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Review

Heart rate variability (HRV) as a way to understand associations between the autonomic nervous system (ANS) and affective states: A critical review of the literature

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ABSTRACT

Evidence suggests affective disorders such as depression and bipolar disorder are characterised by dysregulated autonomic nervous system (ANS) activity. These findings suggest ANS dysregulation may be involved in the pathogenesis of affective disorders. Different affective states are characterised by different ANS activity patterns (i.e., an increase or decrease in sympathetic or parasympathetic activity). To understand how ANS abnormalities are involved in the development of affective disorders, it is important to understand how affective states correlate with ANS activity before their onset. Using heart rate variability (HRV) as a tool to measure ANS activity, this review aimed to look at associations between affective states and HRV in non-clinical populations (i.e., in those without medical and psychiatric disorders). Searches on PubMed and Google Scholar were completed using the following search terms: heart rate variability, autonomic nervous system, sympathetic nervous system, parasympathetic nervous system, affective state, mood and emotion in all possible combinations. All but one of the studies examined (N = 13), demonstrated significant associations between affect and HRV. Findings suggest negative affect, encompassing both diffused longer-term experiences (i.e., mood) as well as more focused short-term experiences (i.e., emotions), may be associated with a reduction in parasympathetic activity as measured through HRV parameters known to quantify parasympathetic activity (e.g., high frequency (HF)-HRV). HRV measures typically linked to reduction in parasympathetic activity appear to be linked to negative affective states in non-clinical populations. However, given the complex and possibly non-linear relationship between HRV and parasympathetic activity, further studies need to clarify specificity of these findings. Future studies should investigate the potential utility of HRV measures as biomarkers for monitoring changes in affective states and for early detection of onset and relapse of depression in patients with affective disorders.

1. Introduction

A compelling body of evidence suggests that several affective disorders are characterised by alterations in autonomic nervous system (ANS) activity, which is part of the central autonomic network involved in stress response and implicated in the pathophysiology of affective disorders (Carney et al., 2005; Alvares et al., 2016; Bassett, 2016; Mulcahy et al., 2019; Lamotte et al., 2021). Heart rate variability (HRV), a measure of the variation in time intervals between adjacent heartbeats, reflects ANS control on the heart which is continuously influenced by respiration, blood pressure and the brain (through the central autonomic network). Measures of HRV therefore reflect activity in the two branches of the ANS, the sympathetic nervous system and parasympathetic nervous system (Shaffer and Ginsberg, 2017).

Altered ANS activity, reflected by changes in HRV, has previously been observed in individuals with affective disorders such as major depressive disorder and bipolar disorder. Several systematic reviews and meta-analyses have demonstrated that HRV is reduced in individuals with depression compared with healthy controls (Kemp et al., 2010; Koch et al., 2019) including within younger populations (Koenig et al.,

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2016) as well as within older populations (Brown et al., 2018). Furthermore, similar patterns have been demonstrated in individuals with bipolar disorder (Faurholt-Jepsen et al., 2017).

Despite strong evidence demonstrating that affective disorders are characterised by alterations in ANS activity, associations between ANS activity and specific affective states (i.e., positive versus negative affect states) in non-clinical populations (i.e., in those without medical and psychiatric disorders) remain unclear. A better understanding of this association is particularly relevant to improve our insight of the role of the ANS in the development of affective disorders and/or its relevance when considering these disorders as a continuum (e.g., at risk, sub-threshold, and reaching full diagnostic criteria).

Lower HRV has been associated with higher levels of affective instability (Koval et al., 2013), a trait known to be associated with poor psychological health (Jones, 2007), low self-esteem (Rhodewalt et al., 1998) and depression (Peeters et al., 2006). Furthermore, Perna et al. (2020) reported that higher HRV might be a predictor of greater mental health resilience as it is associated with appropriate emotional regulation during emotional tasks, and better regulation of cortisol, cardiovascular and inflammatory responses during psychosocial tasks.

