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Exploring early and late pregnancy heart rate variability as incremental predictors of postpartum depression and anxiety symptoms

Allison Eriksson [a,b,*], Matilda Mikkola Jäghammar [a,c], Tomas Furmark [d], Anna Wikman [a], Ulf Elofsson [a], Andreas Frick [e], Emma Fransson [a,c]

[a] Department of Women's and Children's Health, Uppsala University, Uppsala, Sweden
[b] Women's Mental Health during the Reproductive Lifespan – WOMHER, Uppsala University, Uppsala, Sweden
[c] Institute of Environmental Medicine, Karolinska Institutet, Stockholm S-171 65, Sweden
[d] Department of Psychology, Uppsala University, Uppsala, Sweden
[e] Department of Medical Sciences, Experimental Cognitive and Affective Neuroscience Lab, Uppsala University, Uppsala, Sweden

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ABSTRACT

Early identification of postpartum depression and anxiety is critical for enabling timely preventive interventions. Although antenatal self-report measures are strong and widely used predictors of postpartum mental health outcomes, it remains unclear whether physiological markers such as heart rate variability (HRV) provide incremental predictive value beyond established psychological assessments, particularly when measured at different stages of pregnancy. This study investigated whether HRV indices, measured during early and late pregnancy, before and after a mild cognitive-emotional stressor, contribute incremental predictive information for postpartum depression and anxiety symptoms beyond established psychosocial and health predictors. Ninety-one pregnant women completed psychological assessments and HRV measurements before and after a mild cognitive-emotional stressor in both early and late pregnancy. Postpartum depression and anxiety symptoms were assessed using validated questionnaires. Random Forest models identified several HRV indices - particularly low-frequency/high-frequency ratio and indices reflecting parasympathetic activity- as meaningful predictors of postpartum outcomes, alongside established psychological factors. The models demonstrated high predictive accuracy, and model comparisons indicated that HRV measures provided a modest yet statistically reliable improvement, specifically reflected in reduced mean absolute error for depression and state anxiety. These findings suggest that HRV provides complementary physiological information beyond self-report measures, supporting its potential role in refining postpartum risk prediction - particularly in cases where self-report indicators alone may be ambiguous.

1. Introduction

1.1. Depression and anxiety during pregnancy and postpartum

Pregnancy is a transition period that brings substantial physiological, biological, and psychological changes to the mother's body, potentially leading to symptoms of anxiety and depression (Yim et al., 2015). The prevalence of depression and anxiety disorders during pregnancy or the postpartum period is approximately 10–20%; conditions that have consequences for maternal well-being and child development (Fawcett et al., 2019; Woody et al., 2017). Common psychosocial risk factors for depression and or anxiety include younger age, lower education, unemployment, smoking, low income and relationship issues (Yim et al., 2015). Obstetric factors like unplanned pregnancies, previous miscarriages, and high gestational risk also contribute. While these risks vary across pregnancy stages and postpartum, a prior history of anxiety or depression remains a robust predictor of both postpartum depressive and anxiety symptoms (Woody et al., 2017).

Despite the availability of effective interventions to prevent postpartum mental health disorders, their success is largely confined to women already identified as high-risk via self-report (Yim et al., 2015). However, systematic reviews highlight that a substantial proportion of women with significant depressive or anxiety symptoms remain undetected (Fawcett et al., 2019; Woody et al., 2017) - highlighting a critical

* Correspondence to: Department of Women's and Children's Health, Uppsala University, Akademiska sjukhuset, Uppsala 751 85, Sweden
E-mail address: allison.eriksson@uu.se (A. Eriksson).

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flaw in current screening methods. Biological and physiological factors, particularly endocrine and hormonal changes that regulate how the body responds to stress, are rarely incorporated, despite their potential relevance (Yim et al., 2015). Considering the profound impact postpartum symptoms of depression and anxiety can have on both maternal and infant well-being, there is a pressing need to develop and implement objective, predictive measures that can more accurately identify women at elevated risk.

1.2. Heart rate variability during pregnancy

The autonomic nervous system (ANS), which regulates involuntary functions such as heart rate and breathing, undergoes significant adjustments during pregnancy to meet maternal and fetal needs (Brown et al., 2021); dysregulation of this system, characteristic of affective disorders, impairs stress recovery (Shaffer and Ginsberg, 2017). Heart rate variability (HRV), a non-invasive measure of beat-to-beat heart rate changes, reflects the dynamic interplay between the sympathetic and parasympathetic branches of the autonomic nervous system and the capacity of this system to flexibly adapt to internal and external demands (Electrophysiology, 1996). As a proxy for stress reactivity, higher HRV generally indicates a flexible and well-regulated autonomic system; lower HRV suggests dysregulation, making it harder for the body to respond appropriately to challenges and inhibit excessive or maladaptive responses (Koch et al., 2019; Shaffer and Ginsberg, 2017).

During pregnancy, HRV typically decreases due to reduced parasympathetic activity, particularly in the second and third trimesters (Brown et al., 2021). This shift in ANS activity toward increased sympathetic dominance and reduced parasympathetic activity can be further amplified by anxiety, leading to a dysregulation reflected in lower HRV. However, this decline is followed by a gradual restoration of pre-pregnancy ANS activity, beginning shortly before childbirth and continuing into the postpartum period (Shinba et al., 2024).

1.3. Heart rate variability as a predictor of anxiety and depression

Depression and anxiety are associated with altered stress-response mechanisms and reduced parasympathetic activity (Wang et al., 2023). Studies consistently show lower HRV in individuals with depression and anxiety, indicating dysregulation of the ANS (Koch et al., 2019; Tomasi et al., 2024; Wang et al., 2023). Additionally, reduced HRV has been associated with an increased vulnerability to developing depression (Koch et al., 2019). Some studies also highlight maladaptive exaggerated vagal responses to stress, suggesting that both diminished and excessive autonomic reactions may reflect inefficient stress regulation (Schwerdtfeger and Derakshan, 2010). Meta-analyses suggest that the differences in HRV between affected and healthy individuals are moderate, which can impede detecting significant changes with small sample sizes (Wang et al., 2023). Nevertheless, HRV metrics have shown promise as transdiagnostic indicators for tracking the progression of depressive and anxiety symptoms (Chalmers et al., 2014; Koch et al., 2019). HRV biofeedback (HRVB), a non-invasive technique providing real-time feedback to help individuals regulate physiological responses, has also been shown to reduce depressive and anxiety symptoms, suggesting a functional link between autonomic regulation and affective disorders and underscoring its potential clinical utility (Galin and Keren, 2024; Pizzoli et al., 2021).

