Neuroscience and Biobehavioral Reviews 184 (2026) 106585

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

A multi-level meta-analysis of vagally-mediated heart rate variability and post-traumatic stress disorder

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ARTICLE INFO

Keywords:
Vagally-mediated heart rate variability
HRV
PTSD
Post traumatic stress disorder
Multi-level meta analysis
Recording duration

ABSTRACT

Posttraumatic stress disorder (PTSD) is frequently associated with autonomic nervous system (ANS) dysregulation, as evidenced by diminished vagally mediated heart rate variability (vmHRV). To date, no meta-analysis has systematically compared 5-minute and 24-hour vmHRV recordings in PTSD, limiting our understanding of how recording duration influences findings. This study examined differences in vmHRV between individuals with PTSD and controls using both 5-minute and 24-hour recordings. The meta-analysis synthesised data from 24 studies involving 2537 participants and 34 effect sizes. A novel analytical approach was used and involved traditional multi-level meta-analysis, robust variance estimation, and separate analyses across vmHRV indices and recording durations to isolate independent effects. Whilst vmHRV was consistently reduced in individuals with PTSD, the magnitude of this effect was greater in studies utilising 5-minute recordings than those using 24-hour recordings. Therefore, the results indicate that methodological differences in HRV assessment, particularly recording duration, significantly influence the observed magnitude of vmHRV reductions in PTSD. The robust analytical strategy enhances the reliability of vmHRV as a biomarker of ANS dysregulation in PTSD. The findings highlight the need for standardised vmHRV protocols in PTSD research.

1. Introduction

Post-traumatic stress disorder (PTSD) is a complex psychiatric disorder that arises from direct or indirect exposure to actual or threatened death, serious injury, or sexual violence (American Psychiatric Association, 2013). From a physiological standpoint, PTSD is characterised by alterations in Autonomic Nervous System (ANS) function, including reduced Parasympathetic Nervous System (PNS) activity and heightened Sympathetic Nervous System (SNS) activity in response to psychological and physical demands (Buckley and Kaloupek, 2001; Fu, 2022; Park et al., 2017; Pole, 2007; Schneider and Schwerdtfeger, 2020). These autonomic alterations contribute to hyperarousal, heightened stress reactivity, and impaired autonomic flexibility, which are core features of PTSD and negatively affect the regulation of physiological and emotional responses (Kim et al., 2019).

The parasympathetic influence on the heart is primarily mediated by cardiac vagal activity via the tenth cranial nerve, the vagus nerve (Quigley et al., 2024; Shaffer et al., 2014). Cardiac vagal activity enables rapid modulation of heart rate in response to environmental demands, supporting flexible physiological adaptation (Levy et al., 1993). Reduced cardiac vagal activity is associated with increased physiological arousal and reduced autonomic flexibility, linking impaired neural regulation to the stress-related symptomatology observed in PTSD (Gillie and Thayer, 2014; Williamson et al., 2015).

The vagus nerve maintains direct and indirect connections with the prefrontal cortex, a key structure within the Central Autonomic Network (CAN) (Thayer and Lane, 2000, 2009). According to the Neurovisceral Integration Model (Thayer and Lane, 2000, 2009), the CAN comprises interconnected cortical and subcortical structures, including the prefrontal cortex, anterior cingulate cortex, insula, amygdala, and brainstem nuclei, and coordinates autonomic, affective, and cognitive responses to environmental demands (Thayer and Lane, 2000; Thayer et al., 2009). In PTSD, dysregulation of the CAN is evidenced by impaired prefrontal inhibition of subcortical regions such as the amygdala, resulting in heightened sympathetic reactivity, reduced parasympathetic modulation, and diminished vmHRV (Harricharan et al.,

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https://doi.org/10.1016/j.neubiorev.2026.106585
Received 10 September 2025; Received in revised form 20 January 2026; Accepted 27 January 2026
Available online 29 January 2026

2016; Nicholson et al., 2022; Thome et al., 2017).

Heart rate variability (HRV) is defined as variation in the time interval between successive heartbeats (Akselrod et al., 1981; Camm et al., 1996). Whilst HRV broadly reflects autonomic influences on cardiac function, vagally mediated HRV (vmHRV) refers specifically to those components of HRV that index parasympathetic modulation of heart rate via the vagus nerve (Laborde et al., 2017). vmHRV is therefore considered a functional output of the CAN, capturing the extent to which central neural systems regulate cardiac vagal control (Laborde et al., 2018). Research consistently demonstrates that individuals with PTSD exhibit reduced HRV, primarily reflecting diminished cardiac vagal modulation of heart rate (Caldas et al., 2022; Campbell et al., 2019; Fonkoue, Michopoulos et al., 2020; Nagpal et al., 2013; Petersdotter et al., 2025; Schneider and Schwerdtfeger, 2020). Reduced vmHRV in PTSD thus reflects disrupted cardiac vagal activity, reduced autonomic flexibility, and compromised self-regulatory capacity (Dennis et al., 2014, 2016; Fonkoue, Marvar et al., 2020; Fonkoue, Michopoulos et al., 2020; Gillie and Thayer, 2014; Williamson et al., 2015).

The development of HRV has evolved alongside advances in cardiac measurement, from early observations of pulse variability to the development of electrocardiography, which enabled precise quantification of beat-to-beat heart rate fluctuations (Billman, 2011; Hajar, 2018). Subsequent technological developments facilitated continuous 24-hour recordings using portable devices, such as the Holter monitor, allowing examination of HRV across extended periods of daily activity and rest (Billman, 2011). Although early interpretations conceptualised HRV as a marker of overall autonomic balance, pharmacological blockade and neurophysiological studies clarified that high-frequency HRV components primarily reflect cardiac vagal modulation, whilst low-frequency indices do not provide a valid measure of sympathetic activity (Berntson et al., 1997; Billman, 2013; Goldstein et al., 2011; Grossman and Kollai, 1993; Quigley et al., 2024; Shaffer and Ginsberg, 2017). Accordingly, the present study does not examine low-frequency HRV or the LF/HF ratio. Instead, it focuses exclusively on vmHRV indices, including high-frequency HRV (HF-HRV, expressed in ms^2) and the root mean square of successive differences (RMSSD), because the physiological bases are well characterised and supported by empirical evidence (Laborde et al., 2017; Shaffer and Ginsberg, 2017).

HF-HRV and RMSSD are highly correlated and are widely used indices of vagally mediated modulation of heart rate within the respiratory frequency range (Laborde et al., 2017; Shaffer and Ginsberg, 2017). Both indices are influenced by respiration; however, RMSSD appears less sensitive to respiratory variation than HF-HRV (Hill et al., 2009; Quintana et al., 2016; Shaffer and Ginsberg, 2017). In turn, RMSSD is often the preferred measure of vmHRV (Pham et al., 2021).

Respiratory sinus arrhythmia (RSA), characterised by heart rate acceleration during inhalation and deceleration during exhalation, represents a normal physiological phenomenon mediated primarily by cardiac vagal activity (Lehrer et al., 2020; Steffen et al., 2017). RSA typically occurs within the high-frequency range of HRV (Quintana et al., 2016a) and is influenced by respiratory rate and depth (Berntson et al., 1997; Grossman and Kollai, 1993; Hill et al., 2009). Although controlling respiration may reduce measurement variability, extensive respiratory manipulation may be methodologically challenging in psychiatric populations and may interact with experimental demands (Berntson et al., 1997; Quintana et al., 2016a). Despite these considerations, diminished vmHRV has been consistently observed in individuals with PTSD, suggesting reduced cardiac vagal modulation in this population (Campbell et al., 2019; Ge et al., 2020; Nagpal et al., 2013; Schneider and Schwerdtfeger, 2020). For example, Campbell and colleagues (2019) conducted a meta-analysis of 55 studies examining baseline RSA in individuals with PTSD, finding a small but significant reduction in parasympathetic activity. Similarly, Ge et al., (2020) analysed 19 studies focusing on the association between HF-HRV and RMSSD in those with PTSD. The findings highlighted pronounced reductions in both HF-HRV and RMSSD in those with PTSD Ge et al., 2020).

Schneider and Schwerdtfeger (2020) conducted a comprehensive meta-analysis by examining differences in multiple HRV indices between individuals with PTSD and healthy controls, both at rest and during stress. The study investigated indices such as SDNN, RMSSD, HF-HRV, LF-HRV, and the LF/HF ratio, allowing for a thorough assessment of ANS functioning in those with PTSD (Schneider and Schwerdtfeger, 2020). The results indicated lower parasympathetic activity in those with PTSD, as well as increased heart rate, with medium effects observed for total variability (SDNN) and small effects for LF-HRV (Schneider and Schwerdtfeger, 2020). Subgroup analyses and meta-regressions also explored moderating influences of physical health, sex and psychiatric comorbidities, yet did not significantly moderate the relationship between any HRV index and HRV in those with PTSD (Schneider and Schwerdtfeger, 2020).

Although existing meta-analyses have consistently identified reduced vmHRV in PTSD, they have not accounted for differences in vmHRV recording duration and have typically pooled HRV indices across heterogeneous recording periods (Campbell et al., 2019; Ge et al., 2020; Nagpal et al., 2013; Schneider and Schwerdtfeger, 2020). vmHRV can be quantified using 5-minute (short-term) or 24-hour (long-term) recordings, which are not interchangeable and may capture distinct aspects of autonomic regulation (Hayano and Yuda, 2021; Kuusela, 2013; Shaffer and Ginsberg, 2017).

Short-term vmHRV recordings primarily index phasic cardiac vagal modulation under relatively controlled conditions, whereas 24-hour recordings reflect vagal regulation across varying physiological and environmental demands, including circadian influences, sleep, posture, and daily activity (Hinde et al., 2021; Pham et al., 2021). On the other hand, continuous 24-hour vmHRV recordings integrate autonomic responses across a broad range of internal and external demands and are therefore considered more reflective of overall ANS functioning and more strongly associated with long-term health outcomes than 5-minute vmHRV recordings (Pham et al., 2021). As such, different recording durations capture distinct aspects of cardiac vagal regulation (Hayano and Yuda, 2021; Laborde et al., 2017; Quigley et al., 2024; Shaffer and Ginsberg, 2017).

Despite the clear physiological distinctions between short- and long-term vmlHRV recordings, existing meta-analyses may have potentially obscured differences between phasic and tonic autonomic dysregulation in those with PTSD. Accordingly, this study aimed to compare vmHRV between individuals with PTSD and healthy controls using both 5-minute and 24-hour recording periods to provide a more precise estimate of the strength of the association between PTSD and cardiac vagal activity. In addition, the present study aimed to account for differences in effect sizes arising from the vmHRV indices used across primary studies. Furthermore, given the substantial heterogeneity reported in prior meta-analyses, this study further aimed to examine sources of heterogeneity across sampling variance, within-study variance, and between-study variance using a multilevel meta-analytic approach (Assink and Wibbelink, 2016; Cheung, 2019).

2. Methods

The study was conducted according to the PRISMA guidelines and registered in the PROSPERO database (registration number CRD42022330519). At the time of registration, no similar reviews were listed in the PROSPERO database. Data were sourced from five databases: Web of Science, Google Scholar, Embase, Medline, and PsycInfo. This combination of databases was selected based on evidence suggesting that this combination of databases achieves high recall rates, capturing over 95 % of relevant studies in systematic reviews (Bramer et al., 2017). The inclusion of PsycINFO further strengthened coverage, particularly for psychological research (Bramer et al., 2017).

The search terms were generated from scoping searches and were intentionally kept broad to identify all potentially relevant studies. As

Google Scholar limits search strategies to a maximum of 256 characters, including spaces, the search strategy was kept below this threshold for all databases to maintain the consistency of search terms used within each database (Bramer et al., 2017). The final search was conducted on 12/11/2025 and used the following syntax: ("vagally mediated heart rate varia*" or "heart rate varia*" or HRV or "respiratory sinus arrhythmia" or RSA) AND ("trauma* survivor*" or PTSD or "post--traumatic stress disorder" or "posttraumatic stress disorder").

