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Heart rate variability is associated with psychosocial stress in distinct social domains

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ABSTRACT

Objective: Psychosocial stress is associated with substantial morbidity and mortality. Accordingly, there is a growing interest in biomarkers that indicate whether individuals show adaptive (i.e., stress-buffering and health-promoting) or maladaptive (i.e., stress-escalating and health-impairing) stress reactions in social contexts. As heart rate variability (HRV) has been suggested to be a biomarker of adaptive behavior during social encounters, it may be possible that inter-individual differences in HRV are associated with inter-individual differences regarding stress in distinct social domains.
Methods: To test this hypothesis, resting state HRV and psychosocial stress was assessed in 83 healthy community-dwelling individuals (age: 18–35 years). HRV was derived from heart rate recordings during spontaneous and instructed breathing to assess the robustness of possible associations between inter-individual differences in HRV and inter-individual differences in psychosocial stress. Psychosocial stress was determined with a self-report questionnaire assessing stress in distinct social domains.
Results: A series of categorical and dimensional analyses revealed an association between inter-individual differences in HRV and inter-individual differences in psychosocial stress: Individuals with high HRV reported less stress in social life, but not in family life, work life or everyday life, than individuals with low HRV.
Conclusions: On basis of these findings, it may be assumed that individuals with high HRV experience less psychosocial stress than individuals with low HRV. Although such an assumption needs to be corroborated by further findings, it seems to be consistent with previous findings showing that individuals with high HRV suffer less from stress and stress-related disorders than individuals with low HRV.

1. Introduction

As social beings, we rarely spend our time in isolation [1]. Most of our time, we are surrounded by other individuals, making it almost impossible to avoid social interactions. We have to interact with individuals that are well-known to us, like partners and friends, but also with individuals that are less known to us, like colleagues and customers. These interactions are marked by different types of challenges and opportunities, implying that we may experience different levels of stress throughout these interactions [2]. Although interacting with other individuals may help us to cope with stressful experiences [e.g., [3,4]], these interactions may also be stressful for us [e.g., [5,6]]. In particular negative interactions, that is, interactions with individuals that behave unexpectedly or unpredictably in potentially threatening contexts [7], are accompanied by a plethora of stress reactions [8,9]. On the subjective level, we may experience a change in emotion and cognition, like, for example, an increase in negative feelings [e.g., [10,11]] or an increase in attention for negative information [e.g., [12,13]]. On the behavioral level, we may show a change in behavior, like, for example, an increase in agnostic behavior in terms of insults and attacks [e.g., [14,15]] or an increase in affiliative behavior in terms of concessions and compromises [e.g., [16,17]]. On the neurobiological level, we may experience a change in autonomic and endocrine reactivity, like, for example, an increase in cardiovascular activity [e.g., [18,19]] or an increase in glucocorticoid and catecholamine activity [e.g., [20,21]]. Although these stress reactions may help us to cope with other individuals in potentially threatening contexts, they may also put us at risk for several diseases [22]. As psychosocial stress is associated with substantial morbidity and mortality [23], there is a growing interest in biomarkers that indicate whether we show adaptive (i.e.,

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stress-buffering and health-promoting) or maladaptive (i.e., stress-escalating and health-impairing) stress reactions in social contexts.