1.4. The link between HRV and anxiety and depression during pregnancy

Pregnancy studies increasingly suggest that HRV may serve as a feasible physiological marker of perinatal mental health. This is supported by findings on late-pregnancy HRV levels (Brown et al., 2021; Kimmel et al., 2021) as well as studies evaluating HRV as a screening tool for PPD (Shinba et al., 2024), pointing to its potential diagnostic utility. In our previous work, we found that lower late pregnancy HRV predicted postpartum depression and anxiety when combined with psychological measures, though the contribution of the HRV indices was low in comparison to the self-report measures (Eriksson et al., 2024). Importantly, HRV patterns differed between depression and anxiety, suggesting distinct underlying autonomic profiles for each condition. Other studies have similarly shown lower HRV in pregnant women with anxiety and higher HRV in those without (Riddle et al., 2023). Decreased antenatal HRV has also been shown to prospectively predict PPD, with lower second- and third-trimester HRV predicting later symptoms (Singh Solorzano et al., 2022). Moreover, autonomic imbalance during pregnancy has been linked to higher levels of depressive symptoms and stress, suggesting dysregulation between sympathetic and parasympathetic activity (Koch et al., 2019; Wang et al., 2023).

However, substantial gaps remain in understanding longitudinal changes in HRV during pregnancy and how these changes relate to the development and severity of postpartum mood disorders. Although antenatal depression and anxiety symptoms are among the strongest and most readily available predictors of postpartum mental health outcomes (Woody et al., 2017; Yim et al., 2015), it remains unclear whether HRV measures obtained during pregnancy provide incremental predictive information beyond established self-report measures. In particular, relatively little is known about the relevance of early pregnancy HRV, as most prior studies examining HRV in relation to postpartum depression and anxiety have focused on late gestation (Brown et al., 2021; Riddle et al., 2023; Singh Solorzano et al., 2022).

Early pregnancy represents a period of initial physiological and psychological adaptation, during which autonomic regulation is actively changing (Yim et al., 2015). Rather than presuming stability of autonomic markers across gestation, the present study includes early pregnancy HRV to empirically examine whether autonomic indices obtained during this initial adaptation phase provide predictive information for postpartum depression and anxiety, and whether their contribution differs from HRV measured later in pregnancy. Clarifying whether HRV adds value above existing screening tools is critical for determining its potential role in improving early identification and enabling more targeted preventive interventions, particularly in cases where self-report risk is ambiguous.

The aim of the current study was therefore to investigate whether early and/or late pregnancy HRV indices measured before and after a mild cognitive-emotional stressor contribute incremental predictive value for postpartum depression and anxiety symptoms beyond antenatal psychological measures. More specifically, we hypothesized that lower HRV parameters at both time points would be associated with greater depressive and anxiety symptom severity at six weeks postpartum, after accounting for established prenatal symptom predictors.

2. Methods

2.1. Participants and procedure

We utilize data from the 3PAD (Physiological Predictors of Postpartum Anxiety and Depression) study, in Uppsala, Sweden, which investigates physiological predictors of postpartum symptoms of anxiety and depression. Pregnant participants were recruited in Uppsala through clinical flyers, targeted social media, and mailed study invitations. Women expressing interest in the study were required to complete a screening questionnaire regarding their current health status. Exclusion criteria encompassed severe neurological, psychiatric, or somatic disorders (e.g., schizophrenia), the use of medications known to affect autonomic function (e.g., beta-blockers), insufficient proficiency in Swedish, and being under 18 years of age. Participants with known cardiac disease were excluded during screening, and cardiac recordings were visually inspected during preprocessing to ensure adequate signal quality and analyzable sinus rhythm for HRV analysis. Information on diabetes and use of antidepressant medications, including selective serotonin reuptake inhibitors (SSRIs), was obtained via medication reporting during pregnancy. A total of 98 women participated in the 3PAD study between 2023 and 2025. Of those, 3 women did not complete the study due to miscarriage, and 4 women were excluded due to lack of postpartum outcome data. This resulted in a final sample size of 91 women.

The study protocol consisted of three measurement timepoints: two in-person visits during pregnancy and an online follow-up conducted at 6 weeks postpartum. The initial two visits were held in a laboratory setting - one during early pregnancy ($\leq$ 20 weeks gestation) and another during late pregnancy ($\geq$ 35 weeks gestation). At the outset of each visit, participants completed a background and health survey and psychological questionnaires prior to the assessment of physiological data. After the completion of the questionnaires, baseline HRV measurements were obtained via electrocardiogram (ECG) using NeXus-10 MKII, a medical-grade data acquisition device, with BioTrace software from Mind Media (Mind Media B.V., V2018A, The Netherlands). A positive electrode was placed on the inner side of the left wrist and a negative electrode was placed on the inner side of the right wrist. A ground electrode was also placed on the inner arm below the left elbow. The participant was instructed to remain as still as possible throughout duration of the 5-minute HRV measurement. After completion of the baseline HRV measurements, the Emotional Stroop task (EST; Williams et al., 1996) was conducted. The Emotional Stroop task was selected as a mild cognitive-emotional stressor, as it reliably induces emotional interference and increased cognitive load, both of which are known to modulate autonomic nervous system activity (Schwerdtfeger and Derakshan, 2010; Williams et al., 1996). Given ethical considerations in pregnancy, the use of a brief and non-invasive challenge was prioritized over more intensive stress paradigms. Following the EST, an after-stressor HRV measurement was recorded to examine whether individual differences in short-term autonomic modulation under mild cognitive-emotional demand provide information beyond resting autonomic tone. The final online follow-up, aimed at evaluating symptoms of depression and anxiety, was conducted at six weeks postpartum. Participants received a gift card valued at 300 SEK following each measurement timepoint.

This project adhered to the ethical guidelines established by the Swedish Ethical Review Authority and complied with GDPR regulations. Ethical permits for this study were obtained from the Swedish Ethical Review Authority (Dnr 2021–01677) with amendments (2022–06514–02 and 2023–02710–02). Written, informed consent was obtained from all participants prior to participation in the 3PAD study.

2.2. Background and health self-report measures

During the pregnancy visits, participants first responded to a pregnancy survey regarding their background and health. The demographic data collected encompassed place of birth, maternal age, parity, education level, and employment status. Additionally, participants reported information related to their body mass index (BMI), polycystic ovarian syndrome (PCOS; yes or no), level of physical activity (low to none or moderate to high exercise levels), current use of selective serotonin reuptake inhibitors (SSRIs), as these factors are known to be associated with HRV and/or postpartum depressive and anxious symptoms. Information pertaining to recent life events was also gathered, with participants indicating whether they had been affected by these events either very negatively, slightly negatively, or not at all, as well as very positively, slightly positively, or not at all. For analytic purposes, negative life events (NLE) and positive life events (PLE) were derived based on these ratings.

2.3. Psychological self-report measures

Psychological scales included the Edinburgh Postnatal Depression Scale (EPDS; Cox et al., 1987), a widely used screening tool to identify symptoms of depression. The Spielberger State Trait Anxiety Inventory (STAI-S/T; Spielberger et al., 1983) was used to assess both state (transient emotional responses) and trait anxiety (a stable predisposition to perceive situations as threatening), which were evaluated separately in line with the state–trait framework. Participants completed the Difficulties in Emotion Regulation Scale (DERS-16; Bjureberg et al., 2016) which assesses various aspects of difficulties in regulating emotions. The Generalized Anxiety Disorder 7-item Scale (GAD-7; Spitzer et al., 2006) serves as a self-report tool to screen for generalized anxiety disorder, focusing on the frequency of anxiety-related symptoms experienced in the past two weeks.

