreted as direct evidence of resource allocation or trade-offs between interoceptive and exteroceptive processing. This limits our ability to make direct inferences about how internal and external information are jointly coordinated during performance. Recent work (e.g., Ren et al., 2024) introduced a paradigm that concurrently manipulates internal and external cues by coupling/decoupling visual stimulation with the cardiac systole within the same time window, quantifying exteroceptive strength via SSVEP and interoceptive strength via HEP. Applying such approaches to GAD may help clarify how interoceptive and exteroceptive processing relate to one another under joint experimental manipulation. Second, while our computational modeling yields precise behavioral indices of judgment precision and metacognition, the present study lacks convergent neural evidence. Structural MRI work indicates that GAD shows reduced gray-matter volume in interoception-related regions—left medial prefrontal cortex, right orbitofrontal cortex, and anterior cingulate cortex—with left medial prefrontal volume negatively correlated with heartbeat perception sensitivity (Li et al., 2020). Future studies could embed the present interoceptive–exteroceptive framework within neuroimaging or electrophysiological designs to better characterize the neural systems associated with these behavioral patterns in GAD. Because psychiatric comorbidity and psychotropic medication use were exclusionary, the present findings should be generalized cautiously to broader and more clinically heterogeneous GAD populations. In addition, we did not systematically collect illness-duration data, which limited our ability to examine whether chronicity was related to task performance or metacognitive sensitivity. Future work would benefit from incorporating a more complete clinical profile, including illness duration, comorbidity status, and medication history. A further limitation concerns the questionnaire measures. The BAQ and BSIQ were included as exploratory self-report indices of bodily awareness and bodily appraisal, but they do not map directly onto the task-based cardiac judgments indexed by the HRD, and the BSIQ also includes content beyond bodily sensations. Future work would benefit from using more theoretically aligned instruments, such as the Multidimensional Assessment of Interoceptive Awareness (MAIA)—particularly the Not-Distracting and Not-Worrying subscales—which may more directly capture the attentional and evaluative dimensions relevant to the present research question (Rogowska et al., 2023). Additionally, the present sample was sized to detect medium-sized Group × Condition interactions on HRD parameters (f = 0.25). By contrast, the between-group comparisons on the BAQ and BSIQ were secondary exploratory analyses and were not specifically powered to detect small-to-medium questionnaire differences. The non-significant group differences on these measures should therefore be interpreted cautiously.

Although the exteroceptive condition served as a matched auditory temporal judgment control condition, it was not identical to the interoceptive condition in all respects. In particular, the interoceptive condition required directed internal attention and may therefore have placed different demands on internal focus, working memory, and executive control than the auditory–auditory comparison condition. Although we attempted to match the retention interval across conditions, the transient representation of one's cardiac state may have been inherently less concrete and less easily encoded than an auditory sequence. In addition, because feedback was provided only during practice and not during the main task, differential learning or adaptation across condition or group cannot be fully ruled out. These domain-general differences may have contributed to the observed effects. However, the direction of the findings suggests that general task difficulty alone may be insufficient to account fully for the present pattern, although this possibility cannot be ruled out. In addition, variability in moment-to-moment heart rate, pulse-signal quality, or motion-related artifacts may have affected the precision of online cardiac estimation in some participants. Although participants were tested at rest and instructed to minimize movement, future work would benefit from more direct quantification and control of physiological signal quality and heart-rate variability during task performance. A further limitation is that potentially relevant covariates, such as baseline heart rate and anxiety severity, were not included in the present analyses.

Combining self-report measures with an HRD paradigm and psychophysical modeling, the present study suggests that GAD is associated with an altered interoceptive–exteroceptive profile. Relative to healthy controls, individuals with GAD showed greater precision in HRD-based cardiac judgments alongside reduced exteroceptive metacognitive sensitivity. These findings support the view that anxiety may be better understood by considering how internal and external information are differentially engaged during judgment and monitoring, rather than by focusing on either channel in isolation. More broadly, the present results provide a computationally informed perspective on GAD and may help guide future research on how internal and external information processing can be more effectively characterized in anxiety.