The use of HRV as biomarker of ANS activity has attracted particular attention over the past few years in particular in relation to the opportunity to be passively measured with the use of wearable digital devices (Owens, 2020). With the increasing endorsement of remote measurement technologies for assessment, monitoring and treatment of mental and physical health, HRV has strong potential as digital biomarker of ANS activity for future clinical research and clinical practice. However, it is important to underline that the relationship between ANS and HRV can also be modulated by other physiological processes and may not always follow linear models (Saul and Valenza, 2021).

Chronically reduced HRV, as demonstrated in those with depression and bipolar disorder, suggests an underlying autonomic imbalance amongst these clinical populations. Specifically, overall reduced HRV is indicative of reduced parasympathetic vagal activity (Akselrod et al., 1981) suggesting parasympathetic withdrawal may be a potential pathophysiological mechanism underlying affective disorders such as major depressive disorder and bipolar disorder. However, given that previous work focuses on associations between HRV and affective disorders in clinical populations (i.e., those with a clinical diagnosis of depression or bipolar disorder), it is not possible to understand whether alterations in ANS, as measured by HRV, precede, or come after the development of an affective disorder. It is therefore unknown whether alterations in ANS activity, measured by HRV, contribute to the development of clinical symptoms in affective disorders. Looking at associations between different affect states and HRV in non-clinical populations will provide a deeper insight into how the ANS is associated with affect which in turn may help to understand how dysregulation of the ANS may contribute towards the development of affective disorders.

Affect, or affective states, refers to the underlying experience of emotion or mood. More specifically, negative affect refers to the experience of negative emotions or aversive mood states (e.g., feeling sad, anxious, scared or guilty), whilst positive affect refers to positive emotions or mood such as, feeling happy, contented or excited (Watson et al., 1988). Throughout the manuscript we will refer to emotions as subjective mental experience of physiological changes and to emotional regulation as the process by which an individual modifies their emotional response. Up until now, no review has specifically focused on the link between HRV, as an index of ANS activity, and affect. The aim of this review is to investigate whether HRV patterns differ depending on affective states encompassing both diffused longer-term experiences (i.e., mood) as well as more focused short-term experiences (i.e., emotions) amongst non-clinical populations, specifically, those without a diagnosis of an affective disorder. We will first provide an overview of the physiological interpretations of HRV and then move on to summarize current evidence on the association between different affective states and changes in HRV. Lastly, we will briefly discuss how the associations between affect and ANS activity may lead to development of affective disorders, primarily focusing on major depressive disorder.

1.1. Physiological interpretations of HRV

HRV can be calculated using time-domain, frequency-domain and non-linear domain measurements (Shaffer and Ginsberg, 2017). To begin with, we will provide a brief description of these HRV indexes and how they can be used to quantify ANS activity.

1.2. Time-domain HRV measures

Time-domain measures of HRV are the most straightforward to calculate and represent the temporal difference between successive heartbeats, also known as RR intervals, when analysing electrocardiogram (ECG) data (R-waves of the QRS signal on the electrocardiogram) (Shaffer and Ginsberg, 2017). Examples of time domain measures include the standard deviation of the inter-beat-intervals for all sinus beats (SDRR) which measures both parasympathetic and sympathetic activity however, in short-term recordings, primarily reflects parasympathetic activity (Shaffer and Ginsberg, 2017). The standard deviation of inter-beat-intervals of normal sinus beats (SDNN) where normal refers to when abnormal beats that have arisen from outside the right atrium's sinoatrial node have been removed (Shaffer and Ginsberg, 2017), is also a measure of both parasympathetic and sympathetic nervous system activity but primarily parasympathetic activity in short-term recordings. Another commonly used example of a time-domain measure of HRV is the root mean square of successive RR interval differences (RMSSD) (Shaffer and Ginsberg, 2017). RMSSD is the primary time-domain measure used to quantify vagal activity.

1.3. Frequency-domain HRV measures

Frequency-domain measures decompose the HRV signal into its component frequencies, analysing how much of the signal is represented within different frequency bands (Shaffer et al., 2014). The Task Force European Society of Cardiology and the North American Society of Pacing and Electrophysiology separated heart rate oscillations into ultra-low frequency (ULF), very-low frequency (VLF), low-frequency (LF) and high-frequency (HF) (Malik et al., 1996). HF-HRV is a measure of efferent vagal activity making it a reliable indicator of parasympathetic activity (Shaffer et al., 2014).