To supplement the assessment of emotional and psychological well-being, participants completed the Swedish Acceptance and Action Questionnaire (SAAQ; Lundgren and Parling, 2017), which evaluates psychological flexibility and the ability to accept thoughts and emotions as part of effective coping strategies. The Perceived Stress Scale (PSS-10; Cohen et al., 1983) measures the participants' perceptions of stress, which is crucial for understanding mental health during pregnancy. Participants also completed the Resilience Scale (RS-14; Wagnild and Young, 1993) which assesses personal resilience and adaptability in the face of stressors, while the Sense of Coherence Scale (SOC-13; Antonovsky, 1993) evaluates individuals' orientation to life and their capacity to respond to stressful situations, providing additional insights into psychological health and resilience. Together, these questionnaires and self-report surveys aimed to give a comprehensive overview of participants' background and mental health status (Fig. 1). All questionnaires and surveys were administered via REDCap, an electronic data capture tool hosted at Uppsala University (Harris et al., 2009).

2.4. HRV feature selection and data processing

HRV is primarily assessed through time-domain and frequency-domain measures (Shaffer and Ginsberg, 2017). Given the limited consensus on which HRV indices are most informative for postpartum mental health outcomes during pregnancy, we included a commonly used set of time- and frequency-domain measures to allow exploratory evaluation of their relative contributions across gestational stages and task conditions. In this study, time-domain metrics include the standard deviation of normal-normal (NN) intervals (SDNN), which reflects the overall function of both sympathetic and parasympathetic nervous systems, and the root mean square of successive differences (RMSSD) between adjacent NN intervals, which mainly assesses parasympathetic variability (Galin and Keren, 2024; Wang et al., 2023). Common frequency-domain metrics consist of low-frequency power (LF; 0.04–0.15 Hz), high-frequency power (HF; 0.15–0.4 Hz), total power,

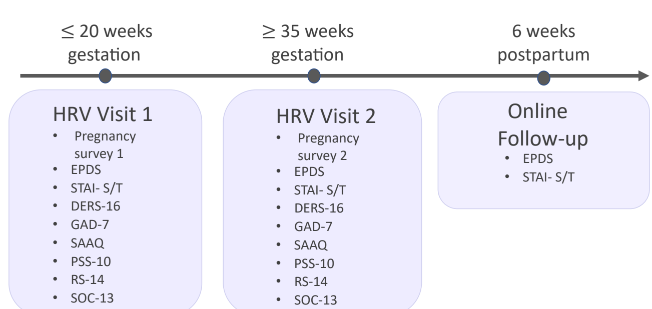

Fig. 1. Overview of the 3PAD study showing self – report survey administration at the two in-person visits during pregnancy (early and late gestation) and one online follow-up at approximately six weeks postpartum. *Note.* HRV = Heart Rate Variability; EPDS = Edinburgh Postnatal Depression Scale; STAI-S/T = Spielberger State–Trait Anxiety Inventory (State and Trait sub-scales); DERS-16 = Difficulties in Emotion Regulation Scale, 16-item version; GAD-7 = Generalized Anxiety Disorder 7-item scale; SAAQ = Swedish Acceptance and Action Questionnaire; PSS-10 = Perceived Stress Scale, 10-item version; RS-14 = Resilience Scale, 14-item version; SOC-13 = Sense of Coherence Scale, 13-item version.

and the LF/HF ratio. LF power reflects mixed autonomic influences, including modulation by both sympathetic and parasympathetic activity, and is shaped in part by baroreflex-related regulatory processes, while HF power is predominantly regulated by the parasympathetic nervous system (Wang et al., 2023). Although the LF/HF ratio has historically been interpreted as an index of sympathetic-parasympathetic balance, this interpretation is increasingly viewed as overly simplistic. Instead, LF/HF is more appropriately considered a composite index reflecting the relative distribution of autonomic modulation across low- and high-frequency bands (Shaffer and Ginsberg, 2017). Total power encapsulates all frequency-domain measurements, reflecting multiple aspects of autonomic nervous system function and the contributions of both parasympathetic and sympathetic systems (Shaffer and Ginsberg, 2017). For each HRV measure, we analyzed both absolute values (measured at baseline and after-stressor) and difference scores, calculated as the difference between the after-stressor and baseline measurements. Baseline values represent resting-state autonomic tone prior to task exposure, whereas after-stressor values reflect autonomic levels measured immediately following a mild cognitive-emotional challenge. Both baseline and after-stressor values are treated as absolute indices of autonomic state at two standardized assessment points. Because HRV was assessed before and after- but not during - the Emotional Stroop task, these difference scores are interpreted as indices of short-term autonomic modulation rather than acute stress reactivity. This approach was applied to all time-domain (SDNN and RMSSD) and frequency-domain measures (LF, HF, total power, and LF/HF ratio) to allow exploratory evaluation of individual variability in autonomic adjustment under mild cognitive-emotional challenge conditions.

HRV data processing was conducted using Kubios HRV Scientific Analysis Software, version 4.1.0 (Tarvainen et al., 2014), a validated software platform for advanced HRV signal processing. Electrocardiogram (ECG) data were recorded at a sampling rate of 256 Hz, providing sufficient temporal resolution for accurate R-wave detection and inter-beat interval (IBI) extraction. Data were processed with a smoothness priors detrending method ($\lambda = 500$), and beat correction was performed using the software's automatic artifact correction algorithm with a correction threshold of 0.3. Ectopic beats and artifacts were automatically identified and interpolated using cubic spline interpolation. The interpolated IBI data were resampled at 4 Hz. HRV analysis was performed using Fast Fourier Transform (FFT) with a Welch's periodogram method (300-second window, 50% overlap), and a spectral resolution of 300 points/Hz. Frequency domain measures were then log-transformed to provide a more normal distribution. All parameters were selected based on established best practices for HRV analysis and in accordance with guidelines provided by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996).

2.5. Statistical analyses

Statistical analyses were performed through R programming language and results were considered significant at $p < 0.05$. Sample characteristics and symptom severity across early pregnancy, late pregnancy, and six weeks postpartum are summarized in Table 1 for the analytic sample ($N = 91$). Continuous variables are reported as mean (SD) and range, and categorical variables as n (%). For depression and anxiety symptom measures (EPDS, STAI-S, STAI-T), the proportion of participants exceeding validated, measure-specific clinical cutoffs (EPDS ≥ 12; STAI-S/T ≥ 40) is additionally reported for descriptive context. Participants who scored below the relevant cutoff at both early and late pregnancy assessments but exceeded the cutoff at six weeks postpartum were classified as *de novo* cases for descriptive purposes.

