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Patients with borderline personality disorder show initially reduced psychophysiological relaxation levels but intact relaxation response

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ABSTRACT

Introduction: Borderline Personality Disorder (BPD) is associated with psychological as well as physiological dysregulation in patients, including reduced parasympathetic activity at baseline and difficulties returning to baseline after a stressor. Whether this impacts the relaxation response independent of a stressor has so far not been investigated.
Methods: In a within-subject design, we compared two relaxation interventions, a virtual reality nature video, and a paced breathing intervention. We assessed a female-only sample, with 20 BPD patients ($mean_{age} = 23.75 \pm 4.39$) during their inpatient treatment and 22 matched healthy controls (HC; $mean_{age} = 22.68 \pm 2.68$). Psychological relaxation was assessed with the Relaxation State Questionnaire (RSQ) and physiological relaxation with vagally mediated heart rate variability (HRV).
Results: We employed multilevel models to test whether BPD significantly influenced the psychophysiological relaxation response. For psychological relaxation, we found an increase in RSQ scores in both groups in response to both interventions. The HC showed overall higher RSQ scores. For physiological relaxation, we found overall higher HRV values in the HC group but no differences in the relaxation response.
Conclusion: BPD patients exhibit lower psychophysiological relaxation levels at baseline and throughout the experiment, while there was no significant difference in response to relaxation interventions when compared to HC. Future studies should focus on interventions targeting baseline psychophysiological relaxation in BPD patients.

1. Introduction

1.1. Borderline personality disorder

Borderline personality disorder (BPD) is characterized by intense emotions that often change rapidly within a short period of time [1,2]. Patients also experience high emotional reactivity with difficulties in regulating both, emotions and tension, often falling back on dysfunctional regulation strategies such as suicidal behavior, self-harm, or impulsive behavior in potentially self-damaging areas (e.g., risky driving, consumption of drugs or alcohol) [1,3]. Interpersonal relationships and identity are also affected and often subject to sudden shifts. BPD affects approximately 0.7 % to 2.7 % of the general population and is associated with considerable costs for the person affected, their families and friends, and the health care system [1–3]. The vast majority suffer from comorbid diseases (85 % affective disorders, 78 % substance use disorders, 30 % posttraumatic stress disorder), making BPD challenging to treat [3].

The etiology of BPD comprises a complex interplay of genetic, physiological, psychological, and social factors, summarized as the Biopsychosocial Model of BPD as first introduced by Linehan [4] and expanded in the following years [5,6]. One of the physiological factors, the autonomic nervous system (ANS), prominently implicated in healthy physiological and psychological functioning (e.g., emotion regulation; [7]), shows significant regulation differences between BPD patients and healthy controls (HC). These differences suggest a reduced activity of

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the parasympathetic nervous system (PNS), indicated by lower vagally mediated heart rate variability (HRV) in BPD patients [8]. Previous studies also found a negative impact of the severity of BPD symptoms on resting state HRV, indicating an increased dominance of the sympathetic nervous system (SNS) linked with a blunted PNS activity [9,10]. Early life adversity (ELA) was found to be a general risk factor for various mental and physiological diseases [11,12] and is related to dysfunctional emotion regulation strategies [13]. ELA also plays a role in the development of BPD, since BPD patients often report extremely adverse childhood experiences with various forms of abuse and/or neglect [3,6]. BPD patients were even found to be 3.15 times more likely to have experienced adverse childhoods than patients with other mental disorders [14]. In summary, the interplay between physiological changes associated with impulsivity and emotion regulation (e.g., changes in ANS activity), adverse childhood experiences, and a lack of adaptive and adequate emotion regulation strategies may contribute to the development of BPD [3–6].

So far, there is no effective pharmacotherapeutic treatment for BPD, however, antidepressants, mood stabilizers, or benzodiazepines are used to manage some symptoms short-term. Psychotherapy was found to be effective in decreasing BPD-related symptoms, especially self-harm and suicidal behavior, while increasing psychosocial functioning up to 21 months post-treatment [3,15]. Dialectic behavioral therapy (DBT) was developed specifically to treat BPD and its effectiveness is supported empirically [4,15,16]. DBT's main components include mindfulness, emotion regulation, and distress tolerance, and it can be used in inpatient as well as outpatient settings [15,16].