2.1. Eligibility criteria

Studies were required to include only participants over 18 years of age. Studies were also required to include at least one vmHRV index recording and calculation. Further, only studies that used 5-minute or 24-hour vmHRV recording durations and explicitly stated the recording duration were eligible for inclusion, as short-term and long-term HRV measurements differ in their physiological meaning (Hayano and Yuda, 2021; Kuusela, 2013; Shaffer and Ginsberg, 2017). Eligible studies were also required to utilise a healthy or trauma-exposed control group where participants did not have a current diagnosis of PTSD, as well as a PTSD group in which participants met diagnostic criteria for PTSD or had above threshold symptoms/symptom severity as assessed via clinical interview or validated self-report measure. Where studies utilised a trauma-exposed control group, this group was prioritised over a healthy control group for analyses.

Existing meta-analyses typically include studies that utilise both trauma-exposed and healthy control groups (Campbell et al., 2019; Ge et al., 2020; Nagpal et al., 2013; Schneider and Schwerdtfeger, 2020). Therefore, the decision to prioritise a trauma-exposed control group over a healthy control group was to more precisely identify PTSD-specific effects. This approach is supported by existing literature which revealed no significant difference in effect sizes between healthy controls and trauma-exposed controls (Campbell et al., 2019). As such, PTSD-related differences in vmHRV are not necessarily amplified when compared to healthy individuals. However, studies using healthy control groups were still included in the analysis to ensure that differences observed in vmHRV could be more confidently attributed to PTSD rather than trauma exposure alone. Studies were excluded if they did not report the required data for calculating effect sizes. Studies were also excluded if they were conducted using non-human participants or were not written in English. Articles for which full-text access was unavailable were excluded from the review.

2.2. Selection process

A stepwise approach was utilised to determine the eligibility of studies. First, titles and abstracts were screened; irrelevant and duplicate studies were excluded. In the second step, a reviewer screened all remaining full-text studies to identify eligible studies. Then, all eligible studies were screened to select all studies that met the pre-defined inclusion criteria. All decisions were checked via consultation with a second reviewer. All decisions were in complete agreement, and no conflicts required resolution. Once consensus was reached, a reviewer began the data extraction process.

2.3. Publication bias

Publication bias was assessed using Egger's regression test by regressing the standard normal deviate of effect sizes on the inverse of their standard errors (Egger et al., 1997).

2.4. Data collection

Both time- and frequency measures of vmHRV were extracted from eligible articles, including HF and RMSSD. In studies using 5-minute vmHRV recordings, only resting state vmHRV measures were extracted to limit the influence of confounding factors (Ge et al., 2020). From studies using 24-hour vmHRV recordings the single mean value reported over the recording period was extracted. Primary studies using 24-hour vmHRV recordings did not report time-resolved or rhythm-based vmHRV parameters. Accordingly, the calculated effect sizes reflect between-group differences in these reported summary measures. For each study, information was extracted regarding the study name, publication year, total sample size, number of participants with PTSD, sample type, trauma type, DSM criteria used, PTSD assessment measure, HRV indices, any transformations applied to the HRV data, and the method of HRV acquisition.

Where data were missing or were reported using graphs, authors were contacted via email; if no response was received, the study was excluded (a list of excluded articles with reasons has been provided separately in supplementary file one). Data regarding the age, gender and trauma type experienced by participants were also extracted.

2.5. Quality assessment

A critical appraisal of the methodological quality of included studies was conducted using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies (Moola et al., 2017). This checklist was utilised because it is specifically designed for analytical cross-sectional studies, which constituted all studies included in this meta-analysis. The JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies evaluates key aspects of study quality across eight dimensions: clarity of inclusion criteria, detailed description of participants and study setting, validity and reliability of exposure measurement, use of standardised criteria for assessing the condition of interest, identification of confounding factors, strategies to address confounders, validity and reliability of outcome measurement, and appropriateness of statistical analysis.

Each dimension is rated as 'Yes', 'No', or 'Not applicable'. The JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies (Moola et al., 2017) does not define explicit cut-off values as its purpose is to assess methodological rigour rather than providing a strict classification system (See supplementary file for complete quality assessment results).

2.6. Calculation of effect size

Hedges' g (Hedges and Olkin, 1985) measure of effect size was calculated for each article and was reported as an overall measure of effect size with 95 % confidence intervals (CI). Hedges' g and Cohens d are similarly effective for calculating effect size in large samples where each condition utilises a similar number of participants (Lakens, 2013). Nevertheless, Hedges' g outperforms other effect size measures when sample sizes are below 20 or are significantly different (Lakens, 2013). The magnitude of Hedges' g effect size was computed per the thresholds that have been defined for Cohen's d; large (0.8), medium (0.5), and small (0.2) (Cohen, 1992).

2.7. Multilevel meta-analytic model

The meta-analysis employed a random-effects model as those with PTSD represent a heterogeneous population (Borenstein et al., 2010). Effect sizes were imputed into a multilevel meta-analytic model (Assink and Wibbelink, 2016; Cheung, 2019). This model examined three variance components that were distributed across the model, including sampling variance (level 1), within-study variance (level 2) and between-study variance (level 3) (Assink and Wibbelink, 2016; Cheung, 2019). Consequently, this provided a more accurate representation of the initially 'generated' data, which naturally adopted a nested model due to the high degree of correlation between vmHRV indices (Cheung, 2019).

Favourability between the reduced model (two levels) and the full

model (three levels) was assessed using the corrected Akaike Information Criterion (AICc) (Burnham and Anderson, 2004; Chakrabarti and Ghosh, 2011). The model with the lowest AICc value was interpreted as demonstrating favourable performance, especially where the difference between models was greater than two, thus ensuring that only meaningful differences were captured (Burnham and Anderson, 2004). The likelihood ratio test (LRT) was used to compare the models, and a significant LRT value ($p < .05$) indicated favourability between the models.

Heterogeneity was expected due to the diversity of the samples utilised in included studies, where significant heterogeneity was observed ($p < .05$), mixed-model regression analysis and the restricted maximum-likelihood estimation (RMLE) methods were used to explore the source of heterogeneity amongst studies. However, the meta-analytical model was applied in three separate ways.

2.8. Methods of applying the multi-level meta-analytic model

2.8.1. Application method one: traditional application

The metafor (Viechtbauer, 2010) package for R Studio (R Core Team, 2020) was used to conduct Application Method One. Short-term, and long-term vmHRV measurements differ in physiological meaning (Kuusela, 2013). Therefore, the first application of the multi-level meta-analytic model (Assink and Wibbelink, 2016; Cheung, 2019) was conducted using effect sizes derived from studies that utilised 5-minute vmHRV recordings in the first analysis. In the second analysis, effect sizes derived from studies that utilised 24-hour vmHRV recordings were used. Furthermore, moderator analyses were conducted to ascertain the contribution of each vmHRV measure to the overall effect. In other words, the moderator analysis sought to reveal which measure i.e., RMSSD or HF-HRV was more strongly associated with PTSD and whether their contributions differ significantly (see Fig. 1 for a schematic representation of the Application Method One).

Although this approach followed the traditional method for applying multi-level meta-analytic models (Assink and Wibbelink, 2016; Cheung, 2019), one of the issues with this approach was that it does not account or interdependent effect sizes (Assink and Wibbelink, 2016; Pustejovsky and Tipton, 2022). As a result, applying the multi-level meta-analytic model in this way did not account for the high degree of correlation between vmHRV measures namely, RMSSD and HF-HRV (Bylsma et al., 2024; Camm et al., 1996; McCraty and Shaffer, 2015; Shaffer and Ginsberg, 2017). In turn, this may have artificially inflated the observed effect (Pustejovsky and Tipton, 2022). As such, Application Method Two extended the traditional approach to multi-level meta-analyses by allowing for the interdependency between effect sizes to be controlled statistically.

2.8.2. Application method two: method for applying the multi-level meta-analytic model whilst accounting for interdependent effect sizes

Studies using 5-minute vmHRV recording durations and those using 24-hour recording durations were each analysed individually. As both RMSSD and HF-HRV capture the same underlying psychophysiological construct i.e., PNS activity (Camm et al., 1996; Shaffer and Ginsberg, 2017) and can therefore be included in the same meta-analytic model, in theory. However, the inclusion of both RMSSD and HF-HRV measures within a single meta-analysis may have introduced interdependency between effect sizes since they are highly correlated (Bylsma et al., 2024; Camm et al., 1996; McCraty and Shaffer, 2015; Shaffer and Ginsberg, 2017). In turn, this may have conflated the true relationship between vmHRV and PTSD. That said, including both measures whilst effectively handling interdependency using a robust variance estimation (RVE) may increase the statistical power of the analysis and provide a robust estimate of the true effect (Pustejovsky and Tipton, 2022).

Therefore, the second application method replicated Application Method One, but extended the method by simultaneously accounting for interdependency between RMSSD and HF-HRV effect sizes. The metafor (Viechtbauer, 2010) and clubSandwich (Pustejovsky, 2020) packages for R Studio (R Core Team, 2020) were used to conduct Application Method Two. The addition of a RVE allowed dependent effect sizes to be included simultaneously in a single meta-regression model, even though the details of the correlation between the two was undetermined (Pustejovsky and Tipton, 2022). Accordingly, the result of the RVE provided a more accurate estimation of the true effect (Pustejovsky and Tipton, 2022). The application of method one and two permitted the comparison of effect size estimates, confidence intervals, and measures of heterogeneity (I^2) between the two models (Pustejovsky and Tipton, 2022). Similarity between the results of the traditional multi-level

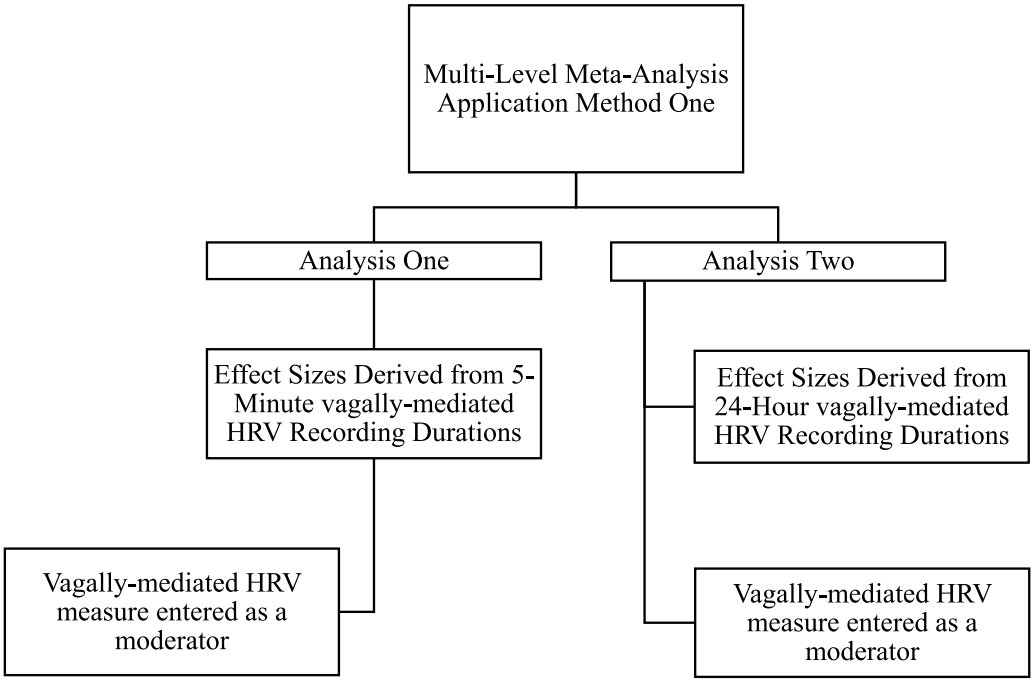


Fig. 1. Schematic representation of the multi-level meta-analysis model using the traditional application method.

meta-analysis (Application Method One) and RVE (Application Method Two) results indicate the robustness of the overall conclusions. In turn, strengthening the reliability and validity of the observed effect of vmHRV in PTSD (see Fig. 2 for a schematic representation of Application Method Two).