With regards to the ANS, the physiological interpretations of the LF band are not as clear. LF-HRV has previously been considered to reflect cardiac sympathetic neural activity (Montano et al., 1994; Rimoldi et al., 1990). However, strong evidence shows that the LF band is not a pure measure of sympathetic activity and that the variability in the frequency band is a result of both parasympathetic and sympathetic activity (Billman, 2013; Reyes del Paso et al., 2013; Valenza et al., 2018; Thomas et al., 2019; Hayano and Yuda, 2019). Despite this, several authors continue to rely on LF-HRV from short-term resting recordings to make inferences about sympathetic activity (Deo et al., 2018; Weinstein et al., 2007). Furthermore, the ratio of LF to HF power (LF/HF ratio) has been, and is continually used by some, to make inferences about the balance between the sympathetic and parasympathetic activity (i.e., sympatho-vagal balance). However, this is based on the assumption that LF-HRV is a pure measure of sympathetic activity, which has been proven not to be the case (Billman, 2013). As a result, the use of the LF/HF ratio as a measure of sympatho-vagal balance has been strongly discouraged (Billman, 2013).

1.4. Non-linear HRV measures

Non-linear measurements index the unpredictability of a HRV time series, which results from the complexity of the mechanisms that regulate HRV (Shaffer and Ginsberg, 2017). Commonly used non-linear HRV

indices include correlation dimension, sample and approximate entropy (SampEn and ApEn, respectively). SampEn and ApEn both measure the regularity and complexity of a time series. A recent study demonstrated that a parasympathetic activity blockage causes a significant reduction in non-linear HRV measures including correlation dimension, SampEn and ApEn (Bolea et al., 2014). As such, it is suggested that these non-linear HRV indices (correlation dimension, SampEn and ApEn), can be used as an indicator of parasympathetic activity. Furthermore, other non-linear HRV indices such as those measured from Poincare plots (a scatter plot derived by plotting every R–R interval against the prior interval), for example, SD1 (Poincaré plot standard deviation perpendicular the line of identity) and SD2 (Poincaré plot standard deviation along the line of identity), are also representative of parasympathetic activity (Rahman et al., 2018).

2. Methods

2.1. Study abstraction

Although our review was intended as a critical rather than systematic review, we will outline here the main steps for retrieving relevant literature for the manuscript to allow for replicability. A search on PubMed and Google Scholar was completed from inception until the 16th of December 2022 using the following search terms: heart rate variability, autonomic nervous system, sympathetic nervous system, parasympathetic nervous system, affect state, mood and emotion in all possible combinations.

2.2. Inclusion and exclusion criteria

Only research papers published in English and in peer-reviewed journals were eligible for inclusion. Articles were included if they: (1) included a measure of affect encompassing both diffused longer-term experiences (for example, negative mood state, depressive symptoms or trait negative affect) or more focused short-term experiences (for example, emotion states including, happiness, anger and sadness), (2) included a measure of HRV, and (3) included a statistical analysis which examined the relationship between a given affective state and HRV outcome amongst non-clinical populations were included in the review. Articles were excluded if they: (1) were not published in English, (2) included participants from clinical populations, (3) did not include a measure of affect, (4) did not include a measure of HRV, and (4) did not include a statistical analysis which examined the relationship between a given affective state and HRV. All included articles are outlined in Table 1.

3. Results

3.1. Search results and article screening

The Pubmed search originally identified 1909 papers. After title and abstract screening, and then subsequent full text screening, 1902 articles were excluded due to not meeting our inclusion criteria; 7 papers met eligibility criteria and were included in our critical review. In addition to the electronic search on Pubmed, we manually searched relevant systematic reviews and reference lists and ran Google searches for eligible studies that may have been missed. Articles for full screening were selected based on the relevance of titles. After full article screening, 6 further papers were included in our review.