Exploratory descriptive comparisons were conducted to characterize background variables and HRV indices across postpartum symptom thresholds using independent-samples *t*-tests or Wilcoxon rank-sum tests, as appropriate. These analyses were conducted to aid interpretation; they were not used to guide inference or model selection. Associations between HRV measures and postpartum depression, state anxiety, and trait anxiety were examined using Spearman correlations with continuous symptom scores. Finally, Random Forest modeling (Breiman, 2001) was utilized to explore the predictive value of physiological measures for continuous postpartum depression and anxiety outcomes.

Table 1
Sample characteristics and depression and anxiety symptom severity across pregnancy and postpartum.

Background variables	n (%) / Mean *(SD)*	Range	
Scandinavian	78 (85.7%)	-	
Maternal age, years	32.6 *(4.2)*	23.0–44.0	
University education	72 (79.1%)	-	
Primiparous	58 (64.4%)	-	
BMI, kg/m^2	26.1 *(4.3)*	18.0–36.8	
Employed full-time	79 (86.8%)	-	
PCOS	5 (5.7%)	-	
Exercise early pregnancy, (moderate to high)	59 (64.8%)	-	
Exercise late pregnancy, (moderate to high)	34 (40.0%)	-	
SSRI use	7 (7.7%)	-	
PLE early pregnancy	31 (34.1%)	-	
PLE late pregnancy	32 (37.6%)	-	
NLE early pregnancy	26 (28.6%)	-	
NLE late pregnancy	27 (31.8%)	-	
Depression (EPDS)	**Mean *(SD)***	**Range**	**n (%) above cutoff (≥ 12)**
Early pregnancy	5.66 *(3.9)*	0.0–17.0	8 (8.9%)
Late pregnancy	5.67 *(4.7)*	0.0–18.0	14 (16.5%)
Postpartum	5.97 *(4.6)*	0.0–21.0	13 (14.3%)
State Anxiety (STAI-S)	**Mean *(SD)***	**Range**	**n (%) above cutoff (≥ 40)**
Early pregnancy	29.9 *(7.5)*	20.0–46.0	14 (15.6%)
Late pregnancy	31.3 (8.1)	20.0–54.0	13 (15.3%)
Postpartum	31.5 (9.5)	20.0–68.0	12 (13.2%)
Trait Anxiety (STAI-T)	**Mean *(SD)***	**Range**	**n (%) above cutoff (≥ 40)**
Early pregnancy	33.9 (9.6)	20.0–58.0	21 (23.3%)
Late pregnancy	33.9 (9.2)	20.0–61.0	21 (24.7%)
Postpartum	34.1 (10.1)	20.0–69.0	21 (23.1%)

Note. Values are presented for the analytic sample ($n = 91$). Continuous variables are reported as mean (SD) and range, and categorical variables as n (%). For depression and anxiety symptom measures, the proportion of participants exceeding validated, measure-specific clinical cutoffs is also shown (EPDS ≥ 12; STAI-S/T ≥ 40). Cutoffs are reported for descriptive purposes only; all depression and anxiety outcomes were analyzed as continuous symptom measures in inferential analyses; BMI = body mass index; EPDS = Edinburgh Postnatal Depression Scale; STAI-S = State Anxiety subscale of the State-Trait Anxiety Inventory; STAI-T = Trait Anxiety subscale of the State–Trait Anxiety Inventory; PCOS = polycystic ovary syndrome; SSRI = selective serotonin reuptake inhibitor; PLE = positive life events; NLE = negative life events.

2.5.1. Data preparation and imputation

Prior to imputation, residual missingness was assessed and missingness was found to be very low (1.8%). Missing data patterns were examined visually using `naniar` package (Tierney and Cook, 2018) and did not indicate systematic or outcome-dependent missingness. All missing data was determined to be 'missing at random' and therefore suitable for imputation. Due to high multicollinearity within the HRV variables, imputation was handled separately using the `missForest` (Stekhoven and Buhlmann, 2012) algorithm. This technique utilizes Random Forest models that can accommodate complex interactions and non-linear relationships, providing a robust approach to handling collinear and missing data without pre-imputation. Missing values in non-HRV data were addressed via multivariate imputation by chained equations (MICE) using the `mice` package in R (van Buuren and Groothuis-Oudshoorn, 2011) and the univariate imputation method employed was predictive mean matching. Ten imputed datasets were created, each representing a complete data scenario for analysis. This process mitigates bias and retains the sample size by approximating missing values based on patterns found in observed data.

2.5.2. Statistical modeling

Random Forest modeling was performed using the R package `randomForest`(Liaw and Wiener, 2002). This method is particularly well-suited for handling high-dimensional, non-linear, and multicollinear data. It achieves robust predictive performance by building an ensemble of decision trees and aggregating their results to minimize variance and overfitting (Breiman, 2001). In this context, Random Forest variable importance reflects the conditional predictive contribution of each predictor within the full feature set, such that predictors that do not add information beyond correlated variables contribute minimally to model performance (Gregorutti et al., 2017). Random Forest models have been successfully applied in previous psychophysiological and clinical prediction studies with moderate sample sizes (e.g., Kizhevska et al., 2025; Yao et al., 2024). The primary postpartum outcomes (EPDS, STAI-S, and STAI-T) were modeled as continuous variables. An iterative modeling approach was applied across all multiply imputed datasets (m = 10) and model performance was evaluated using multiple metrics: Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R-squared values.

Aggregated variable importance scores were generated for each model to identify which predictors significantly influenced the psychological outcomes. The primary metric was out-of-bag (OOB) permutation importance, which estimates the increase in prediction error (MSE) when a variable is permuted, thereby reflecting its unique predictive contribution while controlling for other predictors. As a secondary metric, IncNodePurity was also calculated, representing the total reduction in node impurity (residual sum of squares) achieved when a variable was used for splitting.

Preliminary Random Forest models including all background, psychological, and HRV variables were first generated. All antenatal psychological measures were modeled as continuous variables to preserve variability; continuous antenatal EPDS and STAI scores were included as predictors to evaluate incremental predictive contributions of HRV beyond antenatal symptom severity, rather than to model postpartum symptoms independently of prior symptom levels. Predictors with variable importance below outcome-specific thresholds were then iteratively removed, with thresholds progressively increased, and model performance was re-evaluated. Reduced model performance was defined as a consistent increase in OOB prediction error relative to the previous iteration, indicating loss of predictive stability. Importance thresholds were empirically determined as the lowest values at which performance remained stable across iterations and imputations, rather than to maximize apparent predictive accuracy. Final models for each outcome were built from this minimal predictor set, and variable importance scores were scaled (0−1) relative to the most important predictor for comparability across models.