2.8.3. Application method three: alternative method for applying the multi-level meta-analytic model whilst accounting for interdependent effect sizes

The metafor (Viechtbauer, 2010) package for R Studio (R Core Team, 2020) was used to conduct Application Method Three. Studies using 5-minute vmHRV recording durations and those using 24-hour recording durations were each analysed individually in application method 3. However, the third method of applying the multi-level meta-analytic model involved further subdividing the data derived from eligible studies. Diving the data in this way resulted in only one effect size from each study being included in a meta-analytic model. This meant that a RVE calculation was not needed as the division of the data eliminated potential interdependency prior to the analyses. This method is alternative approach to overcome the issues arising from independent effect sizes. As such, application of multilevel meta-analytic model three resulted in four separate analyses: RMSSD effect sizes derived from 5-minute vmHRV in PTSD studies (Analysis 1), HF-HRV effect sizes derived from 5-minute HRV in PTSD studies (Analysis 2), RMSSD effect sizes derived from 24-hour HRV in PTSD studies (Analysis 3) and HF-HRV effect sizes derived from 24-hour HRV in PTSD studies (Analysis 4) (see Fig. 3 for a schematic representation of multi-level meta--analysis Application Method Three).

3. Results

3.1. Article selection

The database search revealed 1808 articles; some studies appeared in multiple databases. Once 672 duplicate studies were removed, 1136 articles remained for screening. After screening titles and abstracts 976 articles were excluded. The review then sought the remaining 160 articles for retrieval, 9 of which could not be retrieved. The reviewer then determined the suitability of the remaining 151 articles. A further 127 articles were excluded after full-text screening. A second reviewer then checked decisions. Any conflicting decisions were resolved via consultation with a third reviewer if necessary. In total, 24 articles were deemed eligible for inclusion. Fig. 4 summarises the search and screening process in line with PRISMA guidelines (Page et al., 2021)

3.1.1. Publication bias results

Egger's test was used to assess potential publication bias, with standard error included as the predictor in a mixed-effects meta-regression model. For studies using 5-minute vmHRV recordings, the regression test for funnel plot asymmetry indicated no significant publication bias ($z = -1.30$, $p = 0.19$) (See Fig. 5).

For studies using 24-hour vmHRV recordings, Egger's test also did not indicate significant publication bias, although the result approached significance ($z = -1.86$, $p = 0.06$) (See Fig. 6).

These results suggest that the risk of publication bias in all included studies is low.

3.2. Study characteristics

Fourteen articles were included in meta-analyses using effect sizes derived from 5-minute recordings of vmHRV (Blechert et al., 2007; Chang et al., 2013; Kirk et al., 2022; Mäder et al., 2023; Meyer et al., 2016; Moon et al., 2013; Park et al., 2019; Ray et al., 2017; Slewa-Younan et al., 2012; Song et al., 2011; Speer et al., 2020; Spiller et al., 2019; Wahbeh and Oken, 2013; Weggen et al., 2021). All articles included were published between 2007 and 2022 and included 1092 participants. The characteristics of the fourteen articles included in the meta-analyses using effect sizes derived from 5-minute recordings of vmHRV are summarised in Table 1.

Ten articles were included in the meta-analyses using effect sizes derived from 24-hour recordings of vmHRV in those with PTSD and controls. (Agorastos et al., 2013; Bertram et al., 2014; Dennis et al., 2014, 2016; Lakusic et al., 2007; Lee and Theus, 2012; Lee et al., 2013; Rissling et al., 2016; Shah et al., 2013; Shaikh al Arab et al., 2012). All articles were published between 2007 and 2019 and included 1445 participants. The characteristics of the ten articles included in the meta-analyses using effect sizes derived from 24-hour recordings of vmHRV are summarised in Table 2.

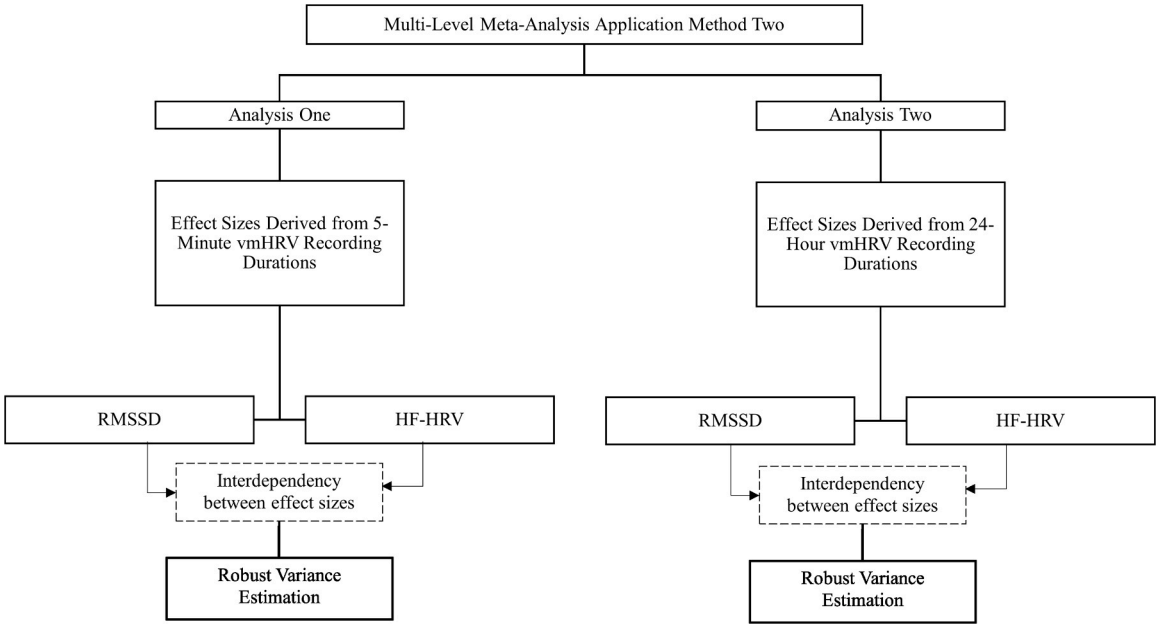


Fig. 2. Schematic Representation of Multi-Level Meta-Analysis Application Method Two.

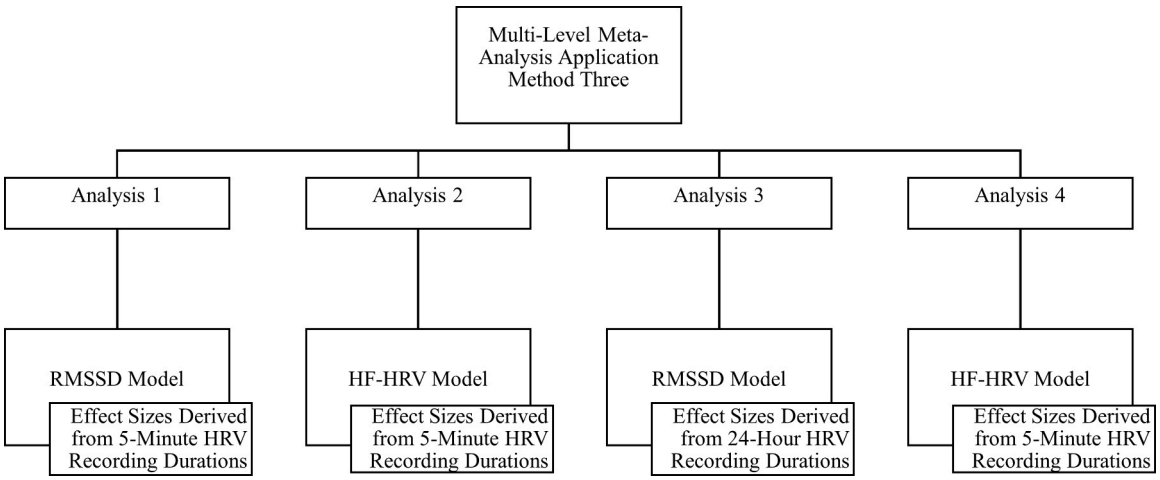
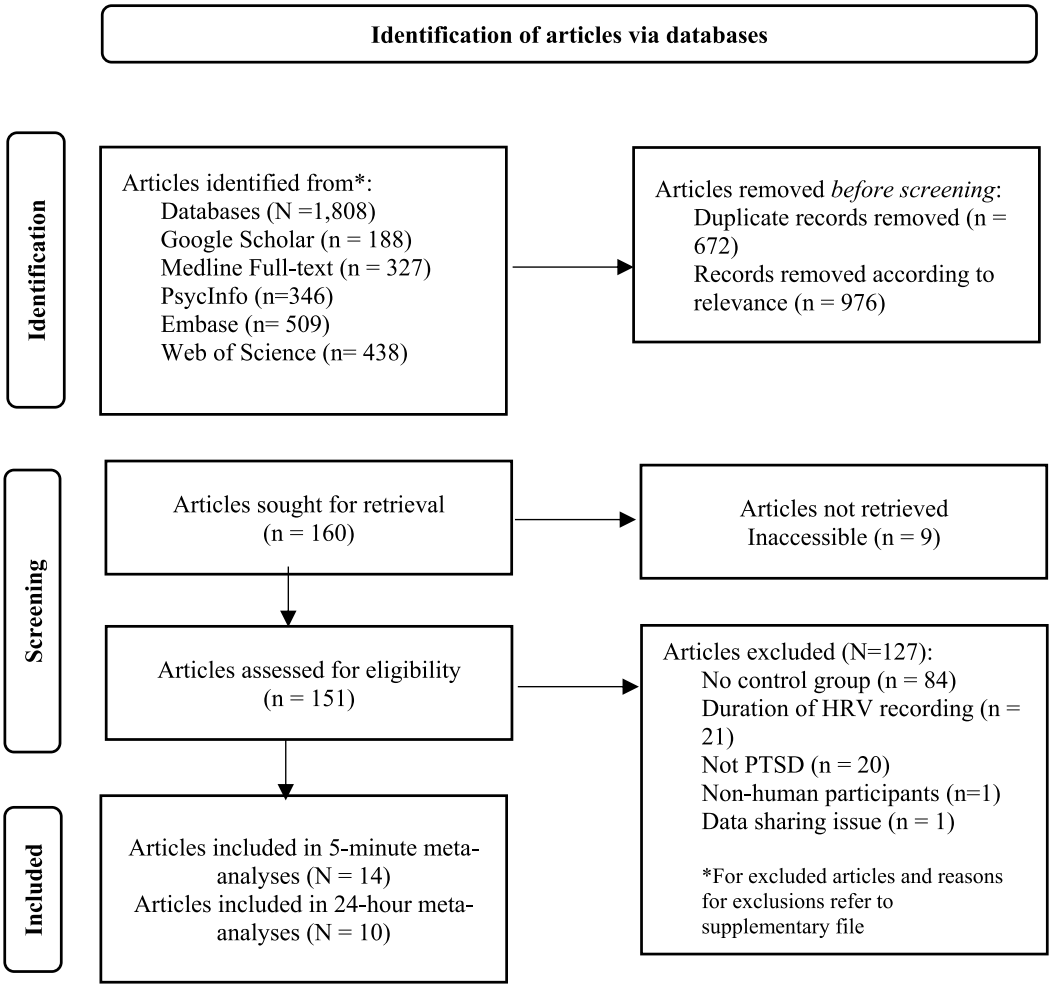


Fig. 3. Schematic Representation of Multi-Level Meta-Analysis Application Method Three.