3.2. Affect and HRV outcomes

Studies on affect and HRV outcomes broadly fell in to two main methodological categories, 1) those that monitor or measure the affective state of an individual within their natural environment, and 2) those that artificially induce affective state changes in laboratory settings

Table 1
Summary of the results of the included studies looking at associations between affect and HRV.

No.	Authors	N	Affect labels	HRV outcome measures	Major findings
1	Sin et al. (2016)	909	- Daily negative affect - Aggregated negative affect	SDRR, RMSSD, HF-HRV	- Negative affect reactivity associated with a reduction in SDRR, RMSSD AND HF-HRV. - Daily aggregated negative affect associated with reduced RMSSD and HF-HRV
2	Young et al. (2017)	266	- Depressed mood	HF-HRV SampEn	- Depressed mood associated with a reduction in HF-HRV
3	Bleil et al. (2008)	653	- Trait negative affect	HF-HRV	- Increased trait negative affect associated with decreased HF-HRV
4	Blood et al. (2015)	127	- Depressive symptoms	HF LF VLF	- Lower HF-HRV was associated with increased self-reported depressive symptoms - Lower VLF-HRV was associated with decreased depressive symptoms - LF-HRV was not significantly associated with depressive symptoms
5	Pichon et al. (2010)	30	- Depressed mood	VLF, LF, HF, LF/HF ratio	- Those who reported an increase in depressed mood from the beginning of the year and three weeks later showed significantly reduced HF and LF-HRV - No significant differences were found for the LF/HF ratio or the VLF-HRV measure
6	Vazquez et al. (2016)	73	- Depressive symptoms	VLF, LF, HF	- Reduced HF-HRV was associated with an increase in depressive symptoms one year later

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Table 1 (*continued*)

No.	Authors	N	Affect labels	HRV outcome measures	Major findings
7	Weinstein et al. (2007)	40	- Negative mood - Depressive symptoms	Lf, HF, LF/HF ratio	- Increased baseline LF/HF was associated with an increase in negative mood and depressive symptoms in response to systematic exercise withdrawal - No significant associations were reported for the LF or HF HRV measures
8	Wu et al. (2019)	50	- Amusement - Anger - Fear - Neutral	RMSSD	- In comparison to the positive affect condition (amusement) negative affect (fear and anger) was associated with reduced RMSSD - In comparison to anger, fear was associated with reduced RMSSD - No significant differences were found between the fearful and neutral, or angry and neutral conditions
9	Deo et al. (2018)	30	- Happy - Unhappy - Neutral	SDNN, RMSSD, LF, HF, LF/HF ratio	- In comparison to both the neutral and happiness affect states, unhappiness was associated with a decrease in HF-HRV and an increase in LF-HRV - In comparison to the neutral and unhappiness affect states, happiness was associated with an increase in HF-HRV and a decrease in LF-HRV
10	Dimitriev et al. (2022)	42	- Positive valence - Negative valence	SDNN, RMSSD, F, HF, approximate (ApEn) and sample entropy	- Negative valence induced by excitatory music was associated with

Table 1 (*continued*)

No.	Authors	N	Affect labels	HRV outcome measures	Major findings
				(SampEn), correlation dimension (D2), Poincare plot indices (SD1, SD2)	significant decreases in SD1, SD2 (non-linear HRV indices), RMSSD, SDNN (time-domain HRV indices), HF- and LF-HRV (frequency domain indices) in comparison to when not listening to music - No significant changes were found in detrended fluctuation analysis (DFA), SampEn, and D2 HRV measures
11	Shi et al. (2017)	48	- Happiness - Sadness	SDNN, RMSSD, PNN50, LF, HF, LF/HF, SampeEn	- Compared to the happiness condition, the sadness condition resulted in increased HF-HRV and decreased LF-HRV and LF/HF ratio
12	Köbele et al. (2010)	20	- Negative mood - Neutral mood	SDNN, RMSSD, LF/HF	- No significant differences found
13	Kop et al. (2011)	20	- Happy - Angry - Frustrated - Depressed	LF, HF, LF/HF ratio	- The magnitude of feeling "happy" during happiness recall was associated with an increase in HF-HRV, whereas an incongruent mood state ("frustrated") was associated with reduced HF-HRV

through manipulation of emotional stimuli (e.g., by showing emotionally charged pictures or videos).