2.5.3. Model comparison without HRV predictors

To quantify the incremental value of HRV indices, a parallel sensitivity analysis was performed. For each outcome-specific final model, Random Forests across the same imputed datasets were refit using only the background and psychological predictors retained by the threshold procedure (i.e., excluding all HRV variables). Within each imputation MSE, RMSE, MAE, and R^2 were computed, then per-imputation differences (Δ = full model - reduced model) were calculated. These Δ-vectors were pooled via Rubin's rule (Rubin, 1987), to generate mean differences and 95% CIs. Differences in predictive performance between full and reduced models quantify the conditional contribution of HRV to model accuracy; metrics with 95% confidence intervals excluding zero were interpreted as evidence of statistically reliable incremental improvement associated with the inclusion of HRV predictors.

3. Results

3.1. Sample characteristics and postpartum symptom severity

At six weeks postpartum, symptom levels of depression and anxiety were generally low to moderate across the sample (Table 1). On average, women reported a mean EPDS score of 5.97 (SD = 4.6), indicating overall low levels of postpartum depressive symptoms. Using the validated cutoff (EPDS $\geq$ 12), 13 women (14.3%) scored above the threshold; of these, 5 (38.4%) represented *de novo* elevations, having not exceeded the cutoff during either early or late pregnancy.

Mean postpartum state anxiety was 31.5 (SD = 9.5) on the STAI-S, with 12 women (13.2%) scoring at or above the clinical threshold (STAI-S $\geq$ 40); among these, 5 women (41.6%) showed *de novo* elevations, first exceeding the cutoff postpartum. Mean postpartum trait anxiety was 34.1 (SD = 10.1) on the STAI-T, with 21 women (23.1%) scoring above the threshold (STAI-T $\geq$ 40), including 4 women (19.0%) whose scores reflected *de novo* elevations relative to pregnancy assessments. Two participants reported the use of amitriptyline, a tricyclic antidepressant, prescribed for migraine prophylaxis rather than for affective disorders. One participant reported the use of metformin for gestational diabetes at the late pregnancy visit only. Two participants reported the use of amitriptyline, a tricyclic antidepressant, prescribed for migraine prophylaxis rather than for affective disorders. See Supplementary Figure 1 for a visual representation of overlap among outcome thresholds and Supplementary Tables 1a/b for exploratory descriptive comparisons of background characteristics.

3.2. Associations between HRV indices and postpartum symptom measures

Associations between heart rate variability (HRV) indices and postpartum depression and anxiety were primarily examined using Spearman correlations with continuous symptom scores (Supplementary Table 5). Late pregnancy after-stressor LF/HF ratio was negatively correlated with postpartum depression (r = -0.21, p = 0.044) and postpartum trait anxiety (r = -0.21, p = 0.048), with a trend toward a negative association with postpartum state anxiety (r = -0.20, p = 0.057). A trend toward a positive association was observed between late pregnancy HF power difference and postpartum state anxiety (r = 0.19, p = 0.072). In contrast, early pregnancy after-stressor LF/HF ratio showed a trend toward a negative association with postpartum trait anxiety (r = -0.18, p = 0.089). Although some associations reached statistical significance, correlation coefficients were small in magnitude, indicating modest effect sizes.

Exploratory group-based comparisons of HRV indices by postpartum symptom thresholds did not reveal significant differences and are presented in the Supplementary Materials (Supplementary Tables 2–4). When comparing baseline to after-stressor HRV measures, no meaningful mean-level changes were observed across indices in early pregnancy. In late pregnancy, a small decrease was observed for total power (p = 0.034); however, the corresponding effect size was small (Cohen's d = −0.10), indicating minimal group-level autonomic modulation. No other late-pregnancy indices showed statistically reliable changes. Baseline-to-after-stressor HRV changes as well as full correlation matrices showing associations among HRV indices, psychological measures, background variables, and postpartum outcomes are provided in Supplementary Excel Tables S1.1–4.

3.3. Random forest modeling for depression outcome

The final Random Forest model for postpartum depression retained variables surpassing a threshold of 25 for variable importance scores (Supplementary Table 6). Performance metrics indicated strong predictive accuracy (MSE = 2.75, RMSE = 1.66, MAE = 1.26, R^2 = 0.87; Fig. 2). Key predictors included early and late pregnancy GAD-7 along

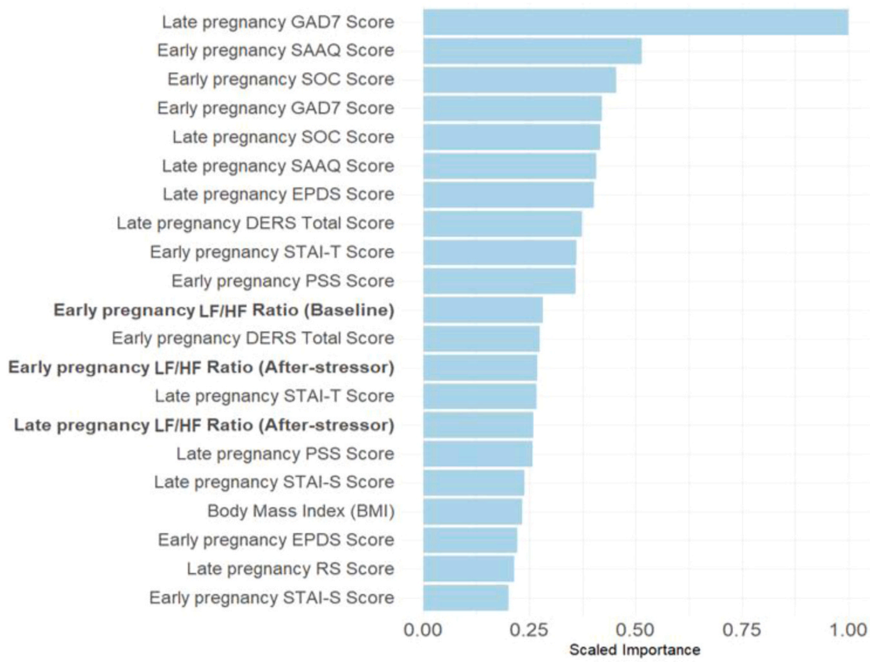

Fig. 2. Scaled variable importance scores for predictors in the postpartum depression model. *Note.* Bar plot depicting scaled variable importance scores from the Random Forest model predicting postpartum depression (EPDS). Higher scores reflect greater contribution to model prediction. HRV and psychological predictors are shown. HRV indices included in the predictive model are shown in bold font.

with other psychological measures. LF/HF ratio at multiple measurement points (early and late pregnancy, both baseline and after-stressor) consistently emerged as an important predictor of depression scores.

3.4. Random forest modeling for state anxiety outcome

With a threshold of 100 for variable importance, the final state anxiety model (Supplementary Table 7) strong predictive capability (MSE = 10.75, RMSE = 3.28, MAE = 2.33, R^2 = 0.88). Key predictors included late-pregnancy GAD-7, BMI, and other psychological measures. HRV indices retained were early-pregnancy LF/HF ratio (baseline and after-stressor) and late-pregnancy LF power after-stressor (Fig. 3a).