From: Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n7

Fig. 4. Summary of Article Selection Process

3.3. Results of quality assessment

The Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Analytical Cross-Sectional Studies indicated that the methodological quality of the included studies was generally high across both 5-minute and 24-hour vmHRV recordings. Most studies clearly defined inclusion criteria and provided detailed descriptions of participants and study settings. Exposure and outcome measures were largely valid and

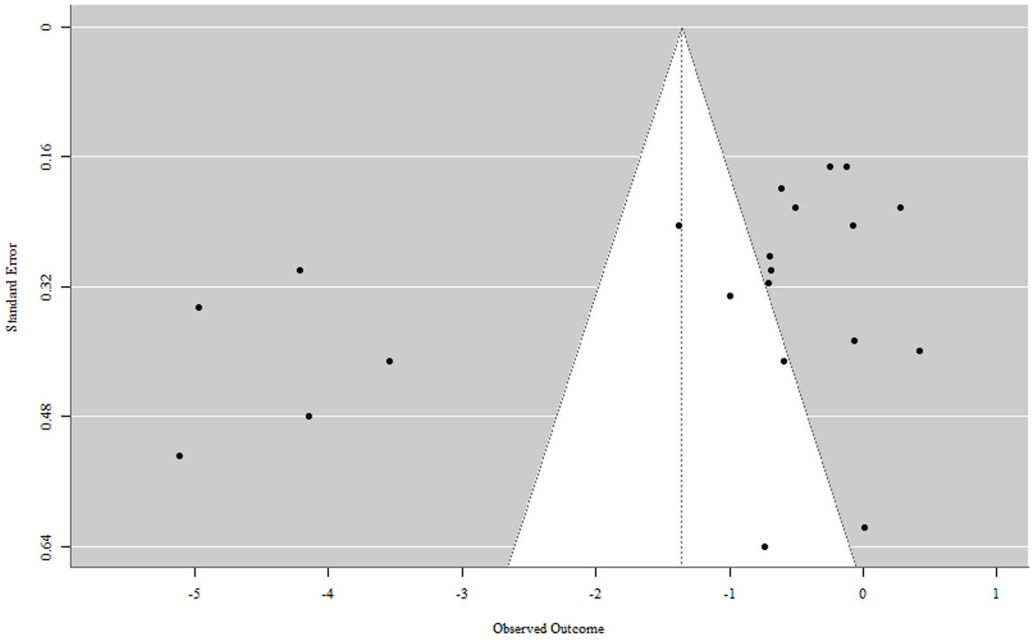


Fig. 5. Funnel plot examining publication bias for studies using 5-minute vmHRV recordings.

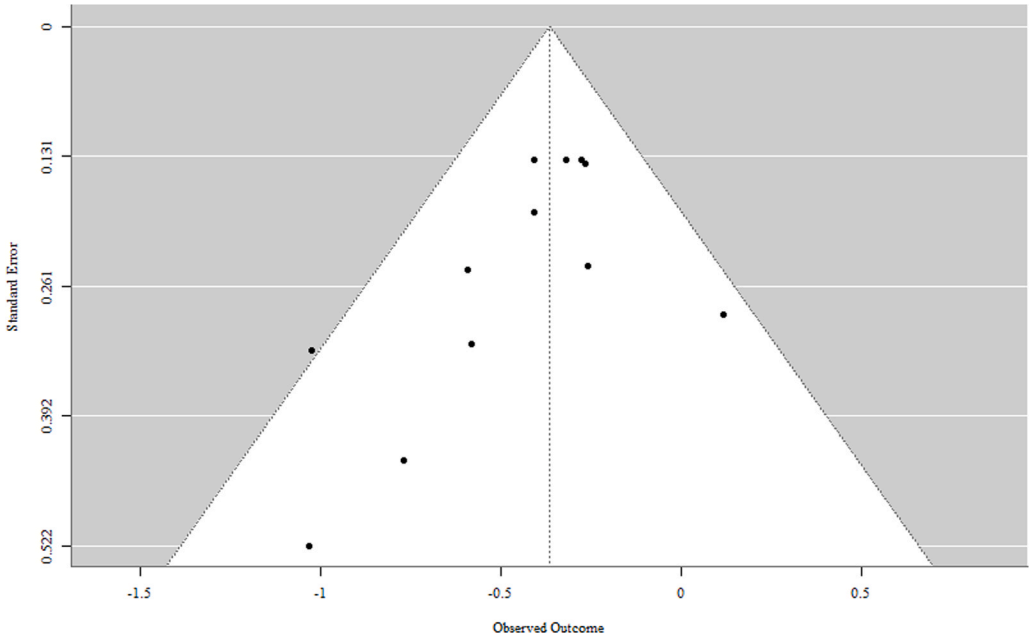


Fig. 6. Funnel plot examining publication bias for studies using 24-hour vmHRV recordings.

reliable, with standardised criteria consistently applied to assess the condition of interest. While potential confounding factors were often identified, strategies to address them were inconsistently reported. Statistical analyses were appropriate in nearly all studies. Overall, the included studies can be considered methodologically robust, with minor limitations primarily related to the management of confounding variables (see Supplementary Materials for full quality appraisal results).

3.4. Overall effect (Level One) of 5-minute vmHRV

The meta-analysis of effect sizes derived from studies using 5-minute recordings of vmHRV ($N = 14$, $k = 21$) demonstrated a large overall association between vmHRV and PTSD ($g = -1.38$, $SE = 0.45$, $t(22) = -3.08$, $p = .01$, CI [-2.32, −0.45]). See Fig. 7 for forest plots of effect sizes.

Significant heterogeneity was revealed between all effect sizes ($Q(22) = 649.15$, $p < .001$). To investigate the sources of heterogeneity two one-sided LRT's were computed independently.

3.5. Within study variance (Level Two) of 5-minute vmHRV effect sizes

The LRT revealed significant within-study variance ($\chi^2(1) = 4.55$, $p = .03$). Further, the full multilevel model ($AICc = 91.46$) provided a better fit than that of the reduced model without the within-study random effect ($AICc = 169.80$). Therefore, it can be concluded that there is significant variability between effect sizes within studies, which supports the inclusion of a within-study variance component in the meta-analytic model.

Table 1
Characteristics of Studies Included in The Meta-Analyses Using Effect Sizes Derived From 5-Minute Recordings of vmHRV.

Study Name	Publication Year	Total Sample	Sample Size PTSD	Sample Type	Trauma type	DSM Criteria	PTSD Measure	HRV indices	Transformation	HRV Acquisition Method
Blechert et al.,	2007	55	23	Clinical	Multiple	IV	CI	RSA (ms)	Log	Five-Minute ECG
Chang et al.,	2013	224	32	Clinical	Multiple	IV	SR	HF (ms^2)	None	Five-Minute ECG
Kirk et al.,	2022	64	18	Student	Multiple	V	CI	RMSSD (ms)	Ln	Five-Minute ECG
Mäder et al.,	2021	122	59	Clinical	Multiple	V	CI	RMSSD (ms), HF(ms^2)	Log	Five-Minute ECG
Meyer et al.,	2016	41	18	Clinical and Community	Multiple	IV	CI	RMSSD (ms), HF(ms^2)	None	Five-Minute ECG
Moon et al.,	2013	61	34	Clinical	Multiple	IV	CI	RMSSD (ms), HF (ms^2)	None	Five-Minute ECG
Park et al.,	2019	141	68	Mixed	Multiple	V	SR	RMSSD (ms), HF (ms^2)	Log	Five-Minute ECG
Ray et al.,	2017	82	41	Clinical and Community	Combat	IV	SR	RMSSD (ms), HF (ms^2)	None	Five-Minute ECG
Slewa-Younan et al.,	2012	35	12	Clinical	NR	NR	CI	HF(ms^2)	None	Five-Minute ECG
Song et al.,	2011	24	14	North Korean Defectors	NR	NR	SR	RMSSD (ms), HF (ms^2)	Ln	Five-Minute ECG
Speer et al.,	2020	8	4	Veterans	Mixed	NR	CI	RMSSD (ms), HF (ms^2)	Ln	Five-Minute PPG
Spiller et al.,	2019	81	23	Refugees	Multiple	IV	CI	RMSSD (ms)	Ln	Five-Minute ECG
Wahbeh & Oken	2013	86	52	Clinical and Community	Combat	IV	CI	HF (ms^2)	Log	Five-Minute ECG
Weggen et al.,	2021	68	13	Student and Community	NR	V	CI	HF (ms^2)	None	Five-Minute ECG

Table 2
Characteristics of Studies Included in The Meta-Analyses Using Effect Sizes Derived From 24-Hour Recordings of vmHRV.

Study Name	Publication Year	Total Sample	Sample Size PTSD	Sample Type	Trauma type	DSM Criteria	PTSD Measure	HRV indices	Transformation	HRV Acquisition Method
Agotastos et al.,	2013	15	7	Military	NR	V	CI	RMSSD (ms)	None	Twenty-Four Hour ECG
Bertram et al.,	2014	46	24	Clinical and Community	Multiple	IV	CI	RSA (ms)	None	Twenty-Four Hour ECG
Dennis et al.,	2014	227	107	Clinical and Community	Multiple	NR	CI	HF (ms^2)	Ln	Twenty-Four Hour ECG
Dennis et al.,	2016	219	99	Clinical and Community	NR	NR	CI	HF (ms^2)	None	Twenty-Four Hour ECG
Lakusic et al.,	2007	68	34	Clinical	Combat	NR	NR	RMSSD (ms), HF (ms^2)	None	Twenty-Four Hour ECG
Lee et al.,	2013	99	11	Veterans	Military Sexual Assault	IV	SR	RMSSD (ms)	Ln	Twenty-Four Hour ECG
Lee & Ttheus.,	2012	125	37	Clinical	Combat	IV	SR	RMSSD (ms)	None	Twenty-Four Hour ECG
Rissling et al.,	2016	209	95	Community	NR	IV	SR	HF (ms^2)	None	Twenty-Four Hour ECG
Shah et al.,	2013	416	31	Community	Combat	IV	CI	HF (ms^2)	Ln	Twenty-Four Hour ECG
Shaikh al Arab et al.,	2012	21	11	Clinical	Road Traffic Accident	IV	CI	RMSSD (ms)	None	Twenty-Four Hour ECG

3.6. Between study variance (Level Three) of 5-minute vmHRV effect sizes

The LRT revealed significant between-study variance ($\chi^2(1) = 5.62$, $p = .02$). Further, the full multilevel model ($AICc = 91.46$) demonstrated a better fit than that of the reduced model without the between-study random effect ($AICc = 94.37$). Therefore, it can be concluded that there is significant variability between effect sizes across studies, thus supporting the inclusion of a between-study variance component in the meta-analytic model.

3.7. Distribution of variance of 5-minute vmHRV effect sizes

The typical within-study sampling variance estimate was calculated, from which the distribution of total variance across the three levels of the meta-analytic model was estimated. This estimation determined the total variance attributed to differences between effect sizes at each level of the model, including sampling variance (level 1) within studies (level 2) and between studies (level 3) (Assink and Wibbelink, 2016; Cheung, 2014; Cheung, 2019). The results revealed that 3.88 % of total variance was attributable to sampling variance, whilst 29.55 % resulted from