CRediT authorship contribution statement

Renlai Zhou: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Shuliang Bai:** Writing – original draft, Formal analysis, Data curation. **Xiaoxue Wang:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Peibing Liu:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

Data availability

Data will be made available on request

References

Ainley, V., Apps, M. A., Fotopoulou, A., & Tsakiris, M. (2016). 'Bodily precision': A predictive coding account of individual differences in interoceptive accuracy. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1708), Article 20160003. https://doi.org/10.1098/rstb.2016.0003

Allen, M., & Friston, K. J. (2018). From cognitivism to autopoiesis: Towards a computational framework for the embodied mind. *Synthese, 195*(6), 2459–2482. https://doi.org/10.1007/s11229-016-1288-5

Allen, M., Levy, A., Parr, T., & Friston, K. J. (2022). In the body's eye: The computational anatomy of interoceptive inference. *PLoS Computational Biology, 18*(9), Article e1010490. https://doi.org/10.1371/journal.pcbi.1010490

Andor, T., Gerlach, A. L., & Rist, F. (2008). Superior perception of phasic physiological arousal and the detrimental consequences of the conviction to be aroused on worrying and metacognitions in GAD. *Journal of Abnormal Psychology, 117*(1), 193. https://doi.org/10.1037/0021-843X.117.1.193

Asfour, N. M., Helal, S. A., Almahdi, A. H., & Basha, A. M. (2024). Cognitive deficits in Generalized Anxiety Disorder: Impairments in attention, executive functioning, and cognitive flexibility among young adults. *Integrative Biomedical Research, 8*(11), 1–7. https://doi.org/10.25163/angiotherapy.81110029

Barrett, L. F., & Simmons, W. K. (2015). Interoceptive predictions in the brain. *Nature Reviews Neuroscience, 16*(7), 419–429. https://doi.org/10.1038/nrn3950

Breuer, F., Meyhöfer, I., Lencer, R., Sprenger, A., Roesmann, K., Schag, K., & Leehr, E. J. (2024). Aberrant inhibitory control as a transdiagnostic dimension of mental disorders–A meta-analysis of the antisaccade task in different psychiatric populations. *Neuroscience & Biobehavioral Reviews, 165*, Article 105840. https://doi.org/10.1016/j.neubiorev.2024.105840

Clark, D. A., Salkovskis, P. M., Breitholtz, E., Westling, B. E., O¨st, L. G., Koehler, K. A., et al. (1997). Misinterpretation of body sensations in panic disorder. *Journal of Consulting and Clinical Psychology, 65*, 203–213. 〈https://doi.org/10.1037//0022-006x.65.2.203〉.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. New York, NY: Routledge Academic.

Craig, A. D. (2003). Interoception: The sense of the physiological condition of the body. *Current Opinion in Neurobiology, 13*(4), 500–505. https://doi.org/10.1016/S0959-4388(03)00090-4

Craig, A. D. (2009). How do you feel—now? The anterior insula and human awareness. *Nature Reviews Neuroscience, 10*(1), 59–70. https://doi.org/10.1038/nrn2555

Critchley, H. D., & Harrison, N. A. (2013). Visceral influences on brain and behavior. *Neuron, 77*(4), 624–638.

Desmedt, O., Heeren, A., Corneille, O., & Luminet, O. (2022). What do measures of self-report interoception measure? Insights from a systematic review, latent factor analysis, and network approach. Article *Biological Psychology, 169*, Article 108289. https://doi.org/10.1016/j.biopsycho.2022.108289.

Dugas, M. J., Savard, P., Gaudet, A., Turcotte, J., Laugesen, N., Robichaud, M., & Koerner, N. (2007). Can the components of a cognitive model predict the severity of Generalized Anxiety Disorder? *Behavior Therapy, 38*(2), 169–178. https://doi.org/10.1016/j.beth.2006.07.002

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion, 7*(2), 336. https://doi.org/10.1037/1528-3542.7.2.336

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fleming, S. M., & Lau, H. C. (2014). How to measure metacognition. *Frontiers in Human Neuroscience, 8*. https://doi.org/10.3389/fnhum.2014.00443

Garfinkel, S. N., Seth, A. K., Barrett, A. B., Suzuki, K., & Critchley, H. D. (2015). Knowing your own heart: Distinguishing interoceptive accuracy from interoceptive awareness. *Biological Psychology, 104*, 65–74. https://doi.org/10.1016/j.biopsycho.2014.11.004

Hallion, L. S., Tolin, D. F., Assaf, M., Goethe, J., & Diefenbach, G. J. (2017). Cognitive control in Generalized Anxiety Disorder: Relation of inhibition impairments to worry and anxiety severity. *Cognitive Therapy and Research, 41*(4), 610–618. https://doi.org/10.1007/s10608-017-9832-2