3.5. Random forest modeling for trait anxiety outcome

The final trait anxiety model (Supplementary Table 8), at a threshold of 90 for variable importance, showed strong predictive performance (MSE = 10.05, RMSE = 3.17, MAE = 2.34, R^2 = 0.90). Key predictors comprised antenatal psychological measures - notably early- and late-pregnancy STAI-T scores - together with HRV indices: early-pregnancy

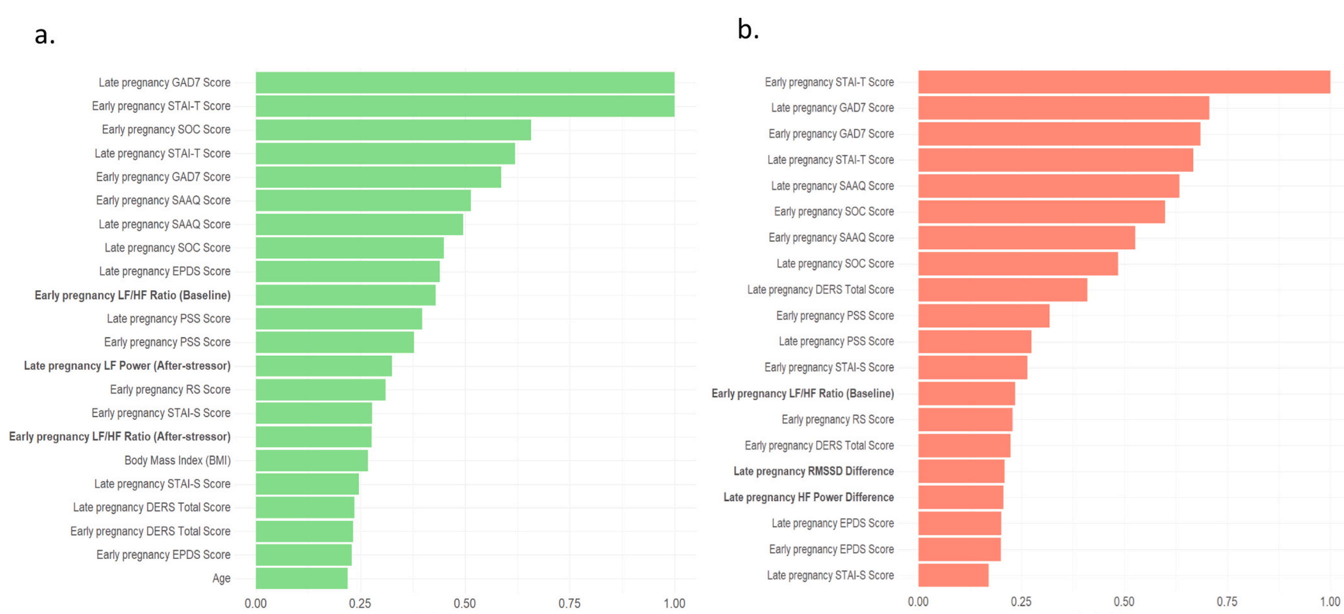

Fig. 3. Scaled variable importance scores for predictors in the (a) postpartum state anxiety and (b) trait anxiety models.*Note.* Bar plots display scaled variable importance scores from the Random Forest models predicting postpartum anxiety outcomes. Model (a) reflects state anxiety (STAI-S), and model (b) reflects trait anxiety (STAI-T). Predictors include HRV indices, and psychological variables. HRV indices included in the predictive model are shown in bold font.

LF/HF at baseline and two late pregnancy markers of autonomic modulation (HF power and RMSSD difference scores; Fig. 3b). Comparison of normalized importance profiles across outcomes are shown in Fig. 4.

3.6. Comparison of random forest model performance with and without HRV indices

Random Forest models including HRV features yielded slightly superior model performance metrics across all outcomes compared to models excluding HRV (Supplementary Table 9a). When results were pooled across imputations, HRV yielded a small but statistically reliable improvement in MAE for postpartum depression (ΔMAE = −0.059, 95% CI [-0.115, −0.003]) and state anxiety (ΔMAE = −0.104, 95% CI [-0.194, −0.014]) (Supplementary Table 9b). For both outcomes, MSE, RMSE, and R^2 also trended positively but confidence intervals crossed zero. No performance differences reached significance for trait anxiety (e.g., ΔMAE = −0.052, 95% CI [-0.157, 0.053]; ΔR^2 = 0.007, 95% CI [-0.003, 0.016]). Variable importance scores for models excluding HRV can be found in Supplementary Tables 10–12.

4. Discussion

This study investigated whether HRV indices measured during early and late pregnancy, both at baseline and after a mild cognitive-emotional stressor, provide incremental predictive value for postpartum depression and anxiety symptoms at six weeks postpartum beyond established antenatal psychological measures. Using separate Random Forest models for depression, state anxiety, and trait anxiety, we evaluated the relative contribution of HRV indices in the context of a multivariate predictor set that included demographic and psychological variables routinely available in clinical settings. Across models, several HRV metrics emerged as contributors to postpartum symptom prediction alongside psychological measures. Comparisons between models with and without HRV indices found that HRV measures in both early and late pregnancy add small but statistically detectable increases in predictive accuracy for postpartum depression and state anxiety models ($\Delta R^2 \approx 0.01$ across outcomes), beyond well-established psychological predictors.

4.1. Significant HRV indices in the random forest postpartum depression model

In the postpartum depression model, LF/HF ratio consistently emerged as the strongest HRV predictor across both gestational periods and measurement points (baseline and after-stressor). This aligned with correlation analyses, which also found lower LF/HF ratio after-stressor to be associated with higher postpartum depression symptoms. Notably, group differences in HRV based on postpartum outcome were not significant in bivariate tests; the added value of HRV emerged only within the predictive models, suggesting that antenatal autonomic indices contribute subtle, complementary information not visible in simple group contrasts. These results differ from prior studies in which elevated LF/HF ratios have often been interpreted as reflecting greater sympathetic influence, although such interpretations remain debated (Shah et al., 2020). Instead, our results suggest that lower after-stressor LF/HF ratios may reflect a lack of flexible autonomic regulation, potentially indicating reduced physiological adaptability.