In recent years, heart rate variability (HRV), an index of consecutive changes in heart beat [24], has been considered as a promising biomarker for adaptive behavior during social encounters [25,26]. Our subjective, behavioral and neurobiological responses to other individuals are orchestrated by a network of prefrontal and (para-)limbic brain regions [25–27]. Activity and connectivity changes in this network of brain regions are associated with changes in HRV [e.g., [28,29,30]], indicating that inter-individual differences in HRV may reflect inter-individual differences regarding the interplay between prefrontal and (para-)limbic brain regions during the regulation of social behavior. HRV measures may, thus, enable us to assess whether an individual shows adaptive or maladaptive behavior during social interactions. Adaptive behavior is generally reflected by a less efficient interplay of prefrontal and (para-)limbic brain regions that is associated with an increase in HRV, whereas maladaptive behavior is generally reflected by a less efficient interplay of prefrontal and (para-)limbic brain regions that is associated with a decrease in HRV. Individuals with high HRV are more sensitive to the emotional states of others [e.g., [31,32–34]] and are more skilled to regulate their emotional and behavioral responses towards others [e.g., [35–37]] than individuals with low HRV. Accordingly, individuals with high HRV are more likely to initiate and maintain positive social interactions than individuals with low HRV [e.g., [38,39]]. It may, thus, be possible that individuals with high HRV also experience less stress during social encounters than individuals with low HRV. This may explain why individuals with high HRV are less likely to suffer from stress-related diseases, like, for example, cardiovascular diseases [e.g., [40,41]] or major depressive disorder [e.g., [42,43]], than individuals with low HRV.

Although inter-individual differences in HRV have been suggested to reflect inter-individual differences in the experience and regulation of stress in social contexts [25–27], this has hardly been investigated yet. We, thus, further investigated whether inter-individual differences in HRV would be associated with inter-individual differences in psychosocial stress. Inter-individual differences in HRV were determined on basis of short-term recordings of heart rate (HR) under resting state conditions, whereas inter-individual differences in psychosocial stress were determined on basis of a self-report questionnaire. The self-report questionnaire assessed inter-individual differences regarding stress experiences in distinct social domains. Some domains were characterized by interactions with familiar individuals, such as family life or social life, and other domains were characterized by interactions with unfamiliar individuals, such as work or everyday life. As our stress levels are more likely to change during interactions with familiar than unfamiliar individuals [e.g., [44,45–51]], we hypothesized that the association between inter-individual differences in HRV and inter-individual differences in psychosocial stress would be more pronounced during encounters with familiar than unfamiliar individuals. Individuals with high HRV were, thus, expected to report less stress in family and social life than individuals with low HRV. Reports of stress in everyday life and work life, on the contrary, were not expected to differ between individuals with high and low HRV. To determine the robustness of the hypothesized association between inter-individual differences in HRV and inter-individual differences in psychosocial stress, we performed a series of categorical and dimensional analyses on basis of HR recordings that were obtained during spontaneous and instructed breathing.

2. Method

2.1. Participants

We performed an a priori power analysis to determine the number of participants that we needed to detect meaningful associations between inter-individual differences in HRV and inter-individual differences in psychosocial stress. G*Power [52] indicated that we had to recruit 82–90 participants in order to have sufficient power ($1 - \beta = 0.80$, $\alpha = 0.05$) to detect medium-sized effects in our dimensional ($r = 0.30$) and categorical ($f = 0.30$) analyses. Using local advertisement, 84 community-dwelling participants were recruited from the urban area of Rostock between June and September 2016. As a consequence, our dimensional analyses were appropriately powered ($1 - \beta = 0.80$) and our categorical analyses were slightly under-powered ($1 - \beta = 0.78$). In order to be included in the study, participants had to be aged between 18 and 35 years and to be native German speakers. Participants with mental disorders and participants who were in psychotherapeutic treatment were excluded from the study. Inclusion and exclusion of participants was determined on basis of a self-report questionnaire assessing sociodemographic (age, sex), anthropometric (height, weight) and psychopathological (mental health) participant characteristics. One participant did not provide valid data due to equipment malfunction and was subsequently excluded from the analyses. We, thus, considered 83 participants that provided valid and complete data in our analyses (see Table 1).

Table 1
Participant characteristics.