1.2. Relaxation

While relaxation is not a core component of DBT, it is often added, either as a separate group intervention or in the course of mindfulness exercises (e.g., breathing exercises). While there are different forms of relaxation interventions (e.g., massages, Meier et al., [17]; guided imagery, Bigham et al., [18]), breathing interventions are easy to implement and have proven to be effective in inducing relaxation [19]. On a physiological level, changes in the ANS are associated with relaxation, namely an increase in PNS activity [20]. Vagally mediated HRV is frequently used to track such changes in PNS activity, even though it can be influenced by other factors (e.g., age, sex, mental or physiological diseases; [21–23]). Since breathing rhythm and PNS activity are linked via the vagus nerve, breathing with a rhythm of six breaths per minute increases physiological relaxation, while also leading to psychological changes associated with relaxation [24,25]. On a psychological level, those changes include an increase in pleasant emotions and a reduction of arousal [26,27].

Exposure to nature stimuli is another effective relaxation intervention. Nature stimuli in both real-life settings and virtual interventions were shown to increase not only HRV but also positive affect [28–32]. While the mechanisms behind breathing exercises function on a physiological level via direct vagal stimulation (baroreceptor reflex), the mechanisms behind the effects of nature exposure are likely psychological. Nature environments that convey security induce relaxation and therefore enable the restoration of resources. A proposed mechanism for these effects has to do with the idea that these environments are considered evolutionary advantageous to humans (Psychoevolutionary Theory; Ulrich, [33]). While the effects of virtual nature interventions on PNS activation are inconsistent, an increased sense of presence in the virtual environment seems beneficial for inducing relaxation [34,35]. Overall, the effectiveness of short-term relaxation interventions on the relaxation response is mixed, with a wide variety of interventions, durations, and measurements used. While our group previously reported on interpersonal factors, like trait mindfulness [36] or a history of ELA, to affect the relaxation response, many questions remain, for example about the effects of psychopathology [30]. So far, one previous study found that patients suffering from major depressive disorder did not show an increase in HRV while viewing a nature video, in contrast to HC [37]. Whether BPD patients are affected similarly is unclear. One other previous study has shown that BPD is associated with changes in the ANS when exposed to and recovering from stress, as well as a reduced baseline vagally mediated HRV [8–10]. However, it remains unclear whether a BPD diagnosis also influences the relaxation response.

1.3. Present study

To fill this gap in the literature we used two short-term relaxation interventions (nature video and paced breathing) and tested their effect on psychological and physiological relaxation in BPD patients and HC. We employed the same study design that we implemented previously to investigate the effects of ELA on the psychophysiological relaxation response in a healthy sample [38]. The design and hypotheses were registered at the Open Science Framework before data analyses (https://osf.io/jsrze). As an index for physiological relaxation, we chose the vagally-mediated HRV parameter root mean square of successive differences (RMSSD), which represents PNS activity independent of breathing cycle [22,23]. The psychological relaxation response was assessed using the Relaxation State Questionnaire [27], which successfully detects short-term changes in subjective relaxation. Both, the BPD patients and the HC group underwent a paced breathing exercise and viewed a 360° nature video as relaxation interventions on two separate sessions. We chose to assess two interventions to be able to reveal different mechanisms behind their effectiveness, if present. Since we found ELA to blunt the relaxation response in healthy participants in a previous study [38] we assessed ELA in this sample as well, using the Childhood Trauma Questionnaire [39] and the Parental Bonding Instrument [40].

We hypothesized an increase in psychological and physiological relaxation in response to the breathing exercise for BPD patients and HC, with an overall lower HRV in the BPD group compared to the HC group. For the nature video, we expected an increase in both relaxation markers only in the HC group, expecting a blunted relaxation response in BPD patients to a virtual nature stimulus, similar to the effect of depression [37].