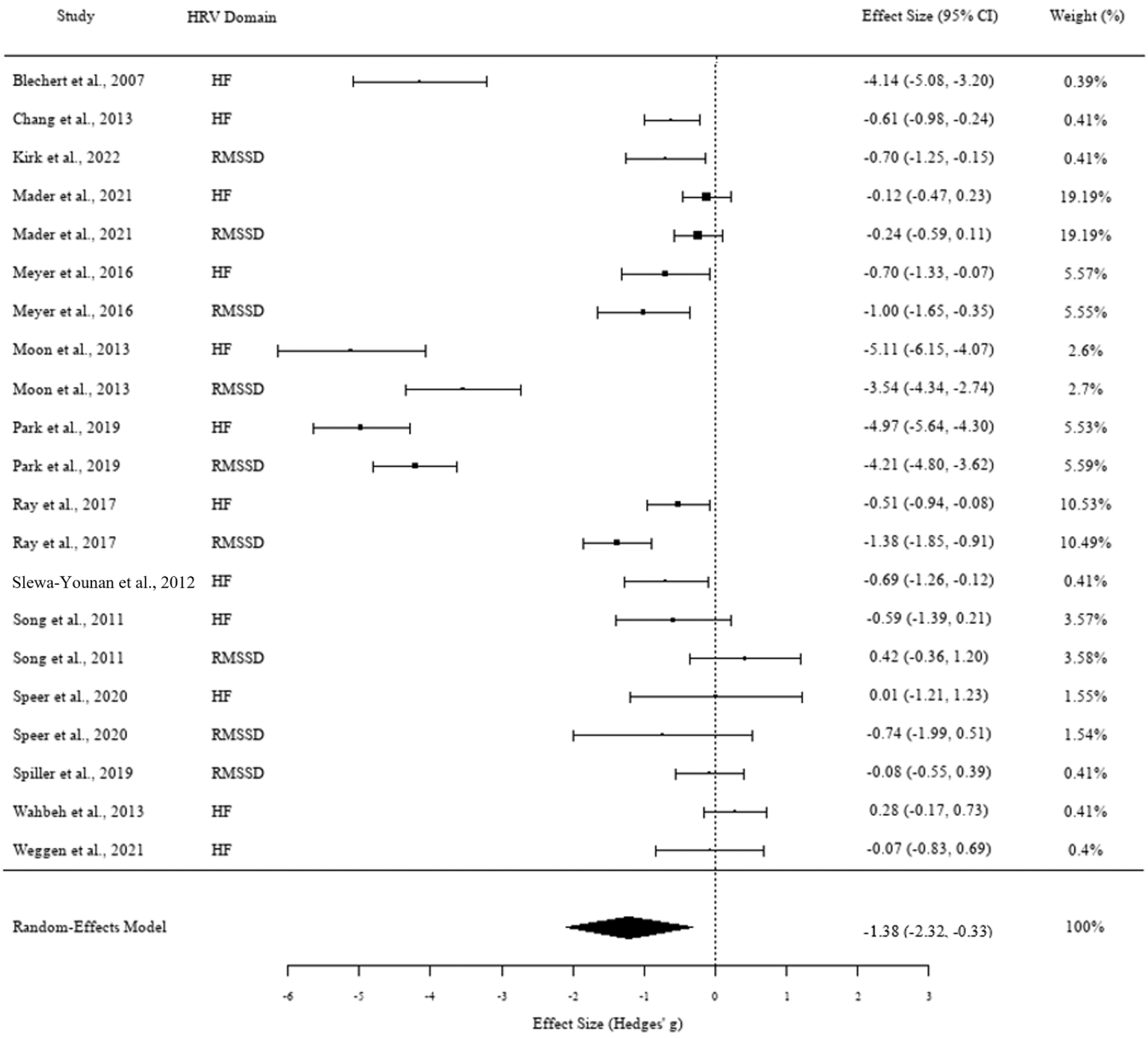


Fig. 7. Forest Plot of Effect Sizes from PTSD Articles Using 5-Minute vmHRV Recordings (Application Method One).

within-study variance and the remainder, 66.57 %, to between-study variance.

Tests of residual heterogeneity did not reveal significant unexplained variance ($QM(22) = 22.72$, $p = 0.418$), suggesting that the multilevel model adequately captured the variability in the data. Therefore, the variability in effect sizes is sufficiently accounted for by the study- and effect-size-level random effects, and additional moderator analyses (e.g., age, gender, medication use) are unlikely to provide meaningful further explanation of the remaining variability between studies. Nonetheless, vmHRV index (HF and RMSSD) was specified as a moderator to examine differences in effect size magnitude between these indices, thereby addressing the study aim of determining which vmHRV measure exhibits the strongest association with PTSD in the context of 5-minute recordings.

3.8. Meta regression of 5-minute vmHRV effect sizes

A meta-regression examined vmHRV index (HF and RMSSD) as a moderator of 5-minute vmHRV effect sizes (k = 23). The moderating effect was significant, $F(1, 21) = 15.41$, $p = .001$. The estimated effect sizes indicated that effect sizes were greater for RMSSD ($g = -1.61$, $SE = 0.14$, CI [−1.93, −0.26]) compared to HF-HRV ($g = -1.05$, $SE = 0.43$, CI [−1.93, −0.16]). Therefore, the results suggest that RMSSD may provide a more sensitive measure of the association between 5-minute vmHRV and PTSD compared to HF-HRV.

3.9. Overall effect (Level One) of 24-hour vmHRV effect sizes

In the meta-analysis of effect sizes derived from studies using 24-hour recordings of vmHRV ($N = 10$, $k = 13$), a significant association was revealed between vmHRV and PTSD yet yielded only a small to moderate overall effect size ($g = -0.46$, $SE = 0.13$, $t(12) = -3.63$, $p = .003$, CI [-0.74, −0.18]). See Fig. 8 for forest plots of effect sizes.

Significant heterogeneity was not observed across the vmHRV effect sizes derived from 24-hour recording durations ($Q(12) = 15.34$, $p = .22$), suggesting that the variability in the observed effect sizes does not extend beyond what is expected from sampling variance.

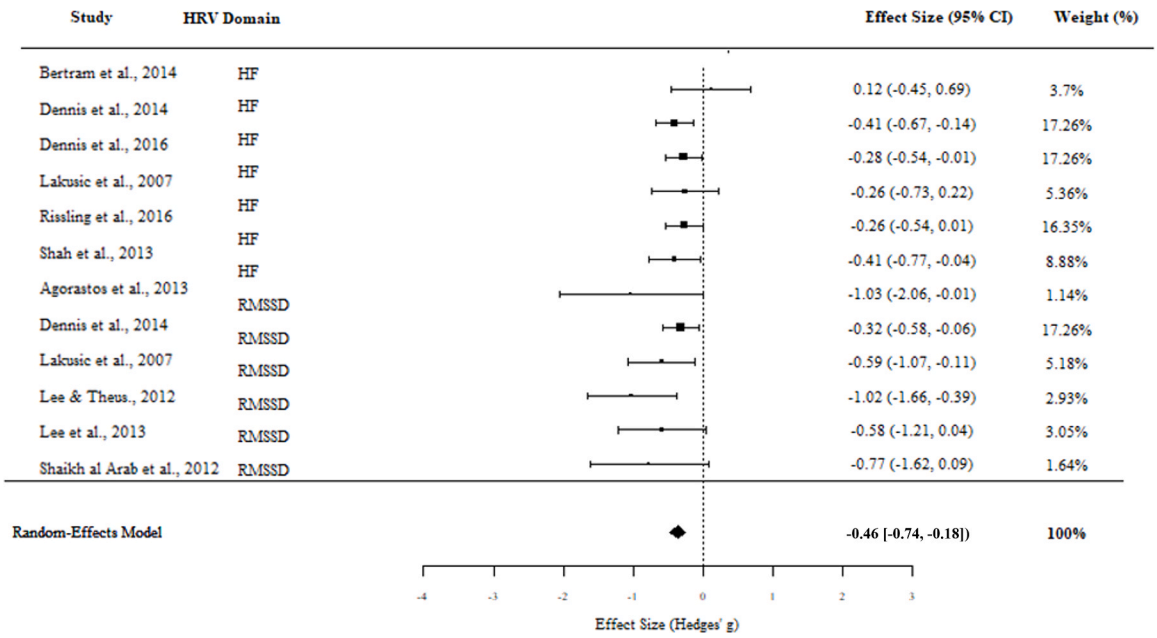


Fig. 8. Forest Plot of Effect Sizes from PTSD Articles Using 24-hour vmHRV Recordings (Application Method One).

3.10. Within study variance (Level Two) of 24-hour vmHRV effect sizes

The LRT did not reveal significant within-study variance ($\chi^2(1) = 1.49$, $p = .22$). Although the reduced model including within-study random effects yielded a lower AICc (AICc = 8.81) than the full model without within-study random effects (AICc = 11.00), the marginal difference in AICc values (ΔAICc = 2.19) was not substantiated by the LRT. Therefore, it can be concluded that there is no significant variability between effect sizes within studies, suggesting that the meta-analytic model adequately accounts for within-study variance.

3.11. Between study variance (Level Three) of 24-hour vmHRV effect sizes

The LRT did not reveal significant between-study variance ($\chi^2(1) = 0.00$, $p = 1.00$). Moreover, the comparison of AICc values indicated that the full model including between-study random effects (AICc = 11.00) did not improve model fit compared to the reduced model without between-study random effects (AICc = 7.33; ΔAICc = 3.67). Despite this marginal difference, there is no evidence of meaningful variability in effect sizes across studies. As such, the observed differences are consistent with expected sampling variance and that including a between-study variance component is unnecessary.

The results suggest that the observed variability in effect sizes is adequately accounted for by sampling variance alone, with no meaningful residual heterogeneity remaining. Accordingly, the distribution of variance across levels was not calculated, nor were moderator analyses (e.g., age, gender, medication use) undertaken, as there was no residual variance for moderators to explain. However, vmHRV index (HF and RMSSD) was included as a moderator to compare the relative magnitude of effect sizes across these indices, thus addressing the study aim of identifying which HRV index demonstrates the strongest association with PTSD when 24-hour HRV recordings are used.

3.12. Meta-regression of 24-hour vmHRV effect sizes

A meta-regression examined vmHRV index (HF and RMSSD) as a potential moderator of 24-hour effect sizes ($k = 13$). The moderating effect did not reach statistical significance ($F(1, 10) = 2.89$, $p = .12$). Therefore, the results indicate that where 24-hour recordings are used, the strength of the association between vmHRV and PTSD does not meaningfully differ according to HRV index.

3.12.1. Application method two – method for applying the multi-level meta-analytic model whilst accounting for interdependent effect sizes

Application Method Two provided an extension to the first application method. As such the level two (within study variance), level three (between study variance) and moderator results are identical to those presented in 2.4 so will not be reported again here. However, Application Method Two extended the traditional application method by incorporating a RVE to account for interdependent effect sizes. As such, a RVE was applied to the multilevel meta-analysis results to account for dependency between effect sizes within studies.

The meta-analysis of effect sizes derived from studies using 5-minute vmHRV recordings revealed a significant overall effect ($b = -1.26$, $SE = 0.42$, $t(13.99) = -3.00$, $p = .01$, $CI[-2.17, -0.36]$), suggesting that there a strong, negative relationship between the PTSD and vmHRV. The overall distribution of effect sizes remained consistent across both Application Method One and two, suggesting that RVE does not substantially alter the primary meta-analytic findings. However, minor variations in the positioning of effect sizes indicate that the RVE accounts for within-study dependence, thus reducing the potential influence of studies contributing multiple effect sizes. This adjustment enhances the robustness of the meta-analytic estimates while preserving the observed heterogeneity across studies. Fig. 9 presents a bubble plot[4] comparing results from the traditional random-effects meta-analysis and those obtained using RVE.

The RVE of effect sizes derived from studies using 24-hour vmHRV recordings, which accounts for within-study dependence, revealed a significant overall effect ($b = -0.36$, SE = 0.04, $t(4.20) = -9.36$, $p < .001$, CI [-0.47, −0.26]), indicating a small to moderate negative relationship between PTSD and vmHRV. The distribution of effect sizes remained consistent across both Application Method One and Two, suggesting that RVE does not substantially alter the primary meta-

[4] The x-axis represents effect sizes, while the y-axis lists the individual studies. Each bubble corresponds to an effect size estimate, with colours distinguishing between HRV domains (HF in red and RMSSD in blue). Bubble size is inversely proportional to the standard error, with larger bubbles indicating greater precision in effect size estimates.