	M (SD)	95% CI
Age	26.35 (4.09)	[25.46, 27.24]
Sex (m/f)	41/42	
Heart rate variability during recordings with spontaneous breathing (HRV-SB)		
RMSSD-SB (ms)	44.00 (28.20)	[37.85, 50.16]
Log-RMSSD-SB (ms)	1.57 (0.25)	[1.52, 1.63]
Heart rate variability during recordings with instructed breathing (HRV-IB)		
RMSSD-IB (ms)	35.20 (24.36)	[29.88, 40.52]
Log-RMSSD-IB (ms)	1.47 (0.26)	[1.41, 1.53]
Stress (KFB)		
Social life	1.91 (0.89)	[1.72, 2.11]
Family life	1.52 (0.76)	[1.35, 1.68]
Work life	1.11 (0.98)	[0.89, 1.32]
Everyday life	0.52 (0.68)	[0.37, 0.67]

Note. 95% CI = 95% confidence interval, m = male, f = female, HRV = heart rate variability, SB = spontaneous breathing, IB = instructed breathing, RMSSD = root mean square of successive differences between consecutive heart beats, Log-RMSSD = log transformed root mean square of successive differences between consecutive heart beats, KFB = modified version of the Hassles and Uplifts Scale [55,61].

All participants provided written-informed consent before taking part in the study and were fully debriefed after completion of the study. The study was approved by the local ethics committee and carried out in accordance with the Declaration of Helsinki.

2.2. Procedure

Participants' visits to the laboratory were scheduled between 8 a.m. and 8 p.m. After arrival at the laboratory, participants were asked to use the bathroom to control for the effects of bladder filling and gastric distension on HRV [53]. Participants were then seated in a comfortable chair and prepared for the HR recording. To control for the effects of breathing patterns on HRV [53], HRV was recorded during spontaneous breathing (5 min) as well as during instructed breathing (5 min). Whereas participants breathed at a self-paced rate during spontaneous breathing, participants breathed at a metronome-paced rate (0.25 Hz) during instructed breathing [54]. HR recording during instructed breathing was always preceded by HR recording during spontaneous breathing to avoid carry-over effects from instructed to spontaneous breathing [54]. After the HR recording, participants completed an online self-report questionnaire that assessed psychosocial stress in different social domains [Kurzer Fragebogen zur Erfassung von

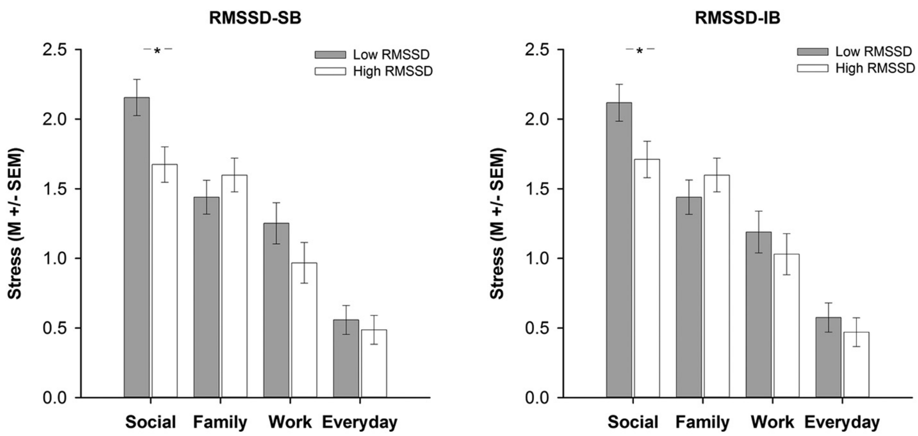

Fig. 1. Barplots demonstrating domain-specific differences in stress between participants with high and low heart rate variability (RMSSD) that was derived from recordings of participants' heart rate during spontaneous (SB; left panel) or instructed (IB; right panel) breathing. Bars represent M ± SEM. $^{*}p \leq 0.05$.

Belastungen, KFB; [55].