2. Methods

2.1. Participants

We invited BPD patients at the local psychiatric clinic (Centre for Psychiatry Reichenau, Germany) undergoing inpatient DBT treatment. We chose to assess only female patients for feasibility reasons since the majority of BPD patients are female [41], and sex affects HRV [23]. Patients were only invited if the treating psychotherapist deemed the patient fit enough for participation in the study. Patients were informed that participating in the study was voluntary, not part of the inpatient treatment, and refusal would have no consequences on their stay at the ward. Both sessions of the within-subjects design took place between November 2022 and August 2023. A total of 24 patients participated in the study. Four patients were excluded (only taking part in one session, getting dizzy when using VR glasses, technical difficulties, having a cardiac pacemaker), leaving a sample of 20 BPD patients (age_{mean} = 23.75 ± 4.39). The HC sample was a selected subset from a bigger sample of 103 subjects (65 women and 38 men), which we had previously tested to investigate the effects of ELA on the relaxation response in healthy participants [38]. Since we had employed the same study design as in the present study, we were able to select 22 female participants (age_{mean} = 22.68 ± 2.68) as HC from this previous sample [38] according to age and Body Mass Index (BMI) to be similar to the BPD patients, see Table 1 for a detailed description of sample characteristics. For both samples, the inclusion criteria were: being fluent in German, being physically healthy (especially no diabetes, epilepsy, or heart diseases), with a BMI between 18.5 and 29.9. While there were stricter

Table 1
Sample characteristics ($N = 42$; values present mean and *SD*, or number of cases).

Total ($N = 42$)	BPD $n = 20$ (47.62 %)	HC $n = 22$ (52.38 %)	*p value*
	$M \pm SD$	$M \pm SD$	
Age (in years)	23.75 ± 4.39	22.68 ± 2.68	0.18
BMI (in kg/m^2)	22.28 ± 2.63	24.51 ± 2.54	<0.001
Nicotine	6.15 ± 6.10	1.14 ± 3.90	<0.001
Alcohol	3.95 ± 4.21	5.41 ± 2.87	0.05
Education			
Secondary School	$n = 2$ (10.00 %)	$n = 0$	
Middle School	$n = 3$ (15.00 %)	$n = 0$	
High School Diploma	$n = 8$ (40.00 %)	$n = 18$ (81.80 %)	
Apprenticeship	$n = 5$ (25.00 %)	$n = 1$ (4.50 %)	
Bachelor	$n = 2$ (10.00 %)	$n = 3$ (13.60 %)	
Medication			
Antidepressant	$n = 3$	$n = 0$	
Neuroleptic	$n = 2$	$n = 0$	
Oral contraceptive	$n = 0$	$n = 1$	
Depressive Symptoms (BDI)	27.00 ± 8.14	6.55 ± 4.74	<0.001
Parental Bonding (PBI)			
No father figure	$n = 5$	$n = 1$	<0.001
Paternal care	15.13 ± 10.97[1]	24.10 ± 7.76[2]	<0.001
Paternal overprotection	16.33 ± 10.52[1]	8.81 ± 7.01[2]	<0.001
No mother figure	$n = 0$	n = 0	<0.001
Maternal care	16.15 ± 9.02	28.77 ± 7.49	<0.001
Maternal overprotection	18.10 ± 10.36	11.68 ± 7.81	0.002
Childhood Trauma (CTQ)			
Emotional abuse	16.73 ± 6.11	9.09 ± 4.36	<0.001
Physical abuse	9.25 ± 6.14	5.77 ± 1.88	<0.001
Sexual abuse	9.95 ± 5.54	5.41 ± 1.39	<0.001
Emotional neglect	16.17 ± 6.78	8.68 ± 3.30	<0.001
Physical neglect	9.68 ± 4.03	6.81 ± 1.99	<0.001

Notes. BPD = patients with borderline personality disorder, HC = healthy controls, BMI = Body Mass Index; Nicotine = cigarettes smoked per day; Alcohol = alcoholic beverages consumed per week, patients referred to consumption behavior outside of inpatient treatment; BDI = Beck Depression Inventory; scores for father and mother care and overprotection were collected with the Parental Bonding Instrument; scores for emotional abuse, physical abuse, sexual abuse, emotional neglect, and physical neglect were collected with the Childhood Trauma Questionnaire.

[1] Data collected from $n = 15$ participants.