Hickman, L., Seyedsalehi, A., Cook, J. L., Bird, G., & Murphy, J. (2020). The relationship between heartbeat counting and heartbeat discrimination: A meta-analysis. *Biological Psychology, 156*, Article 107949. https://doi.org/10.1016/j.biopsycho.2020.107949

Hirsch, C. R., & Mathews, A. (2012). A cognitive model of pathological worry. *Behaviour Research and Therapy, 50*(10), 636–646. https://doi.org/10.1016/j.brat.2012.06.007

Houghton, D. C., Stein, D. J., & Cortese, B. M. (2020). Exteroceptive sensory abnormalities in childhood and adolescent anxiety and obsessive-compulsive disorder: A critical review. *Journal of the American Academy of Child & Adolescent Psychiatry, 59*(1), 78–87. https://doi.org/10.1016/j.jaac.2019.06.007

Kessler, R. C., Brandenburg, N., Lane, M., Roy-Byrne, P., Stang, P. D., Stein, D. J., & Wittchen, H. U. (2005). Rethinking the duration requirement for Generalized Anxiety Disorder: Evidence from the National Comorbidity Survey Replication. *Psychological Medicine, 35*(7), 1073–1082. https://doi.org/10.1017/S0033291705004538

Khalsa, S. S., Adolphs, R., Cameron, O. G., Critchley, H. D., Davenport, P. W., Feinstein, J. S., & Zucker, N. (2018). Interoception and mental health: A roadmap. *Biological psychiatry: cognitive neuroscience and neuroimaging, 3*(6), 501–513. https://doi.org/10.1016/j.bpsc.2017.12.004

Legrand, N., & Allen, M. (2022). Systole: A python package for cardiac signal synchrony and analysis. *Journal of Open Source Software, 7*(69), 3832. https://doi.org/10.21105/joss.03832

Legrand, N., Nikolova, N., Correa, C., Brændholt, M., Stuckert, A., Kildahl, N., Vejlø, M., Fardo, F., & Allen, M. (2022). The heart rate discrimination task: A psychophysical method to estimate the accuracy and precision of interoceptive beliefs. *Biological Psychology, 168*, Article 108239. https://doi.org/10.1016/j.biopsycho.2021.108239

Li, H., Zhang, B., Hu, Q., Zhang, L., Jin, Y., Wang, J., & Li, C. (2020). Altered heartbeat perception sensitivity associated with brain structural alterations in generalised anxiety disorder. *General Psychiatry, 33*(1), Article e100057. https://doi.org/10.1136/gpsych-2019-100057

Pang, J., Tang, X., Li, H., Hu, Q., Cui, H., Zhang, L., & Li, C. (2019). Altered interoceptive processing in Generalized Anxiety Disorder—A heartbeat-evoked potential research. *Frontiers in Psychiatry, 10*, 616. https://doi.org/10.3389/fpsyt.2019.00616

Paulus, M. P., & Stein, M. B. (2010). Interoception in anxiety and depression. *Brain structure and Function, 214*(5), 451–463. https://doi.org/10.1007/s00429-010-0258-9

Petzschner, F. H., Garfinkel, S. N., Paulus, M. P., Koch, C., & Khalsa, S. S. (2021). Computational models of interoception and body regulation. *Trends in Neurosciences, 44*(1), 63–76. https://doi.org/10.1016/j.tins.2020.09.012

Petzschner, F. H., Weber, L. A., Gard, T., & Stephan, K. E. (2017). Computational psychosomatics and computational psychiatry: Toward a joint framework for differential diagnosis. *Biological Psychiatry, 82*(6), 421–430. https://doi.org/10.1016/j.biopsych.2017.05.012

Pezzulo, G., Rigoli, F., & Friston, K. (2015). Active inference, homeostatic regulation and adaptive behavioural control. *Progress in Neurobiology, 134*, 17–35. https://doi.org/10.1016/j.pneurobio.2015.09.001

Ren, Q., Marshall, A. C., Liu, J., & Schütz-Bosbach, S. (2024). Listen to your heart: Trade-off between cardiac interoceptive processing and visual exteroceptive processing. *NeuroImage, 299*, Article 120808. https://doi.org/10.1016/j.neuroimage.2024.120808

Ring, C., & Brener, J. (2018). Heartbeat counting is unrelated to heartbeat detection: A comparison of methods to quantify interoception. *Psychophysiology, 55*(9), Article e13084. https://doi.org/10.1111/psyp.13084