2.3. Heart rate variability

HR was recorded continuously with a chest belt system, the RS800CX HR monitor (Polar Electro Oy, Kempele, Finland), providing a sampling rate of 1000 Hz. HR monitors like the RS800CX have been shown to record HR as accurate as conventional electrocardiogram systems [56,57]. Device specific software (Polar ProTrainer 5; Polar Electro Oy, Kempele, Finland) was used to transfer the recorded data to a computer for further data processing with Kubios HRV 2.2 [58]. The recorded data was visually inspected, detrended (smoothn priors: $\lambda = 500$) and, whenever necessary, corrected using adaptive filtering, before it was subjected to a time-domain analysis for the determination of the root mean square of successive differences between consecutive heart beats [RMSSD; [59]]. Compared to other HRV indices, RMSSD represents the most robust short-term measure of changes in HR that are mediated by the vagus nerve [60]. To avoid interpretational issues arising from the use of less robust measures [60], no further HRV indices were used for the analyses.

2.4. Stress

The KFB [55], a self-report questionnaire that represents a modified version of the Hassles and Uplifts scale [61], was used to assess psychosocial stress in different social domains, such as social life, family life, work life and everyday life. The KFB comprises 16 items, ranging from 0 (does not apply) to 6 (does apply). Each item describes a particular situation, with items assessing stress in family and social life describing specific situations that involve partners or friends and items assessing psychosocial stress in work and everyday life describing general situations that do not involve partners or friends. Items assessing stress in family and social life, thus, refer to interactions with familiar individuals and items assessing stress in work and everyday life refer to interactions with unfamiliar individuals. For each domain, participants' item scores were averaged, with higher averages indicating more stress in social life, family life, work life or everyday life. In line with previous studies [55], the KFB displayed good psychometric properties in the present study (social life: Cronbach's $\alpha = 0.82$; family life: Cronbach's $\alpha = 0.77$; work life: Cronbach's $\alpha = 0.83$; everyday life: Cronbach's $\alpha = 0.72$), indicating its validity and reliability.

2.5. Statistical analysis

All statistical analyses were conducted using SPSS 22 (SPSS Inc., Chicago, IL, USA). To investigate whether inter-individual differences in HRV would be associated with inter-individual differences in psychosocial stress, several analyses were performed. A median-split was used to differentiate between participants with high and low RMSSD. On basis of the median-split, analyses of covariance (ANCOVAs) were computed to compare stress in different domains between participants with high and low RMSSD. In addition, partial correlations between RMSSD and stress in different domains were computed. As sociodemographic (age, sex) and anthropometric (body mass index) participant characteristics may affect the association between inter-individual differences in HRV and inter-individual differences in psychosocial stress [23,62,63], these characteristics (age, sex, body mass index) were under statistical control in the aforementioned analyses. These analyses were performed for RMSSD that was derived from HR recordings during spontaneous (SB) and instructed (IB) breathing to assess the robustness of possible findings. Correspondence between RMSSD-SB and RMSSD-IB was determined on basis of correlations between the respective recordings (Intra-class correlations, ICC: absolute agreement, two-way ANOVA). Prior to all analyses, RMSSD was log transformed (log 10) to establish normality distribution, which was confirmed by Komolgorov-Smirnov and Shapiro-Wilk tests. The significance level for all analyses was set at $p \leq 0.05$ and effect size measure (η_p^2 and r) were determined to facilitate the interpretation of the respective findings [64]. Due to the hypothesis-driven nature of the analyses, the findings were not corrected for multiple comparisons.