[2] Data collected from $n = 21$ participants.

rules in place for the healthy sample (no caffeine, alcohol, and nicotine four hours before the experiment, no intensive sports 12 h before the experiment) we chose not to implement the same restrictions on the BPD sample, since sport is part of the treatment plan and asking patients to refrain from smoking probably would have led to significant difficulties in recruitment. However, none of the patients consumed alcohol during their stay at the ward, as this is a prerequisite for the inpatient DBT treatment. Inclusion criteria were implemented to limit modulating effects on HRV [22,23,42] and to minimize the potential risks of using VR glasses since the use can trigger epileptic seizures [43]. All patients who were prescribed antidepressants were taking selective serotonin reuptake inhibitors, which have a weak association with lower baseline HRV that is postulated to be caused by other factors than the medication [44]. Similarly, neuroleptics were not found to be associated with changes in HRV [45]. The study procedure was approved by the Ethics Committee of the University of Konstanz ('28/2022' approved on 27.06.2022) and followed the guidelines of the Declaration of Helsinki.

2.2. Study procedure

This study was a within-subjects design, with all participants undergoing both conditions five to nine days apart. The order of the conditions was randomized using a coin toss. With this study design, we aimed to follow the Vagal Thank Theory [46], which postulates that it is important to measure physiological markers at baseline (Resting), during the intervention (Reactivity), and afterward (Recovery), to assess the complete response dynamic induced by the interventions (see Fig. 1 for a graphical representation of the study procedure). At the first session, participants provided written informed consent. Subsequently, both appointments followed the same procedure starting with participants applying the sensor to measure their cardiac activity. Participants were given ten minutes of either drawing a mandala or reading a non-arousing local newspaper to allow their heart activity to arrive at baseline level before a three-minute baseline was recorded (Resting). During the baseline participants watched a fixation cross, sitting with feet on the floor to make baseline and interventions as comparable as possible, as recommended when assessing HRV [22]. Directly after that, they rated their psychological relaxation for the first time (Relaxation Rating 1), followed by the intervention of either watching a 360° nature video with virtual reality (VR) glasses or doing a paced breathing exercise for seven minutes (Reactivity). After the intervention, they rated their psychological relaxation a second time (Relaxation Rating 2) before being given a ten-minute period to read or draw (Recovery). The sessions ended with different questionnaires being assessed (e.g., sociodemographic questionnaire, ELA questionnaires).

2.3. Relaxation interventions

Both interventions were already implemented in a previous study to investigate the effects of ELA on the relaxation response in a healthy sample [38], see Fig. 2 for a depiction of both interventions. During the VR nature video intervention ("nature") participants watched a 360° video recorded by us in the Swiss Alps near Davos (camera: Insta360 Pro 2, Insta360, California, USA). We used VR glasses (Meta Quest 2; Meta Platforms Inc., California, USA) to present the video to increase the sense of presence in the virtual environment to promote the relaxing effect of the video [34,35]. The video included the recorded sounds of a running river, wind, and birds. With sounds and showing predominantly green mountains and a flowing river this video meets the criteria for a nature environment that can be perceived as relaxing [47,48]. During the breathing exercise ("breath") we employed the app "Awesome Breathing: Pacer Timer"[49] to guide participants to breathe six breaths per minute (four seconds inhale, six seconds exhale), a rhythm that was found to successfully induce psychological and physiological relaxation [25,50].

2.4. Measurements

2.4.1. Physiological relaxation

We chose to assess RMSSD as an index of vagally-mediated HRV, since it was shown to adequately represent PNS activity independent of breathing cycle [22,23]. All HRV markers are based on the beat-to-beat variance of R-R intervals, RMSSD is allocated to the time-domain markers and calculated based on the time between two peaks of a heart rhythm [21–23]. Initially, we planned to calculate the frequency-domain marker high-frequency HRV as well, however, since it is strongly influenced by breathing depth and rhythm [19,23] we chose to solely focus on RMSSD. While intervals of five minutes are considered to be the gold standard when calculating RMSSD, shorter intervals have been shown to yield valid results as well [51]. To keep the experiment as short as possible, we chose to calculate three-minute intervals. To record heart activity, participants applied a Polar H10 Sensor (Polar Electro GmbH Deutschland, Germany) with a chest strap. To record the data from the sensor, we used the app "HRV Logger" [52] running on an iPad that connected to the sensor via Bluetooth, where the data was stored until preprocessing.