3.3. Findings from naturalistic studies

Several studies have found evidence for an association between negative affect and reduced parasympathetic activity as demonstrated by HRV indices which are known to quantify parasympathetic vagal activity. Specifically, four studies (Bleil et al., 2008; Michels et al., 2013; Sin et al., 2016; Young et al., 2017) have shown, negative affect is associated with a reduction in the frequency-domain measure, HF-HRV. Firstly, Sin et al. (2016) demonstrated this association in a sample of 909 healthy controls. Participants reported daily negative affect and

affective reactivity during telephone interviews on eight consecutive evenings and short-term ECG recordings were recorded on a separate occasion. Whilst stressor frequency was unrelated to HRV, aggregated daily negative affect, higher negative affect in response to stressors and increased levels of stress was associated with significantly lower resting state HF-HRV. Likewise, Bleil and colleagues found negative affect was associated with significantly reduced HF-HRV in a community sample of 653 participants (Bleil et al., 2008) from resting state short-term HRV recordings. Similarly, Young et al. (2017) took short-term HRV recordings and found that that increased levels of self-reported depressed mood were associated with a reduction in parasympathetic activity as measured by HF-HRV. Furthermore, an association between reduced parasympathetic activity, measured by HF-HRV calculated from short-term HRV recordings, and negative affect has also been demonstrated in younger samples (Blood et al., 2015; Michels et al., 2013). In a sample of children aged 5–10 years old, self-reported negative affect (including anger and sadness), as well as positive affect (including happiness), were assessed in relation to resting state short-term HRV recordings (Michels et al., 2013). Whilst no associations were found between levels of happiness and HF-HRV, higher levels of reported anger were associated with a reduction in HF-HRV across the group. In girls specifically, higher levels of anxiety and sadness were also associated with a reduction in HF-HRV. Similarly, in a sample of healthy adolescents aged 10–17, Blood et al. (2015) reported that self-reported depressive symptoms were significantly associated with reduced a reduction in HF-HRV when measured during a resting state.

Further supporting that negative affect is associated with a reduction in parasympathetic activity, Sin et al. (2016) and Michels et al. (2013) both demonstrated that negative affect is associated with a reduction in HRV quantified in the time-domain measure, the root mean square of successive differences (RMSSD) between normal heartbeats from short-term HRV measurements. As with HF-HRV, RMSSD is also considered to reflect parasympathetic vagal activity. Specifically, reduced RMSSD was associated with higher levels of aggregated daily negative affect, higher negative affect in response to stressors and increased levels of stress (Sin et al., 2016), as well as increased levels of self-reported negative emotions including anger and sadness (Michels et al., 2013).

Using prospective longitudinal designs, several studies have suggested that ANS activity, measured through different HRV indices, may also be associated with affect states over time (Pichon et al., 2010; Vazquez et al., 2016; Weinstein et al., 2007). One study investigated whether short-term HRV recordings could predict depressive symptoms one year later in a sample of 73 adolescents (Vazquez et al., 2016). Results demonstrated that reduced parasympathetic activity, as measured by HF-HRV, at baseline was significantly associated with self-reported depressive symptoms including, anhedonia, negative mood and negative self-esteem, one year later. Similarly, Pichon et al. (2010) demonstrated in a sample of university students, that those who reported an increase in depressive symptoms between the beginning of the school year (baseline) and three weeks later after an exam period, had significantly lower HF-HRV at baseline when HRV measurements were taken from short-term resting state recordings (Pichon et al., 2010). Together, these findings (Pichon et al., 2010; Vazquez et al., 2016) suggest reduced parasympathetic activity, indexed by a reduction in HF-HRV, may be important in the development of later depressive symptoms.