3. Results

3.1. Stress and recordings of heart rate variability during spontaneous breathing

A series of one-way ANOVAs was performed to compare stress in different domains between participants with low and high RMSSD whose HR was recorded during spontaneous breathing (see Fig. 1). To differentiate between participants with low and high RMSSD, a median-split was used (RMSSD-SB: $Mdn = 37.70$ ms). Except for stress in social life [$F(1,78) = 6.888$, $p = 0.010$, $\eta_p^2 = 0.081$], participants with low and high RMSSD did not differ in their stress experiences [family life: $F(1,78) = 0.842$, $p = 0.362$, $\eta_p^2 = 0.011$; work life: $F(1,78) = 1.837$, $p = 0.179$, $\eta_p^2 = 0.023$; everyday life: $F(1,78) = 0.237$, $p = 0.628$, $\eta_p^2 = 0.003$]. Participants with high RMSSD-SB reported less stress in their social life than participants with low RMSSD-SB. To further illustrate these differences in stress reports between participants differing in RMSSD-SB, correlation analyses were performed between stress in different domains and RMSSD-SB (see Fig. 2). Mirroring the aforementioned findings, RMSSD-SB correlated with stress in social life [$r(78) = -0.207$, $p = 0.033$ (one-sided)] but not with stress in work life [$r(78) = -0.076$, $p = 0.253$ (one-sided)], family life [$r(78) = 0.091$, $p = 0.211$ (one-sided)] or everyday life [$r(78) = 0.036$, $p = 0.376$ (one-sided)].

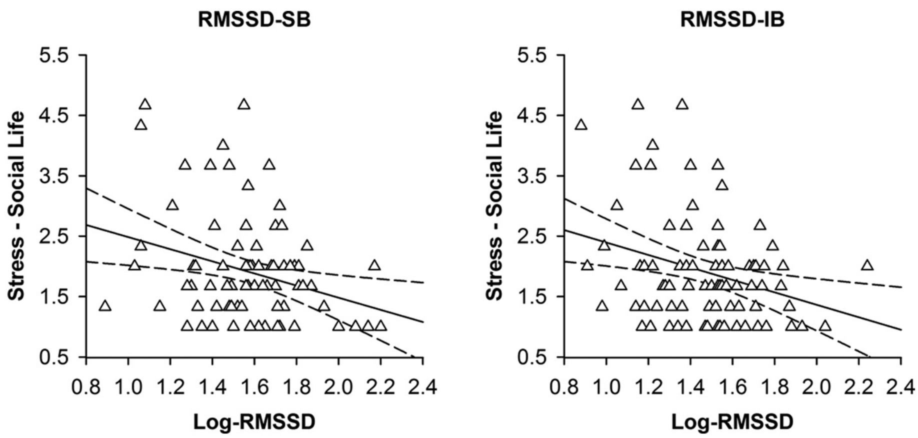

Fig. 2. Scatterplots with lines of best fit and 95% confidence interval demonstrating bivariate associations between stress in social life and log-transformed heart rate variability (Log-RMSSD) that was derived from recordings of participants' heart rate during spontaneous (SB; left panel) or instructed (IB; right panel) breathing.

3.2. Stress and recordings of heart rate variability during instructed breathing

On basis of a median-split (RMSSD-IB: *Mdn* = 35.20 ms), another series of one-way ANOVAs were performed to compare stress in different domains between participants with low and high RMSSD whose HR was recorded during instructed breathing (see Fig. 1). There was, again, a difference regarding stress in social life [$F(1,78) = 4.674$, $p = 0.034$, $\eta_p^2 = 0.057$] but not in family life [$F(1,78) = 0.833$, $p = 0.364$, $\eta_p^2 = 0.011$], work life [$F(1,78) = 0.557$, $p = 0.458$, $\eta_p^2 = 0.007$] or everyday life [$F(1,78) = 0.505$, $p = 0.480$, $\eta_p^2 = 0.007$] between participants with high and low RMSSD. Similarly as above, participants with high RMSSD reported less stress in social life than participants with low RMSSD. A correlation analysis (see Fig. 2) also revealed a correlation between RMSSD and stress in social life [$r(78) = -0.249$, $p = 0.013$ (one-sided)] but not between RMSSD and stress in family life [$r(78) = 0.109$, $p = 0.168$ (one-sided)], work life [$r(78) = -0.040$, $p = 0.364$ (one-sided)] or everyday life [$r(78) = 0.046$, $p = 0.343$ (one-sided)].

3.3. Recordings of heart rate variability during spontaneous and instructed breathing

Intra-class correlations were computed to investigate the correspondence between indices of RMSSD that were derived from recordings of HR during spontaneous or instructed breathing. There was a high correlation between RMSSD-SB and RMSSD-IB [ICC: $r(82) = 0.898$, 95% CI = [0.604, 0.958]], indicating a high correspondence between the different RMSSD indices.