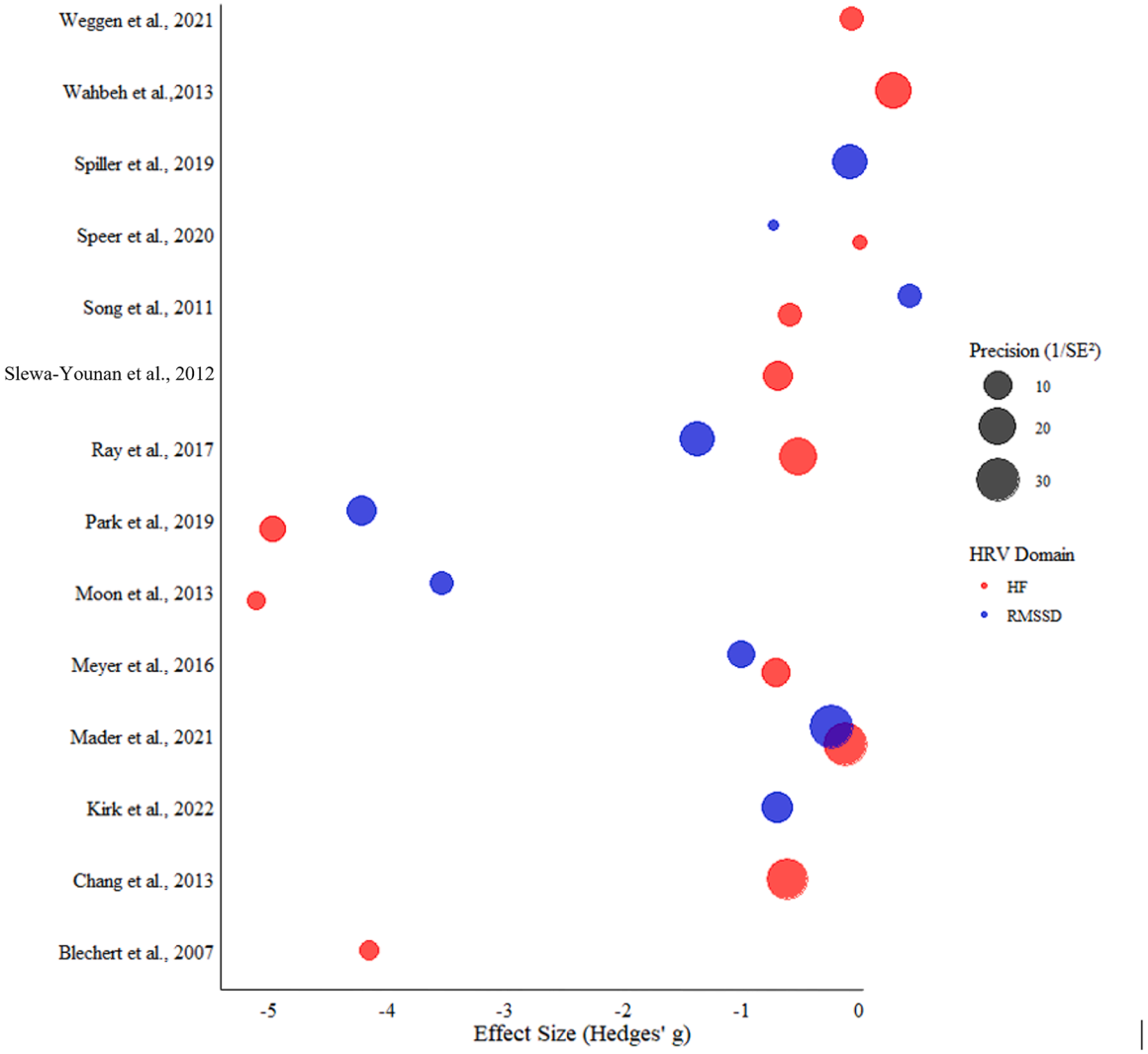


Fig. 9. Bubble Plots Comparing Traditional and RVE-Adjusted Meta-Analytic Estimates of Effect Sizes Derived from Studies Using 5-Minute vmHRV Recording Durations.

analytic findings. Minor variations in effect size positioning indicate that RVE successfully adjusts for the potential influence of studies contributing multiple effect sizes. Fig. 10 presents a bubble plot comparing results from the traditional random-effects meta-analysis and those obtained using RVE.

3.12.2. Meta-analysis of effect sizes derived from studies using 5-minute recordings of vmHRV

3.12.2.1. Overall effect (Level One). The meta-analysis of effect sizes derived from studies using 5-minute recordings of vmHRV ($N = 9$, $k = 9$) demonstrated a large overall association between RMSSD and PTSD ($g = -1.63$, $SE = 0.59$, $t(9) = 2.77$, $p = .02$, CI [-2.97, −0.30]. See Fig. 11 for forest plots of effect sizes.

The meta-analysis of effect sizes derived from studies using 5-minute recordings of HF-HRV ($N = 12$, $k = 12$) demonstrated a large overall association between HF-HRV and PTSD ($g = -1.41$, $SE = 0.53$, $t(112) = -2.65$, $p = .02$, CI [-2.56, −0.25]. See Fig. 12 for forest plots of effect sizes.

Significant heterogeneity was revealed between effect sizes derived from studies using 5-minute recordings of RMSSD ($Q(9) = 322.47$, $p < .001$) and HF-HRV ($Q(12) = 313.23$, $p < .001$). To investigate the sources of heterogeneity two one-sided LRT's were computed independently for each 5-minute vmHRV measure.

3.12.2.2. Within study variance (Level Two). The first LRT did not reveal significant within-study variance in the meta-analysis of effect sizes derived from studies using 5-minute recordings of RMSSD ($\chi^2(1) = 0$, $p = 1$). The AICc values for 5-minute RMSSD recordings indicated that the fit of the reduced model ($AICc = 40.73$) was better than that of the full model ($AICc = 42.73$). The second LRT did not reveal significant within-study variance in the meta-analysis of effect sizes derived from studies using 5-minute recordings of HF-HRV ($\chi^2(1) = 0$, $p = 1$). Further, the AICc values for HF-HRV indicated that the reduced model ($AICc = 53.83$) was better than that of the fit of the full model ($AICc = 55.83$). Therefore, it can be concluded that there is no significant variability between effect sizes within studies using 5-minute RMSSD of HF-HRV recording durations.

3.12.2.3. Between study variance (Level Three). The first LRT did not reveal significant between-study variance in the meta-analysis of effect sizes derived from studies using 5-minute recordings of RMSSD ($\chi^2(1) = 0$, $p = 1$). However, the AICc values for effect sizes drawn from 5-minute RMSSD recordings indicated that the fit of the reduced model ($AICc = 40.73$) was better than that of the full model ($AICc = 42.73$). The second LRT did not reveal significant between -study variance in the

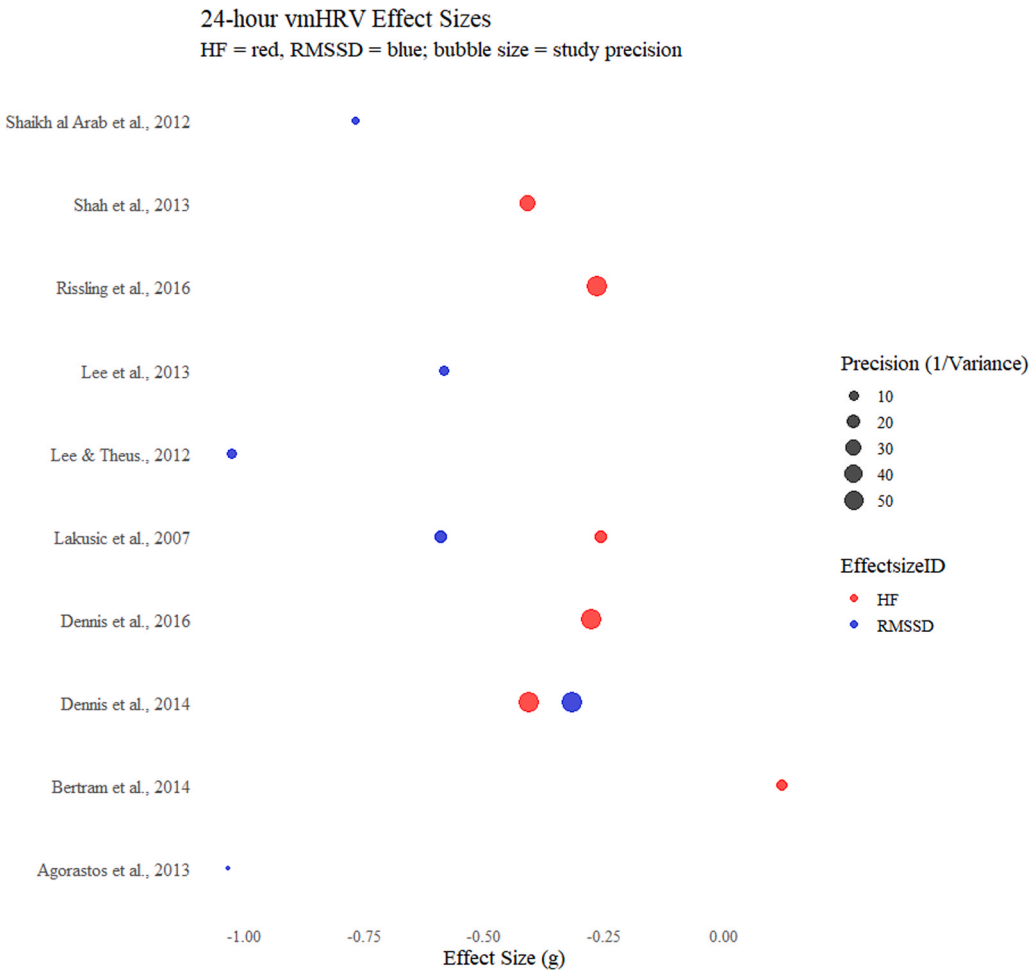


Fig. 10. Bubble Plots Comparing Traditional and RVE-Adjusted Meta-Analytic Estimates of Effect Sizes Derived from Studies Using 24-Hour vmHRV Recording Durations.

meta-analysis of effect sizes derived from studies using 5-minute recordings of HF-HRV ($\chi^2(1) = 0$, $p = 1$). Further, the AICc values for HF-HRV indicated that the fit of the reduced model ($AICc = 53.83$) was better than that of the full model ($AICc = 55.83$). Therefore, it can be concluded that there is no significant variability among effect sizes between studies using 5-minute RMSSD of HF-HRV recording durations. Therefore, it can be assumed that variance does not extend beyond that of sampling variance (Assink and Wibbelink, 2016; Cheung, 2014; Cheung, 2019). As such, variance distribution across the model was not calculated, nor were moderator analyses.

3.12.3. The meta-analysis of effect sizes derived from studies using 24-hour recordings of vmHRV results

3.12.3.1. Overall effect (Level One). The first meta-analysis of effect sizes derived from studies using 24-hour recordings of vmHRV ($N = 6$, $k = 6$) demonstrated a moderate to large overall association between RMSSD and PTSD ($g = -0.59$, $SE = 0.14$, $t(5) = -4.28$, $p = .008$, CI [-0.95, −0.24]. See Fig. 13 for forest plots of effect sizes.

The meta-analysis of effect sizes derived from studies using 24-hour recordings of HF-HRV ($N = 5$, $k = 5$) demonstrated a small to moderate overall association between HF-HRV and PTSD ($g = -0.31$, $SE = 0.07$, $t(5) = -4.48$, $p = .007$, CI [-0.47, −0.13]. See Fig. 14 for forest plots of effect sizes.

Significant heterogeneity was not observed between effect sizes derived from studies using 24-hour recordings of RMSSD ($Q(5) = 6.06$, $p = 0.30$) or HF-HRV ($Q(5) = 3.18$, $p = .67$). As a result, neither within-study nor between-study variance components were modelled, because each study contributed only a single effect size and formal tests of heterogeneity indicated no significant variability across studies. Consequently, moderator analyses were also deemed unnecessary, as there was no residual variance to explain.

4. Discussion

The present study examined differences in cardiac vagal activity between individuals with PTSD and healthy controls by synthesising findings from studies using either 5-minute or long-term 24-hour vmHRV recording durations. Previous meta-analyse concerning vmHRV in PTSD routinely combine recording durations in univariate models, which may have obscured the influence of recording duration on observed effect sizes (Campbell et al., 2019; Ge et al., 2020; Nagpal et al., 2013; Schneider and Schwerdtfeger, 2020). Therefore, the current study applied a novel multi-level meta-analytic method to vmHRV data in PTSD populations. Overall, the meta-analytic findings indicated a large negative effect of PTSD on cardiac vagal activity in studies using 5-minute recordings, whereas the effect was small to moderate, though still significant, in studies using 24-hour recordings. This distinction highlights the influence of recording duration in interpreting PTSD-related cardiac vagal alterations which has significant implications for future research and clinical practice.