Weinstein et al. (2007) investigated whether negative mood induced by exercise withdrawal was associated with changes in HRV from short-term resting state HRV recordings. HRV was measured before and after a period of withdrawal from regular exercise. As expected, exercise withdrawal was associated with a significant increase in reported negative mood. Some evidence was found for an association between reduced parasympathetic activity and negative mood as a result of exercise withdrawal. A trend level association was reported between reduced baseline HF-HRV and increased negative mood. Furthermore, a significant association was found between increased LF/HF ratio (i.e., increased LF to HF power) at baseline and negative mood induced by exercise withdrawal. As discussed earlier, based on the assumption, LF-HRV represents sympathetic activity and HF-HRV represents parasympathetic activity, the LF/HF ratio has previously been used as a measure of sympatho-vagal balance. Given that the association between LF/HF ratio and negative mood reported by Weinstein et al. (2007) was primarily driven by reduced HF-HRV as a predictor of negative mood, results can be interpreted as showing an association between reduced parasympathetic activity and increased negative mood in response to exercise withdrawal. Authors also go on to suggest their findings provide evidence for an association between sympathetic dominance and increased negative mood. However, based on the issues with interpreting sympathetic activity from the LF band from short-term heart rate recordings, it cannot be concluded from these findings that a switch towards sympathetic dominance is associated with negative mood as authors suggest.

3.4. Findings from experimental laboratory studies

Given the higher level of control in experimental laboratory studies, through manipulation of emotionally charged stimuli, experiments of this form can evoke more specific affective states than non-laboratory, naturalistic studies.

Several experimental studies have found evidence that negative affect is associated with a reduction in parasympathetic activity and furthermore, show that positive affect may be associated with an increase in parasympathetic activity (Deo et al., 2018; Kop et al., 2011; Wu et al., 2019). Wu et al. (2019) investigated how specific emotions, including amusement, anger and fear, influence HRV quantified by RMSSD, a measure of parasympathetic activity, amongst a sample of 50 Chinese college students. Affective videos from the standardized Chinese affective video system (CAVS) (Xu et al., 2010) were used to evoke these specific emotions, as well as a neutral emotion state. ECG recordings were taken whilst participants watched the video clips (i.e., emotional elicitation). Parasympathetic activity, reflected by a reduction RMSSD, was significantly lower during the fear and anger (negative affect) conditions, in comparison to the amused (positive affect) condition. In addition, RMSSD was lower in the fearful condition compared to in the anger condition possibly suggesting a fearful affect state leads to greater parasympathetic withdrawal than anger. No significant associations were found when comparing HRV outcomes between the emotion conditions (anger, fear and happiness) and the neutral affect state. Similarly, Deo et al. (2018) performed an experimental mood state induction procedure whereby participants were shown three groups of affective pictures categorised into positive, negative and neutral sets whilst simultaneously recording heart rate variability for five minutes (short-term recording). The parasympathetic domain of HRV, HF-HRV, significantly increased in the positive affect condition compared to the negative and neutral conditions further supporting that negative affect is associated with reduced parasympathetic activity. Furthermore, in the negative mood induction procedure, LF/HF ratio and LF-HRV significantly increased. Again, based on the assumption that the LF-HRV band represents sympathetic activity, authors concluded that negative mood states lead to a shift of autonomic function towards sympathetic dominance. However, as mentioned before, the LF band is not considered a reliable measure of sympathetic activity (Hayano and Yuda, 2019), clear conclusions with regards to how findings of LF-HRV relate to ANS activity cannot be made.

One other study used emotionally charged music to elicit different emotional states amongst forty-two participants. The presentation of music evoking strong negative emotion and high levels of arousal was found to result in a significant reduction in the non-linear HRV measures SD1 and SD2, both measures associated with parasympathetic activity (Dimitriev et al., 2022). Results from this study further support an association between negative affect and parasympathetic withdrawal.