4. Discussion

In the present study, we investigated whether inter-individual differences in HRV would be associated with inter-individual differences in psychosocial stress. In accordance with our predictions, we found an association between inter-individual differences in HRV and inter-individual differences regarding stress in social life. Individuals with high HRV reported less stress in social life than individuals with low HRV, indicating a decrease in psychosocial stress with increasing HRV. Contrary to our predictions, there was no association between inter-individual differences in HRV and inter-individual differences regarding stress in family life. Stress in family life involved interactions with partners, which were described as participants' most important attachment figure [55], whereas stress in social life involved interactions with friends, which were no further described [55]. Given the importance of attachment figures for our mental and physical well-being [65,66], it is conceivable that interactions with partners are characterized by more intimacy than interactions with friends [e.g., [51,67–69]]. We may, thus, be more familiar with our partners than with our friends, implying that it may be more likely that our friends behave unexpectedly and unpredictably than our partners. Our friends may also be more likely to engage in threatening behavior than our partners with whom we lead intimate relationships that are characterized by mutual trust and respect. It may, thus, be more likely that we experience stress during interactions with our friends than with our partners [e.g., [49–51]]. This may explain why the association between inter-individual differences in HRV and inter-individual differences in stress were more pronounced in participants' social life than in participants' family life. Intriguingly, the association between inter-individual differences in HRV and inter-individual differences regarding stress in social life emerged in a series of analyses, including dimensional analyses (i.e., correlation of psychosocial stress with HRV across all participants) as well as categorical analyses (i.e., comparison of psychosocial stress between participants with high and low HRV). Moreover, breathing patterns, which are known to affect HRV [53], did not change the association between inter-individual differences in HRV and inter-individual differences regarding stress in social life. The association between inter-individual differences in HRV and inter-individual differences in psychosocial stress, thus, appeared to be quite robust. However, the association was weaker than expected, indicating a need to further analyze this association in future studies. To determine the stability and replicability of our findings, it may be worthwhile to perform analyses that do not depend on a median-split, that consider more than the selected set of covariates and that employ a strict control for multiple comparisons.

As our findings suggest that inter-individual differences in HRV may be associated with inter-individual differences regarding stress in social life, it may be speculated that inter-individual differences in HRV are similarly associated with inter-individual differences regarding the initiation and maintenance of social relationships. Individuals with high HRV may experience less stress during social encounters than individuals with low HRV, presumably because individuals with high HRV are more apt at regulation emotional and behavioral responses towards others than individuals with low HRV [e.g., [35–37]]. Individuals with high HRV may, thus, be more likely to be in a calm and relaxed state during social interactions than individuals with low HRV. In the absence of distracting states of arousal, individuals with high HRV may be more likely to recognize and remember the emotional states of their interaction partner than individuals with low HRV [e.g., [31–34]], which may help individuals with high HRV to adapt their behavior more successfully to the situational demands than individuals with low HRV. As a consequence, individuals with high HRV may be more likely to initiate and maintain positive social relationships than individuals with low HRV [e.g., [38,39]]. Due to the positive nature of their relationships [2], individuals with high HRV may receive more instrumental support (e.g., provision of financial assistance or material aid), more informational support (e.g., provision of advice or guidance) and more emotional support (e.g., provision of empathy or sympathy) than individuals with low levels of HRV. Pre-existing differences in stress coping between individuals with low and high HRV may, thus, be exacerbated by different levels of social support given to individuals with low and high HRV. Coping with stressful experiences may be further enhanced in individuals with high HRV (upward spiral) but may be further compressed in individuals with low HRV (downward spiral), increasing the likelihood of stress-related diseases in individuals with low HRV as compared to individuals with high HRV [70,71].