2.4.2. Psychological relaxation

We assessed psychological relaxation using the Relaxation State Questionnaire (RSQ; Steghaus & Poth, [27]) directly before and after the

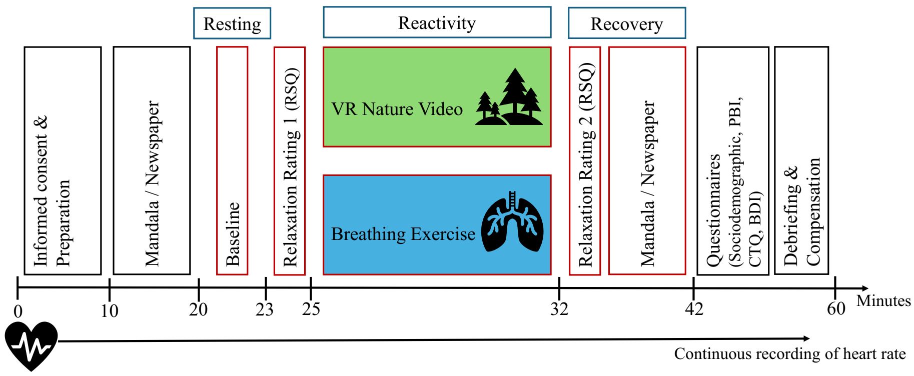

Fig. 1. Graphical representation of the study procedure. Red frames indicate which experimental phases were included in the HRV analyses, blue frames indicate the phases according to the Vagal Tank Theory [46]. Figure based on Fig. 1 in [38]. Notes: RSQ = Relaxation State Questionaire; VR = virtual reality; PBI = Parental Bonding Instrument; CTQ = Childhood Trauma Questionnaire; BDI = Becks Depression Inventory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A. Nature video. B. Paced breathing exercise.

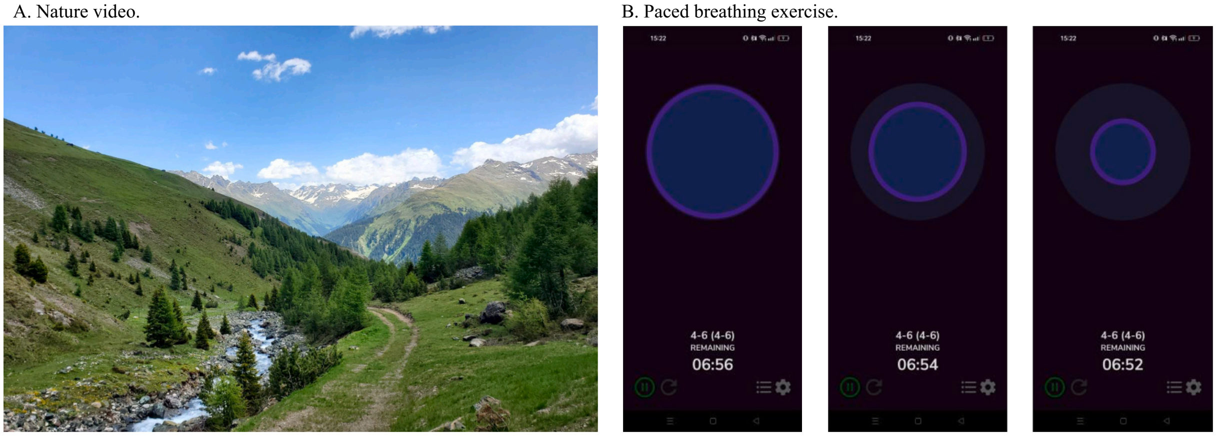

Fig. 2. Depictions of both relaxation interventions.

interventions to measure changes in psychological relaxation. The RSQ was shown to have good reliability (ω = 0.83; Steghaus & Poth, [27]) and consists of 10 statements about physical (e.g., "my muscles feel loose") and mental ("right now, I am completely calm") relaxation. Agreement to each statement can be given on a five-point Likert scale. Those values are summed up to the RSQ score (min = 5, max = 50) with higher values indicating higher levels of psychological relaxation.