Despite the higher level of control in experimental laboratory

studies, there are more inconsistencies within the literature. The argument in favour of decreased parasympathetic activity during negative affective states and increased parasympathetic activity during positive affective states is contradicted by findings from various experimental studies. Shi et al. (2017) assessed the differences in a range of HRV measures whilst happiness and sadness emotions evoked by video clips (a 'comedy sketch' for the happiness condition and a 'touching movie clip' for the sadness condition). In comparison to the happiness condition, during the sadness condition, HF-HRV increased whilst LF-HRV and LF/HF ratio significantly decreased. In contrast with what has been reported previously, these findings suggest that the induction of negative affect led to increased parasympathetic activity (i.e., increased HF-HRV). One major limitation of this study is that self-reported changes in affective state in response to the emotion induction procedures were not measured and so it is not known whether the intended affective state was evoked in participants in each condition. Instead, authors assumed the participant's affect state matched that of the condition (i.e., happiness versus sadness), which may not have been the case, as evidence suggests video clips are not always successful in inducing the intended affective state (Gilman et al., 2017).

Further adding to the inconsistencies within the literature of experimental studies, one other study (Köbele et al., 2010) found no significant differences in any of the HRV indices measured (SDNN, RMSSD, LF, HF and LF/HF ratio) before and after a negative mood induction procedure despite participants reporting a significant increase in negative affect five-minutes after the negative mood induction procedure. Importantly, as well as measuring affective states, this study also measured levels of arousal (i.e., the strength of the associated emotional state) using the Self-Assessment Manikin (SAM) (Lang et al., 1980). Whilst participants reported increased negative affect after the negative mood induction, levels of reported arousal did not change. Thus, the lack of differences in HRV may be because the mood induction procedure was not successful in evoking a mood state that was intense enough to lead to autonomic changes and so no difference in HRV was found.

If the experimental procedures are not successful in truly evoking the intended affective state, invalid associations and inaccurate conclusions will be made. This is particularly supported by a study by Kop et al. (2011) showing how the association between HRV and mood responses varied depending on whether the mood induction task was successful in evoking the intended emotion (i.e., feelings of happiness during happy event recall). To begin with, authors report that, happiness recall was associated with an increase in LF-HRV but not HF-HRV. However, in those who reported actually feeling 'happy' during the happiness recall (i.e., congruent affect state), the results emerged in the opposite direction: HF-HRV increased but LF-HRV did not. This supports the idea that parasympathetic activity is in fact associated with positive affect. Furthermore, feelings of frustration during happiness recall (i.e., incongruent affect state) were associated with decreased HF-HRV and increased LF/HF ratio again supporting the association between negative affect and decreased parasympathetic activity. These results show how the correlations between HRV and affective states can differ depending on the success of the mood induction task, highlighting that caution should be taken when interpreting associations between affect and HRV in laboratory studies whereby affective states are experimentally induced.

4. Discussion

The purpose of this review was to investigate the associations between HRV and affective states to further understand ANS patterns during negative and positive affect states. In summary, all but one of the studies examined (Köbele et al., 2010), demonstrated significant associations between affect and HRV. Overall, strongest evidence exists for an association between a reduction in parasympathetic activity, measured through HRV measures including HF-HRV and RMSSD, and negative affect. These associations were found in studies that examined self-reported levels of negative affect (e.g., depressed mood, aggregated daily negative affect and sadness) as well as in studies that looked at the immediate effect of artificially induced negative affect states on HRV. Together, results suggest increased levels of negative affect are associated with a reduction in parasympathetic activity.

What is clear from the existing literature is that there is a comparatively larger body of evidence for the association between heartbeat dynamics and negative affect (as compared to positive affect). Interestingly, this observation appears to be mirrored by a recent finding in the modelling literature, where a probabilistic model, which was trained to predict affect from heartbeat time series, exhibited greater confidence when predicting cases of negative affect compared with positive affect (Harper and Southern, 2020). This hints at the idea that signatures of negative affect in the heartbeat signal may contain more information than signatures of positive affect. This raises further questions on the neurobiological distinctions between these two psychological states.