Across all three methods, the results were consistent, indicating that neither within- or between-study variance influenced the findings. That said, small differences in effect estimates across models reflect the

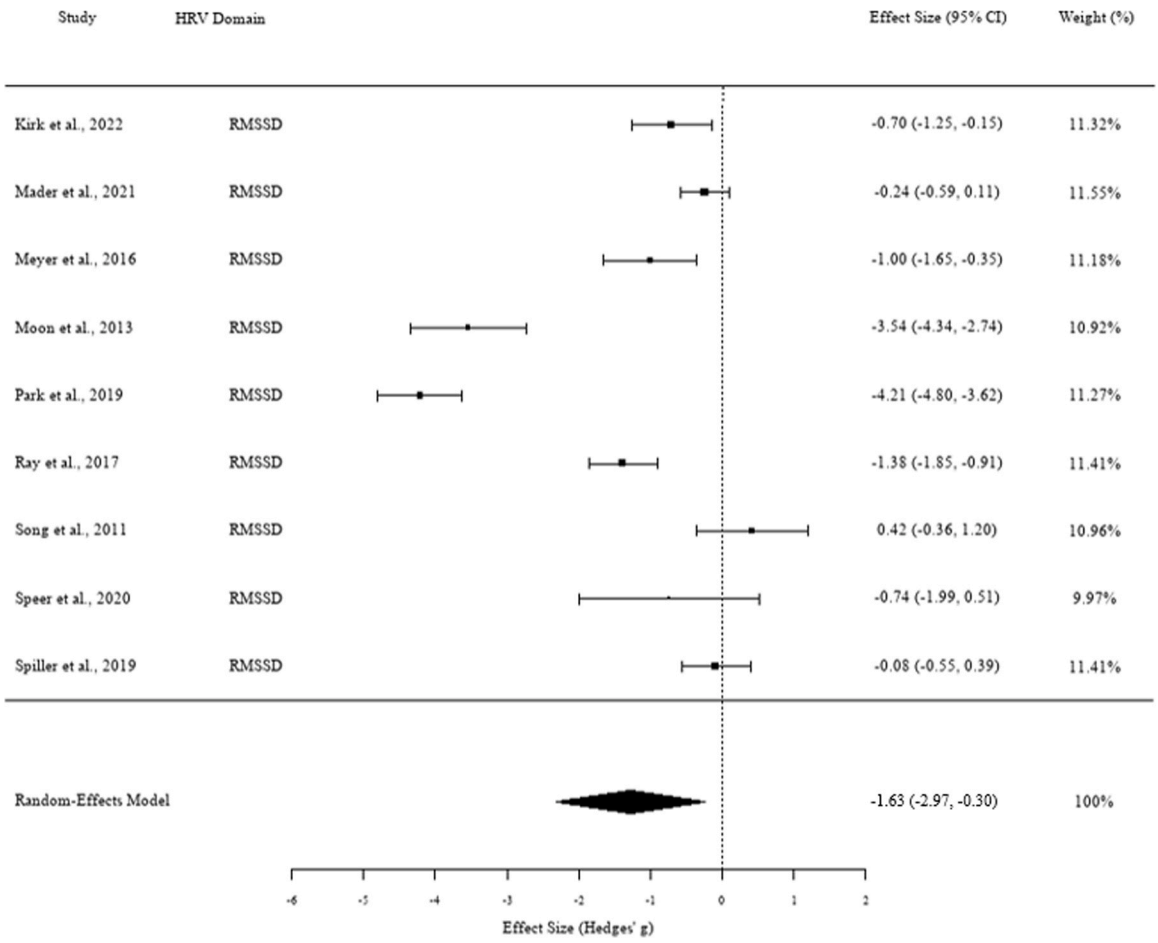


Fig. 11. Forest Plot of Effect Sizes from PTSD Articles Using 5-Minute RMSSD Recordings (Application Method Three).

adjustment for within-study non-independence implemented by RVE, without altering the substantive interpretation of the findings. As such, the consistency in the observed effect sizes across the three meta-analytic methods supports the reliability and validity of the conclusion that cardiac vagal activity is significantly reduced in those with PTSD. However, the difference in effect magnitude observed across studies using 5-minute versus 24-hour vmHRV recordings indicates that recording duration is an important methodological consideration when interpreting the association between cardiac vagal activity and PTSD.

The Neurovisceral Integration Model (Thayer and Lane, 2000, 2009) posits that vmHRV reflects the functional integrity of a distributed cortico–subcortical network which regulates vagal output to the heart. Therefore, reduced vmHRV is believed to index diminished inhibitory control over subcortical threat and arousal systems which are a core feature of PTSD (Gillie and Thayer, 2014; Jeon et al., 2024; Petersdotter et al., 2025; Rabellino et al., 2017). However, the present findings indicate that the magnitude of PTSD-related reductions in cardiac vagal activity differs according to recording duration.

The larger effect observed in studies using 5-minute vmHRV recordings likely reflects the fact that brief recording periods primarily capture moment-to-moment fluctuations in CAN regulation and by proxy, vmHRV (Camm et al., 1996; Ewing et al., 1991; Jensen et al., 2016; Liu et al., 2022). In contrast, 24-hour recordings integrate cardiac vagal activity across the full circadian cycle, including periods of reduced behavioural and cognitive demand such as sleep (Li et al., 2019; Min et al., 2008; Zhu et al., 2018). The smaller but still significant effect observed in 24-hour recordings therefore suggests a persistent reduction in cardiac vagal activity in PTSD.

The current findings support the consensus that vmHRV during short-term recordings strongly influenced by transient prefrontal inhibitory control over subcortical threat and arousal systems (Cattaneo et al., 2021; Jeon et al., 2024; Lane et al., 2009; Petersdotter et al., 2025; Thome et al., 2017). At the same time, 24-hour vmHRV recordings primarily reflect longer-term autonomic functioning rather than momentary fluctuations in autonomic state (Amekran et al., 2025; Dennis et al., 2017; Gitler et al., 2025). As such, from a Neurovisceral Integration perspective (Thayer and Lane, 2000, 2009), the larger effects observed in studies using 5-minute vmHRV recordings likely reflect greater reductions in cardiac vagal activity during contexts that place acute cognitive, emotional, or stress-related demands on those with PTSD (Kotov et al., 2024; Souza et al., 2013; Wittbrodt et al., 2020).

On the other hand, the smaller effects observed in studies using 24-hour vmHRV recordings likely reflect a sustained attenuation of cardiac vagal activity across varying physiological states, including rest, activity, and sleep, thereby indexing more consistent alterations in autonomic regulation rather than acute, contextual demands (Li et al., 2019; Min et al., 2008; Shaffer and Ginsberg, 2017; Zhu et al., 2018). Therefore, the differences in effect size magnitude captured in 5-minute compared to 24-hour vmHRV recording durations may be more pronounced during 5-minute vmHRV assessments due to acute reductions in cardiac vagal activity resulting from episodes of heightened arousal, hypervigilance, and exaggerated emotional responses (Kotov et al., 2024; Souza et al., 2013; Wittbrodt et al., 2020). Therefore, the present findings suggest that PTSD is characterised by chronic dysregulation of cardiac vagal control, manifesting as exaggerated reductions in vagal cardiac activity during periods of heightened environmental or cognitive demand and a persistent attenuation of vagal withdrawal across rest, activity, and sleep (Dennis et al., 2017).

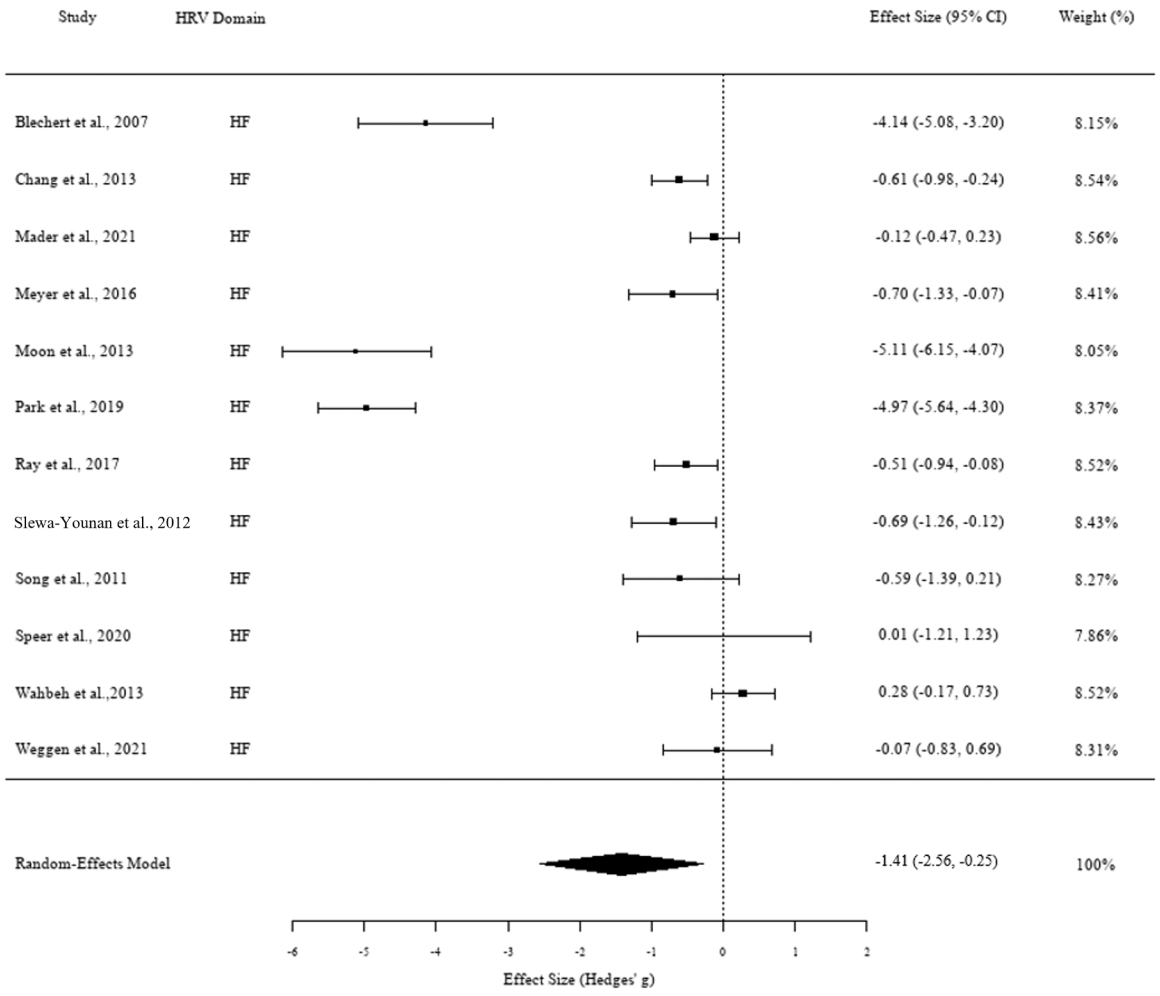


Fig. 12. Forest Plot of Effect Sizes from PTSD Articles Using 5-Minute HF-HRV Recordings (Application Method Three).

Although the nature of cardiac vagal activity in PTSD has been established by the primary meta-analytic techniques, it is also important to consider whether this pattern differs depending on the specific vmHRV index used. Whilst the present study examined differences in 5-minute and 24-hour cardiac vagal activity between individuals with PTSD and healthy controls, it also accounted for the influence of the different vmHRV indices sued in primary studies. The meta-regressions conducted across both 5-minute and 24-hour recordings found no significant moderating effect of vmHRV index, indicating that RMSSD and HF-HRV show comparable reductions in PTSD. This is notable given that HF-HRV is more sensitive to respiratory rate than RMSSD (Hill et al., 2009; Quintana et al., 2016a; Shaffer and Ginsberg, 2017).

The current study examined sources of heterogeneity across three levels including sampling variance (level one), within-study variance (level two) and between-study variance (level three). Short-term, 5-minute studies often fail to control or adjust for respiration, which could theoretically introduce heterogeneity, whereas 24-hour recordings naturally capture slower, more regular breathing during sleep and the full circadian cycle. Despite these physiological differences, the absence of significant heterogeneity in the present analyses suggests that both HF-HRV and RMSSD provide robust estimates of reduced cardiac vagal activity in PTSD, and that respiration-related variance does not meaningfully alter the overall conclusions. Consequently, the observed differences in effect magnitude between 5-minute and 24-hour vmHRV recordings are more likely attributable to the temporal scope of measurement rather than to differences in vmHRV index or respiratory confounds. Whilst the current findings support the utility of either RMSSD or HF-HRV in studies of PTSD, careful control or reporting of respiration remains important, particularly in short-term recordings where transient fluctuations may have a larger impact.