2.4.3. Early life adversity

Since there is no universally accepted definition of ELA there is a great variability in assessing it i [53]. Here, we chose to implement measurement via two questionnaires to cover different concepts of ELA. The Childhood Trauma Questionnaire (CTQ; original: Bernstein et al., [39]; German translation: Wingenfeld et al., [54], Cronbach's α = 0.94) assesses different types of childhood trauma on the subscales of emotional abuse, emotional neglect, physical abuse, physical neglect, and sexual abuse with five items each for the first sixteen years of life. Higher scores indicate higher levels of abuse or neglect, therefore indicating greater exposure to ELA (min = 5, max = 25). The Parental Bonding Instrument (PBI; original: Parker et al., [40]; German translation: Benz et al., [55]; Cronbach's α = 0.86 to 0.95) focuses on parental caregiving behavior, separated for maternal and paternal behavior. For each parent participants answer items on the two subscales "care" (e.g., "spoke to me in a warm and friendly voice"; min. 0, max. 36) and "overprotection"(e.g., "tried to control everything"; min. 0, max. 39), with lower levels of care and higher levels of overprotection indicating ELA. In addition to the scores for each subscale, we combined them to an overall parenting style for each parent according to thresholds reported previously (affectionless constraint: low care and high overprotection; affectionate control: high care and high overprotection; neglectful parenting: low care and low overprotection; optimal parenting: high care and low overprotection; Parker et al., [40]).

2.4.4. BPD related covariates

All BPD participants were assessed during their inpatient treatment at the Center for Psychiatry Reichenau, Germany while being enrolled in the DBT program for eight to ten weeks. We included the number of weeks that they had already spent on the DBT ward as a possible covariate during data analysis. Part of the inpatient treatment included filling out the short version of the Borderline Symptom List (BSL-23; Wolf et al., [56]; Cronbach's α = 0.94 to 0.97) every week to assess the severity of BPD-related symptoms (e.g., "In the course of the last week I experienced stressful inner tension") and self-harm behavior (e.g., "During the last week I hurt myself by cutting, burning, strangling headbanging, etc."). For each of the 23 statements concerning symptoms, patients could rate their agreement on a five-point Likert scale, which was summed up to a total BSL score (min. 0, max. 92), with higher values indicating greater severity of symptoms. Since the severity of BPD symptomatology was found to influence HRV [9,10] we collected the questionnaires filled out during the week in which data collection took place. We assessed if additional psychological diagnoses were reported via self-report answers and based on the official patient file (yes or no). Sixteen of the 20 included patients reported comorbidities, while the clinical patient files indicated comorbidities for 11 patients. Due to the discrepancy between self-report and patient file, we included both in the data analyses. Depression was the most common comorbidity in both datasets.

2.4.5. Covariates

Since age, BMI, sleep (hours slept in the previous night), smoking (cigarettes per day), and alcohol consumption (glasses of alcoholic beverages per week) influence HRV [21,22] we assessed them via self-report questionnaires. Further, depressive symptoms were assessed via the Beck Depression Inventory (BDI-II; original: Beck et al., [57]; German translation: Pietsch et al., [58]), as they have been shown to affect HRV as well [59,60].

2.4.6. Data analysis plan

All steps of the data preprocessing and analysis were executed with R [61] using the interface R Studio [62]. After preprocessing the raw signal, RMSSD was calculated using the package "RHRV" [63]. We calculated six three-minute intervals of interest: one during the baseline, two during the intervention, and three following the intervention. Before psychological and physiological relaxation data was entered into data analysis we employed winsorizing to minimize the influence of extreme outliers (defined as ±3*SD* from the mean of the sample).

We calculated multilevel models using the package "multilevel" [64] since data was nested (changes over time nested in participants, nested in groups [HC or BPD], nested in conditions [nature or breath]). We calculated the basic model for RMSSD and RSQ scores as outcome variables, investigating which intercept and time trend fitted the data best before adding group and condition as predictors. As the last step, the potential covariates (sleep duration in the previous night, age, BDI, BMI, alcoholic beverages consumed per week, cigarettes consumed per day) were added to each model. For the models including the BPD patients only, the additional covariates BSL score, time spent at the ward, comorbidity based on self-report, and comorbidity based on patient file were included. Only covariates reaching significance are reported. Model fit was calculated using the maximum likelihood method and model fits of nested models were compared using Chi-squared test. Since higher scores of ELA are strongly correlated with psychopathology and our group tested the link between ELA and the relaxation response in a healthy sample in another study [38], we investigated the effects of ELA on the psychophysiological relaxation response only in the BPD subsample. As markers of ELA, we used the scores of the CTQ subscales emotional abuse, physical abuse, sexual abuse, physical neglect, and emotional neglect, as well as maternal and paternal care and overprotection in addition to maternal and paternal parenting style as derived from the PBI. Graphs were created using "ggpubr" [65].