This interpretation is consistent with meta-analytic evidence outside the perinatal period showing reduced HRV across time- and frequency-domain measures in major depression, underscoring reduced HRV as a hallmark of depressive samples (Koch et al., 2019). It also aligns with more recent evidence that HRV alterations may precede depressive onset and aid early risk identification (Galin and Keren, 2024). Within perinatal populations, similar patterns have been observed, with lower HRV during the second and third trimesters prospectively predicting PPD (Singh Solorzano et al., 2022). The present findings extend prior evidence, including our earlier exploratory study (Eriksson et al., 2024), where late-pregnancy HRV indices in a different cohort, were retained

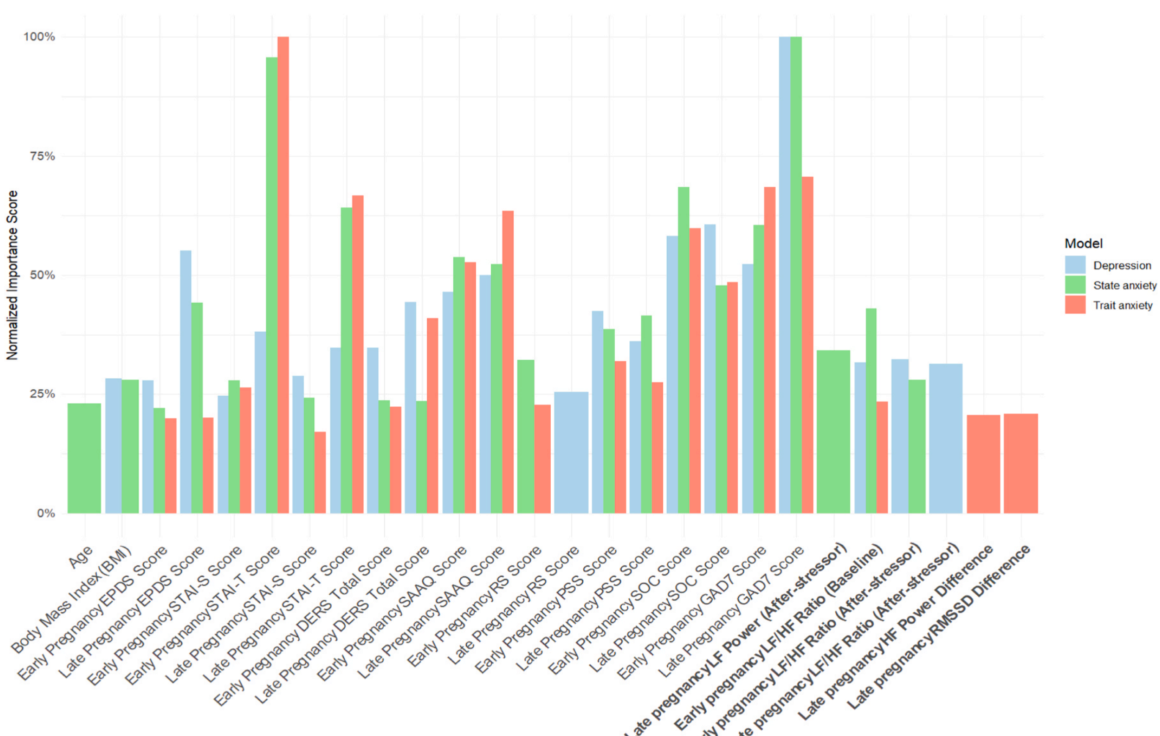

Fig. 4. Comparison of normalized importance scores for predictor variables across depression, state anxiety, and trait anxiety models.*Note.* This figure compares normalized variable importance scores for predictors retained in each Random Forest model. Variables are categorized by domain (background, psychological, HRV), and color-coded by outcome type. HRV indices are shown in bold font.

only when combined with psychosocial variables. Here, we show that absolute antenatal HRV indices- rather than difference-based autonomic modulation indices -provided the strongest incremental predictive contribution to postpartum depression. Collectively, the observed LF/HF patterns may indicate that impaired autonomic regulation under cognitive-emotional demand places individuals at heightened risk for PPD, and that repeated antenatal HRV measurements may modestly improve risk estimation when combined with psychosocial models.

4.2. Significant HRV indices in the random forest postpartum state anxiety model

In the postpartum state anxiety model, which predicted acute anxiety symptoms, the LF/HF ratio during early pregnancy once again emerged as an important predictor, showing trend-level agreement with correlations. By contrast, late pregnancy LF power after-stressor was retained as a predictor despite no corresponding correlation with state anxiety. In the prediction model, both LF/HF ratio and LF power contributed in a negative direction, suggesting that lower autonomic activity may be linked to greater risk of postpartum state anxiety. Rather than reflecting heightened stress sensitivity, as often interpreted with elevated LF or LF/HF measures, these findings may instead point to blunted autonomic reactivity or impaired sympathetic-parasympathetic balance. Such patterns are consistent with research showing that diminished physiological responsiveness, whether due to hypoarousal or autonomic inflexibility, can signal vulnerability to anxiety, particularly in emotionally demanding contexts like the perinatal period (Kimmel et al., 2021).

It is also consistent with meta-analytic evidence showing reduced HRV across anxiety disorders more broadly (Chalmers et al., 2014), and with recent reviews proposing HRV as a biomarker of anxiety risk (Tomasi et al., 2024). Within perinatal research, attenuated HRV responses in late pregnancy have similarly been observed among women with antenatal anxiety (Riddle et al., 2023), reinforcing the notion that impaired autonomic responsivity may reflect perinatal anxiety vulnerability. The inclusion of both early and late pregnancy HRV metrics in the predictive model further highlights the importance of tracking physiological reactivity longitudinally, and adds to our earlier work by demonstrating that indices from both gestational periods, rather than late pregnancy alone, can contribute to prediction (Eriksson et al., 2024). As gestation progresses, autonomic adaptations may mask or amplify individual differences in stress system functioning, which in turn can influence emotional outcomes postpartum (Riddle et al., 2023). These findings underscore the need to consider both hyper- and hypo-responsivity in models of perinatal anxiety risk.

4.3. Significant HRV indices in the random forest postpartum trait anxiety model

In the trait anxiety model, several HRV indices were retained as predictors despite showing no significant bivariate correlations with STAI-T scores. Specifically, lower early pregnancy LF/HF ratio at baseline, along with two indices capturing autonomic modulation from baseline to after-stressor - HF power and RMSSD difference scores - contributed in the prediction model. This suggests that trait-like anxiety vulnerability may be better explained by a combination of reduced baseline flexibility and individual variability in short-term autonomic modulation during mild cognitive-emotional challenge, rather than by static HRV levels at individual time points alone.

While parasympathetic increases are typically viewed as adaptive, our LF/HF findings may reflect a baseline regulatory bias toward reduced flexibility, particularly in individuals with chronic anxiety traits. The additional retention of HF power and RMSSD difference scores within the predictive model reinforces this interpretation, suggesting that individual variability in short-term parasympathetic modulation under mild cognitive-emotional challenge contributes to trait anxiety risk. Rather than indicating classical stress recovery or exaggerated vagal reactions, these patterns may reflect differences in autonomic stability or regulatory flexibility. This interpretation is consistent with broader evidence that both diminished and dysregulated vagal modulation are associated with persistent anxiety (Chalmers et al., 2014; Schwerdtfeger and Derakshan, 2010). Perinatal research has similarly reported altered HRV profiles among women with antenatal anxiety (Riddle et al., 2023). Extending our earlier exploratory study, which examined anxiety as a single outcome (Eriksson et al., 2024), the present results show that when state and trait dimensions are separated, HRV contributes little to trait anxiety prediction.