Furthermore, some evidence suggests an association between negative affect and an increase in LF-HRV and LF/HF ratio (Deo et al., 2018; Weinstein et al., 2007). Based on the assumption, LF-HRV represents sympathetic activity, authors suggest (Deo et al., 2018; Weinstein et al., 2007), increased sympathetic activity and/or a shift of autonomic function towards sympathetic dominance is associated with negative affect. However, these claims are based on the false assumption that sympathetic activity can be inferred from LF-HRV measured via short-term ambulatory recordings which has been proven not to be a reliable indicator of sympathetic activity. The physiological correlates of the LF band require further elucidation until confident claims can be made as to how LF-HRV and the LF/HF ratio represent the ANS in the context of mood states and emotional responses.

Several converging lines of evidence suggest chronic reductions in parasympathetic activity may play a role in the development of affective disorders, such as depression, possibly through its effects on other physiological systems (Cooper et al., 2015; Grimonprez et al., 2015; Won and Kim, 2016). Specifically, parasympathetic vagal activity is known to regulate inflammatory responses by decreasing the production of pro-inflammatory cytokines, known as the vagal-inflammatory pathway. A recent meta-analysis demonstrated that decreased HRV was associated with an increase in a range of cytokines (Williams et al., 2019). Reduced HF-HRV was associated with increased levels of tumour necrosis factor (TNF), interleukin-1 (IL-1), interleukin-6 (IL-6) and C-reactive protein (CRP). In addition, SDNN, a time-domain measure, was associated with a reduction in TNF, IL-6 and CRP. Thus, the decrease in parasympathetic activity, in the context of negative affect, will likely lead to an increase in pro-inflammatory cytokines. Strong evidence suggests increased inflammation is involved in the pathogenesis of depression (Baumeister et al., 2014; Miller and Raison, 2016; Zunszain et al., 2012). Based on this, findings that negative affect leads to decreased parasympathetic activity, suggests a possible biological pathway through which negative affect may contribute to development of affective disorders such as depression. Whilst short-lived reductions in parasympathetic activity (e.g., in the context of normal daily negative affect), are not likely to have harmful effects, chronic negative affect, may increase risk of depression through the vagal-inflammatory pathway.

Several meta-analyses have demonstrated that compared with healthy controls, a variety of HRV measures including, HF-HRV, LF-HRV, RMSSD and SDNN, are significantly reduced in those with depression (Gorman and Sloan, 2000; Hamilton and Alloy, 2016; Koch et al., 2019). Based on findings such as these, it has been suggested that reduced HRV may be a risk factor for the development of depression and may constitute as a biomarker of illness (Beauchaine and Thayer, 2015; Kim et al., 2017). One issue with this hypothesis is that it is difficult to disentangle the direction of the relationship between reduced HRV and depression because many of the studies which look at the association between HRV and depression have been done in already depressed patients. Therefore, it is not known whether reduced HRV precedes or

follows the development of depression. The findings from this review showing an association between reduced HRV and negative affect reported in healthy controls suggest that the reduction in parasympathetic activity in the context of negative affect is part of a normal physiological process. However, persistent and/or frequent negative affect could become harmful because of the downstream consequences this has on other physiological systems. Persistent and/or prolonged negative affect, leading to chronic reductions in parasympathetic activity may become harmful by leading to chronic increases in inflammation, a well-known risk factor for depression. Given the implications reduced HRV has for parasympathetic nervous system activity and consequently, the inflammatory system, this provides evidence to suggest that reduced HRV precedes depression onset and may act as a risk marker for illness.

5. Conclusions

In conclusion, our review supports an association between negative affect and a reduction in a range of HRV measures suggesting negative affect may be associated with a reduction in parasympathetic activity. The potentially important downstream consequences of this association have been discussed in the context of depression and highlight how chronic dysregulation of the ANS in the context of persistent/chronic negative affect may represent one of the pathophysiological mechanisms contributing towards the development of affective disorders and suggesting dysregulation of ANS activity as a potential biomarker for affective disorders. However, further research is needed to explore the proposed pathways, in particular, considering that the relationship between ANS and HRV could also follow more complex non-linear models. The study of HRV provides a promising method for further investigation of ANS, specifically in the context of negative affective states, and to further understand biological mechanisms involved in development of affective disorders, such as depression.

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