Regarding the neurobiological mechanisms mediating the association between inter-individual differences in HRV and inter-individual differences in psychosocial stress, it is noteworthy that a network of prefrontal and (para-)limbic brain regions has been suggested to mediate subjective, behavioral and endocrine reactions to psychosocial stressors [63,72]. Functional [e.g., [73,74–78]] and structural [e.g., [79,80]] alterations in the prefrontal cortex, anterior cingulate cortex, the amygdala and hippocampus have been shown to alter these stress reactions, presumably because the interplay between prefrontal and (para-)limbic brain regions is altered during immediate and delayed processing of psychosocial stressors [77,78]. Moreover, the altered interplay between prefrontal and (para-)limbic brain regions has been shown to be implicated in the release of glucocorticoids, catecholamines and proinflammatory cytokines [e.g., [81–83]], which after prolonged and repeated release increase the risk for stress-related diseases [8,9,23]. Of note, an altered interplay between prefrontal and (para-)limbic brain regions has also been shown to be associated with inter-individual differences in HRV [e.g., [28–30]], implying that inter-individual differences in HRV may reflect inter-individual differences in the experience and regulation of psychosocial stress that are mediated by activity and connectivity changes in a network of prefrontal and (para-)limbic brain regions. As inter-individual differences in HRV serve as a proxy for inter-individual differences regarding the interplay between prefrontal and (para-)limbic brain regions during the processing of psychosocial stressors, it is not surprising that inter-individual differences in HRV are associated with inter-individual differences in stress as well as with inter-individual differences in mental and physical health [70,71]. Inter-individual differences in HRV have, thus, been suggested to differentiate between individuals that are more or less at risk to develop or maintain stress-related diseases. Although it remains to be determined whether HRV qualifies as a biomarker for stress and stress-related diseases [84], our findings suggest that this may indeed be the case.

On the basis of the present and previous findings, we assume that inter-individual differences in HRV may reflect inter-individual differences in stress that may possibly be mediated by inter-individual differences regarding the interplay between prefrontal and (para-)limbic brain regions during the processing of psychosocial stressors. This interplay may be altered in individuals with low HRV, increasing the likelihood of stress-enhancing and health-impairing stress reactions on the subjective, behavioral and neurobiological level. As a consequence, individuals with low HRV may have difficulties in initiating and maintaining positive social relationships, thereby putting themselves at risk for further stress experiences that may have deleterious effects on their mental and physical health. Individuals with high HRV, on the contrary, may be more likely to show stress-buffering and health-enhancing stress reactions because of a normal interplay between prefrontal and (para-)limbic brain regions during the processing of psychosocial stressors. These individuals are, thus, more likely to initiate and maintain positive relationships, which may help them to further cope with their stress-enhancing and health-impairing experiences. Although these assumptions appear to be consistent with recent theories regarding the neurobiological mechanisms mediating the association between inter-individual differences in HRV and inter-individual differences in stress and stress-related diseases [25,26,70,71], they need to be tested in future studies that combine psychophysiological with neurophysiological methods. It may be of particular relevance to investigate whether inter-individual differences in HRV are similarly associated with inter-individual differences regarding objective measures of psychosocial (e.g., cortisol or alpha-amylase levels) as with inter-individual differences regarding subjective measures of psychosocial stress (e.g., self-report questionnaires). It may also be interesting to investigate whether the association between inter-individual differences in HRV and inter-individual differences in psychosocial stress are in fact mediated by the proposed network of prefrontal and (para-)limbic brain regions. Multimodal studies combining subjective and objective measures to investigate the association of inter-individual differences in HRV and inter-individual differences in psychosocial stress in larger samples of individuals with and without stress-related diseases will help to determine whether HRV qualifies as a biomarker for stress and health.

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Competing interest statement

The authors have no competing interests to report.

Contributors

AL, AMM and MW designed the study. AMM and RJ collected the data. AL, MW and RP analyzed the data. AL wrote the manuscript. AOH, AMM, MW, RJ and RP contributed to writing, reviewing and editing of the manuscript. All authors approved the final version of the manuscript.

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