4.1. *Limitations*

The findings of this meta-analysis should be interpreted with caution due to variations in the quality of the primary studies included. First, more studies could have been included if the recording duration of the study had been reported or authors had adhered to established guidelines (see Camm et al., 1996). Second, primary studies fail to accurately report sufficient information for moderation analyses to be conducted and a lack of standardised experimental and reporting methods. This issue has been highlighted in several previous meta-analyses regarding HRV in PTSD (Schneider and Schwerdtfeger, 2020; Ge et al., 2020). However, these findings enhance the existing understanding by demonstrating that the observed association between vmHRV and PTSD is greater during 5-minute recordings compared to 24-hour-recordings. Given that recording duration is often unreported, previous meta-analyses may have inadvertently overestimated the true effect of vmHRV in those with PTSD. Therefore, these findings extend prior concerns by providing empirical evidence that methodological variability in recording durations, may bias effect size estimates. Therefore, standardised reporting practices are essential for developing a more accurate understanding of autonomic dysregulation in PTSD.

Each of the application methods applied in this paper are also not without limitations. Application Method One is limited by its failure to

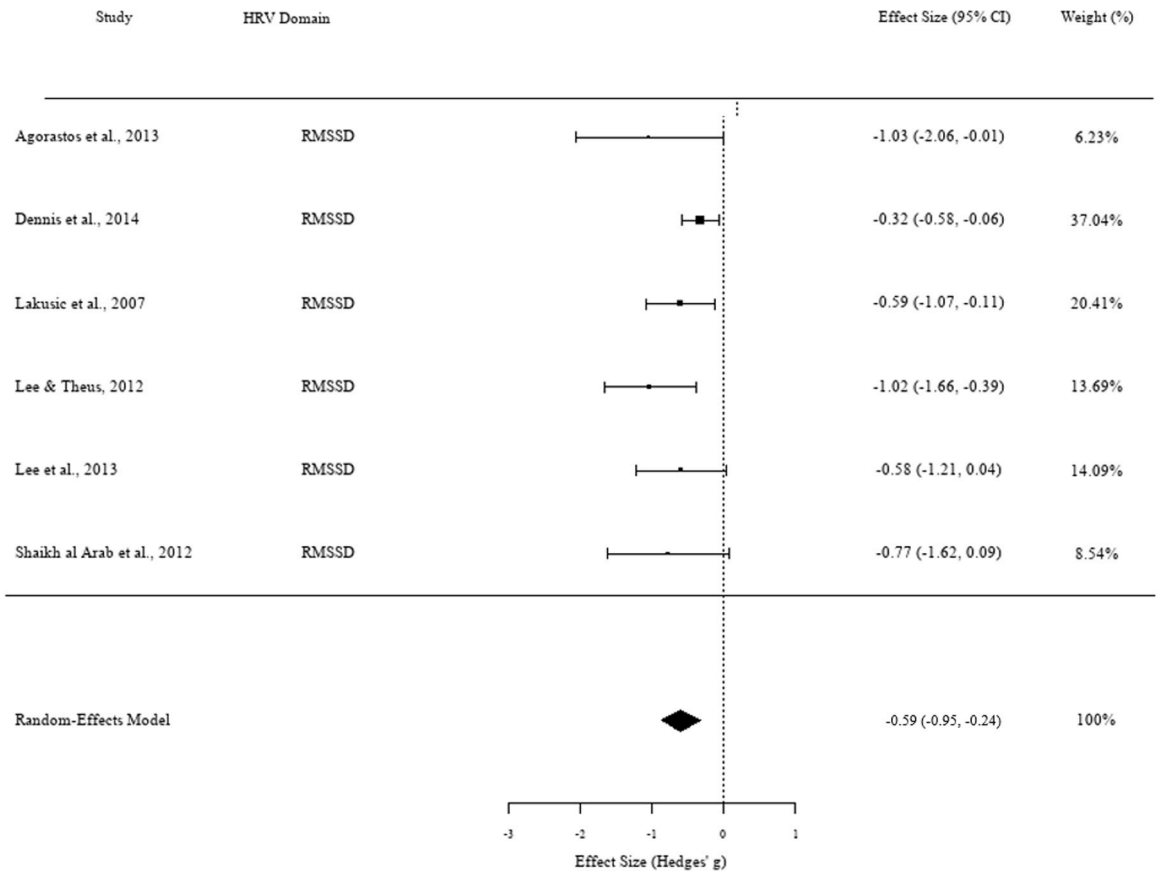


Fig. 13. Forest Plot of Effect Sizes from PTSD Articles Using 24-Hour RMSSD Recordings (Application Method Three).

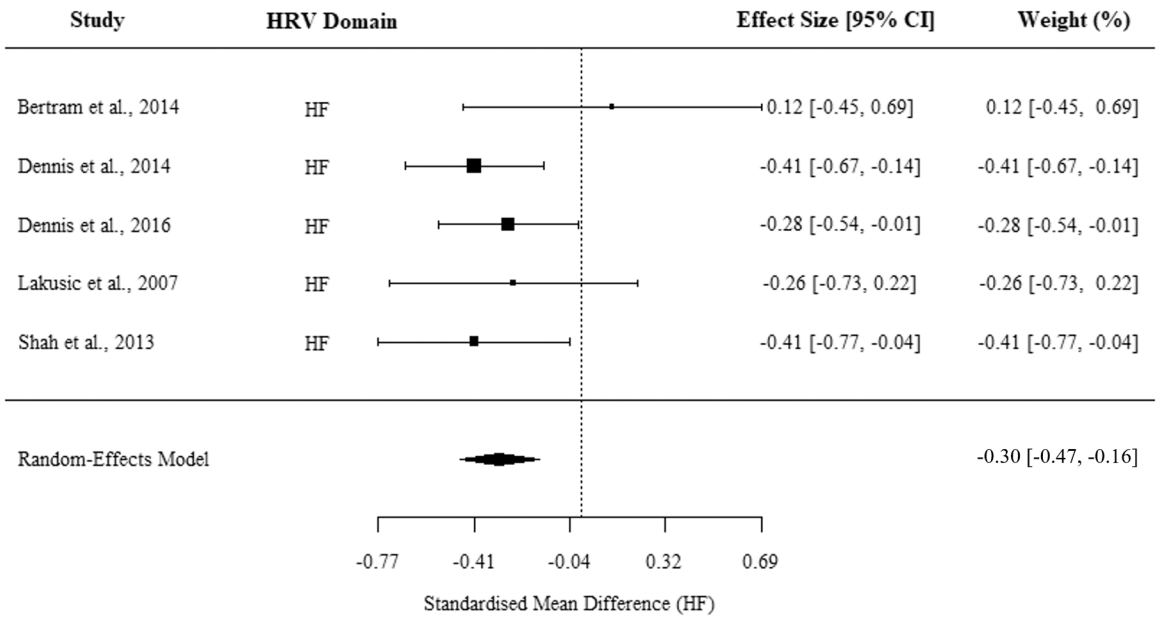


Fig. 14. Forest Plot of Effect Sizes from PTSD Articles Using 24-Hour HF-HRV Recordings (Application Method Three).

account for interdependent effect sizes derived from the same study. That said, Application Method Two provides an extension to Application Method One and therefore accounts for interdependency between effect sizes even where the details of how they are related are undetermined or cannot be explicitly described (Pustejovsky and Tipton, 2022). Application Method Three works in a similar way to a univariate meta-analysis and thus reduces heterogeneity between-effect sizes. However, this approach may not provide a true estimation of the observed effect as it reduces the sample size of the analysis. Furthermore, subdividing the data poses a risk of overfitting the multi-level model, particularly where sample sizes are limited. Therefore, Application Model Three may increase the risk of type I and type II errors. In

turn, this application method may result in non-replicable significant effects or overly complex models which are difficult to reliably interpret.

All things considered, Application Model Two balances statistical rigor whilst retaining sufficient power, making it the most appropriate and reliable approach for investigating the association between vmHRV and PTSD. Furthermore, the low degree of variation in findings between each application method demonstrates a consistent underlying effect. In turn, the present meta-analysis provides robust evidence supporting the association between PTSD and vmHRV. Moreover, despite the limitations of primary studies, the overall conclusions remain valid. Whilst there are variations in study quality, the fundamental relationship between PTSD and diminished vmHRV supports existing meta-analytic findings (Campbell et al., 2019; Ge et al., 2020; Nagpal et al., 2013; Schneider and Schwerdtfeger, 2020).

4.2. Future research directions

The present findings highlight several priorities for future research in the measurement and interpretation of vmHRV in PTSD populations. First, future research would benefit from greater standardisation of vmHRV study methods, particularly in short-term recordings. Studies vary widely in recording duration, participant posture, task instructions, breathing procedures, time of day and analytical decisions (i.e., data transformation), yet these factors are often inconsistently reported or uncontrolled. Such methodological variation limits comparability across studies and complicates interpretation of PTSD-related differences in cardiac vagal activity.

At the same time, existing studies using 24-hour vmHRV recording durations in PTSD population typically report only aggregated mean values, without time-resolved or circadian metrics such as MESOR, amplitude, or acrophase. As such, averaging 24-hour vmHRV recordings may obscure context-specific fluctuations in cardiac vagal activity, such as differences that are more pronounced during wakeful or stress-exposed periods compared to sleep or rest. In turn, this may reduce the sensitivity of 24-hour recordings to detect differences in cardiac vagal activity between PTSD and control groups. Future research should therefore consider time-of-day and circadian influences, for example by reporting MESOR, amplitude, or other rhythm-based metrics through repeated or continuous measurements, to more precisely capture both transient and persistent patterns of autonomic dysregulation in PTSD populations.

In addition, the lack of consistency in vmHRV methods and reporting practices also constrains future meta-analyses, as heterogeneous study methods reduce the ability to test methodological moderators. Therefore, improving transparency and consistency in vmHRV methods and reporting practices between-studies would ultimately reduce both within- and between-study variance. In turn, standardised methodologies will enhance comparability across investigations into the relationships between cardiac vagal activity and PTSD.

Second, current meta-analyses on vmHRV and PTSD largely rely on univariate effect sizes, which may fail to capture the nested and interdependent nature of physiological data. Continued use of multi-level and robust variance estimation methods are essential to appropriately model the complexities of psychophysiological data in those with PTSD, to ensure that conclusions about cardiac vagal activity reflect true physiological patterns underlying the observed effects. Therefore, future studies should consider employing multi-level meta-analytic models to account for nested data structures and interdependency between effect sizes to improve the accuracy and validity of the inferences drawn about cardiac vagal activity in PTSD.

Finally, future studies should consider combining both short-term and long-term vmHRV recordings within-subjects to distinguish context-sensitive reductions in cardiac vagal activity from more persistent dysregulation in those with PTSD. In turn, combining these approaches may permit researchers to link transient dysregulation to persistent autonomic patterns. The resultant findings may assist in developing the understanding of how acute dysregulation in response to contextual-demands may be associated with chronic reductions in cardiac vagal activity. Such findings may provide valuable insights into the relationship between cardiac vagal activity and both immediate symptom expression and longer-term health consequences in PTSD.

Author contributors

RT and SR conceptualised the paper. RT conducted literature search and performed study selection, data extraction, and quality assessment. RT and PT designed and conducted data analysis. RT and SR informed the interpratation of the findings and their implications. RT, SR and PT prepared the manuscript. All authors checked the study results and revised the manuscript to the final version.

Funding

There re no funding sources to declare.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgements

The authors would like to thank Professor Charlie Frowd for his valuable assistance with the statistical analyses. His expertise and guidance contributed significantly to the interpretation and presentation of the results. I would also like to extend my deepest gratitude to Dr. Sarita Robinson for her guidance, mentorship, and invaluable support throughout this project. Her expertise, encouragement, and thoughtful insights have greatly shaped both the direction and quality of this work. I am deeply grateful for her generosity with her time and her knowledge, without which this project would not have come to fruition.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2026.106585.

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