Ring, C., Brener, J., Knapp, K., & Mailloux, J. (2015). Effects of heartbeat feedback on beliefs about heart rate and heartbeat counting: A cautionary tale about interoceptive awareness. *Biological Psychology, 104*, 193–198. https://doi.org/10.1016/j.biopsycho.2014.12.010

Rogowska, A. M., Tataruch, R., & Klimowska, K. (2023). Validation of the shortened 24-item multidimensional assessment of interoceptive awareness, version 2 (Brief MAIA-2). *Scientific Reports, 13*(1), Article 21270. https://doi.org/10.1038/s41598-023-48536-0

Ruscio, A. M., Hallion, L. S., Lim, C. C., Aguilar-Gaxiola, S., Al-Hamzawi, A., Alonso, J., & Scott, K. M. (2017). Cross-sectional comparison of the epidemiology of DSM-5 Generalized Anxiety Disorder across the globe. *JAMA Psychiatry, 74*(5), 465–475. https://doi.org/10.1001/jamapsychiatry.2017.0056

Seth, A. K. (2013). Interoceptive inference, emotion, and the embodied self. *Trends in Cognitive Sciences, 17*(11), 565–573. https://doi.org/10.1016/j.tics.2013.09.007

Sheehan, D. V., Lecrubier, Y., Sheehan, K. H., Amorim, P., Janavs, J., Weiller, E., Hergueta, T., Baker, R., & Dunbar, G. C. (1998). The Mini-International Neuropsychiatric Interview (M.I.N.I.): The development and validation of a structured diagnostic psychiatric interview for DSM-IV and ICD-10. *Journal of Clinical Psychiatry, 59*(20), 22–33.

Shields, S. A., Mallory, M. E., & Simon, A. (1989). The body awareness questionnaire: Reliability and validity. *Journal of Personality Assessment, 53*(4), 802–815. https://doi.org/10.1207/s15327752jpa5304_16

Spitzer, R. L., Kroenke, K., Williams, J. B. W., & Löwe, B. (2006). A brief measure for assessing Generalized Anxiety Disorder: The GAD-7. *Archives of Internal Medicine, 166*(10), 1092–1097. https://doi.org/10.1001/archinte.166.10.1092

Suksasilp, C., & Garfinkel, S. N. (2022). Towards a comprehensive assessment of interoception in a multi-dimensional framework. *Biological Psychology, 168*, Article 108262. https://doi.org/10.1016/j.biopsycho.2022.108262

Teed, A. R., Feinstein, J. S., Puhl, M., Lapidus, R. C., Upshaw, V., Kuplicki, R. T., Bodurka, J., Ajijola, O. A., Kaye, W. H., Thompson, W. K., Paulus, M. P., & Khalsa, S. S. (2022). Association of Generalized Anxiety Disorder with autonomic hypersensitivity and blunted ventromedial prefrontal cortex activity during peripheral adrenergic stimulation: A randomized clinical trial. *JAMA Psychiatry, 79*(4), 323–332. https://doi.org/10.1001/jamapsychiatry.2021.4225

Teng, C., Otero, M., Geraci, M., Blair, R. J. R., Pine, D. S., Grillon, C., & Blair, K. S. (2016). Abnormal decision-making in Generalized Anxiety Disorder: Aversion of risk or stimulus-reinforcement impairment? *Psychiatry Research, 237*, 351–356. https://doi.org/10.1016/j.psychres.2015.12.031

Todd, P. M., & Gigerenzer, G. (2012). *Ecological rationality: Intelligence in the world*. OUP USA.

Vancleef, L. M. G., & Peters, M. L. (2008). Examining content specificity of negative interpretation biases with the Body Sensations Interpretation Questionnaire (BSIQ). *Journal of Anxiety Disorders, 22*(3), 401–415. https://doi.org/10.1016/j.janxdis.2007.05.006

Verdonk, C., Teed, A. R., White, E. J., Ren, X., Stewart, J. L., Paulus, M. P., & Khalsa, S. S. (2024). Heartbeat-evoked neural response abnormalities in Generalized Anxiety Disorder during peripheral adrenergic stimulation. *Neuropsychopharmacology, 49*(8), 1246–1254. https://doi.org/10.1038/s41386-024-01806-5

Wells, A. (2010). Metacognitive theory and therapy for worry and Generalized Anxiety Disorder: Review and status. *Journal of Experimental Psychopathology, 1*(1), 133–145. https://doi.org/10.5127/jep.007910