4.4. Interpretation of model comparison

The sensitivity analysis shows that adding HRV to antenatal self-report brings a small but reliable refinement in predictive accuracy. The most consistent benefit was a modest reduction in absolute error for both depression and state anxiety models; overall explained variance and squared-error metrics also trended positively but remained within the bounds of imputation uncertainty. This pattern suggests that HRV captures a unique physiological signal that subtly sharpens risk estimates, particularly for borderline cases, without substantially altering overall model fit.

One plausible explanation for why HRV incrementally improved predictive accuracy specifically in depression and state anxiety models, but not trait anxiety, relates to the conceptual differences between these psychological constructs. Depression and state anxiety are strongly influenced by transient physiological and emotional states, making them closely aligned with dynamic autonomic nervous system fluctuations captured by HRV measures. In contrast, trait anxiety reflects a stable predisposition that may be better explained by enduring psychological and behavioral factors than by short-term autonomic variability. From an implementation standpoint, HRV assessments may best serve as an adjunct to, rather than a replacement for, existing questionnaires, especially in settings where self-report data are incomplete or potentially biased. The modest reductions in prediction error observed here suggest that HRV is unlikely to support universal screening, but may offer incremental value as a secondary indicator in cases where self-report measures alone provide ambiguous risk estimates. The additional time, cost, and resources required for HRV assessments should be balanced against these incremental predictive benefits.

A key interpretive consideration is whether inclusion of after-stressor HRV indices is justified given the minimal mean-level HRV changes observed in response to the Emotional Stroop task. The inclusion of these indices was not intended to demonstrate strong physiological stress responses, but rather to test whether standardized within-session autonomic variation provides information beyond resting HRV alone. In this framework, after-stressor measures function as structured probes of dynamic autonomic adjustment under controlled cognitive-emotional demand. Their modest and outcome-specific contribution suggests that dynamic physiological features may refine risk estimation beyond self-report measures alone, although the magnitude of this incremental improvement was small.

Several background and psychosocial variables showed bivariate associations with postpartum symptoms but did not retain importance in the multivariate Random Forest models. This pattern reflects the conditional nature of variable importance in ensemble methods, whereby predictors that are correlated with other features may show reduced importance once shared variance is accounted for (Breiman, 2001; Gregorutti et al., 2017). Negative life events provide one illustrative example of this process: although associated with outcomes at the bivariate level, they did not add predictive value beyond correlated antenatal symptom and stress-related measures. This underscores that the modeling approach was designed to identify variables with unique incremental contribution rather than to catalog all correlates of postpartum symptoms.

4.5. Limitations

Several limitations should be noted. First, the modest sample size and the generally healthy, well-educated, and relatively homogeneous nature of the cohort restricts generalizability and may have obscured smaller effects. In addition, the limited number of participants exceeding clinical symptom thresholds constrains statistical power and may increase the risk of Type II error, potentially contributing to the absence of significant group-level HRV differences. The exclusion of participants with severe psychiatric disorders further restricted outcome variability and limits applicability to clinical populations. Although symptom prevalence in the sample was comparable to population-based estimates, the observed incremental contribution of HRV was modest and should therefore be interpreted cautiously. Although a subset of participants developed postpartum symptoms in the absence of elevated antenatal symptoms (i.e., *de novo* cases), their small number precluded adequately powered subgroup analyses. Accordingly, these participants were pooled with those showing antenatal symptoms, which may obscure differences in predictors specific to *de novo* onset. Additionally, the cognitive-emotional stressor used (Emotional Stroop task) was selected for feasibility and ethical appropriateness during pregnancy but represents a relatively mild challenge and did not elicit substantial mean-level HRV modulation in this sample. Accordingly, baseline-to-after-stressor differences should not be interpreted as classical indices of acute stress reactivity or recovery. Moreover, because HRV was assessed after rather than during the task, we were unable to directly quantify peak autonomic reactivity. These difference scores are therefore best interpreted as reflecting individual variability in short-term autonomic modulation under mild cognitive-emotional challenge conditions. Finally, although the Task Force (Electrophysiology, 1996) guidelines recommend reporting both absolute and normalized units for frequency-domain measures, we focused on log-transformed absolute values due to their suitability for modeling and the reduction of multicollinearity in our predictive analyses. This may limit direct interpretability of sympathetic-parasympathetic balance.

4.6. Future directions

Future research involving larger, more diverse cohorts is needed to validate the stability and generalizability of these models and to reduce uncertainty related to limited statistical power. Larger samples would also enable focused investigation of *de novo* postpartum depression and anxiety as a distinct subgroup, allowing direct tests of whether physiological predictors such as HRV contribute differentially to risk in the absence of antenatal symptom elevation.

Methodologically, future studies would benefit from recording HRV concurrently with stress exposure and from incorporating more potent or standardized stress paradigms to better differentiate acute autonomic reactivity from short-term autonomic modulation following cognitive-emotional challenge. Including tonic heart rate alongside HRV measures may further enhance interpretability, given the inverse relationship between heart rate and absolute HRV values. Finally, while self-report questionnaires remain central to perinatal mental health screening, brief autonomic assessments may offer incremental value as adjunctive tools, particularly for women with ambiguous symptom profiles. The increasing availability of wearable HRV devices also presents opportunities for longitudinal, real-world monitoring and personalized, non-pharmacological interventions targeting perinatal distress.

5. Conclusion

This study offers novel insight into the incremental predictive contribution of early pregnancy HRV indices, and supports the relevance of late pregnancy HRV indices, in identifying risk for postpartum depression and anxiety outcomes when considered alongside well-established psychosocial assessments. By integrating HRV with antenatal psychosocial assessments, our models showed modest but reliable improvements in predictive accuracy, particularly for depression and state anxiety. These findings suggest that HRV provides complementary physiological information beyond self-report rather than serving as a standalone screening tool, and highlight the importance of considering both diminished and exaggerated autonomic responses as potential risk markers. As the field moves toward precision prevention, incorporating brief, non-invasive physiological screening into prenatal care may help refine risk stratification - particularly in cases where self-report indicators are ambiguous - and support the development of more targeted interventions.

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CRediT authorship contribution statement

Emma Fransson: Writing – review & editing, Supervision, Software, Resources, Methodology, Funding acquisition, Conceptualization. **Andreas Frick:** Writing – review & editing, Supervision, Methodology. **Ulf Elofsson:** Writing – review & editing, Resources, Methodology. **Anna Wikman:** Writing – review & editing, Methodology. **Tomas Furmark:** Writing – review & editing, Resources, Methodology, Conceptualization. **Matilda Mikkola Jäghammar:** Writing – original draft, Project administration, Investigation. **Allison Eriksson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation.

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

Artificial intelligence tools (e.g., ChatGPT by OpenAI) were used to assist with language editing and text refinement. The authors reviewed and approved all content.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2026.107813.

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