3. Results

3.1. Psychological relaxation (RSQ)

3.1.1. Main analyses

The basic model with the best fit for RSQ scores as outcome included a random intercept and a fixed linear slope per participant, with the Inter-Class Correlation Coefficient (ICC) indicating that 66.46 % of the variability within the dataset can be attributed to interindividual differences. Adding a main effect of group (BPD or HC) and a main effect of condition (nature or breath) significantly improved the model fit, none of the interactions reached significance. Of the added covariates only the main effect of BDI significantly improved the model fit. The final model included a random intercept, a fixed linear slope indicating the main effect of time and the main effects of group, condition, and BDI. Belonging to the HC group as well as the nature condition were associated with higher RSQ values, while higher BDI scores were linked to lower RSQ values (see Table 2 for the parameters of the final model). Fig. 3 depicts changes in RSQ scores over time.

3.1.2. Additional analyses: Effect of ELA in BPD patients

The basic model which included only the BPD patients included a random intercept (β = 52.55, $p < .001$, 95 % CI [30.38, 74.72]) and a fixed linear slope (β = 3.40, $p < .001$, 95 % CI [2.15, 4.65]), ICC: 28.10 %). Adding the PBI and CTQ scores to the basic model revealed a significant main effect of sexual abuse (β = −2.50, p = .008, 95 % CI [−4.26, −0.74]), a main effect of self-reported comorbidity (yes or no; β = −25.33, p = .04, 95 % CI [−48.65, −2.01]) and a significant interaction of sexual abuse and self-reported comorbidity (β = 2.30, p = .014, 95 % CI [0.53, 4.07]) with marginal $R^2 = 0.427$, conditional $R^2 = 0.521$ and ICC = 0.16 for the final model. Higher scores of sexual abuse and having self-reported comorbidity were associated with lower RSQ scores. For the interaction effect, post-hoc tests revealed higher sexual abuse scores in the group without self-reported comorbidity. Within the subgroup with self-reported comorbidity, higher sexual abuse scores were associated with lower RSQ scores. However, these results should be interpreted with caution since only four patients did not indicate self-reported comorbidities.

Table 2
Parameters of the final model for RSQ in the total sample.

Predictors	*Estimates*	*CI (95 %)*	*p value*
(Intercept)	28.70	25.11–32.28	<0.001
time	2.61	1.59–3.62	<0.001
group	6.58	3.54–9.62	<0.001
condition	1.04	0.02–2.05	0.049
BDI	−0.15	−0.27 – -0.02	0.027
Random effects			
σ^2	11.03		
τ_{00}	4.08		
N	42		
Observations	168		
Marginal R^2	0.70		

3.2. Physiological relaxation (RMSSD)

3.2.1. Main analyses

The basic model with RMSSD as criterion variable included a random intercept per participant (ICC of 72.57 %) and a fixed linear slope, indicating a significant main effect of time. The main effect of group and the main effect of condition significantly improved the model fit, and no interaction reached statistical significance. The HC group was associated with higher RMSSD values, as was the nature.

condition. Concerning the covariates, only the main effect of hours slept in the previous night reached significance, indicating lower values of RMSSD were unexpectedly associated with more hours slept in the previous night (see Table 3). Changes in RMMSD over time are depicted in Fig. 4.

3.2.2. Additional analyses: effect of ELA in BPD patients

Investigating the influence of the CTQ subscales on RMSSD in the BPD subsample, we found no significant improvement of the model fit by adding a random or fixed time effect, leaving the basic model with the random intercept (β = 21.63, p = .088, 95 % CI [−2.99, 46.25]) and an ICC of 60.85 %. Of the CTQ subscales only the main effect of physical neglect significantly improved the model fit (β = 3.37, $p < .001$, 95 % CI [1.74, 5.01]), indicating higher scores of physical neglect to be associated with higher RMSSD scores, in contrast to our expectations. Of the covariates adding self-reported comorbidity (β = 14.15, p = .076, 95 % CI [−1.48, 29.77]) and hours slept in the previous night (β = −3.96, $p <$ .001, 95 % CI [−5.89, −2.03]) significantly improved the model fit, even if the main effect of self-reported comorbidity did not reach significance in the final model. More hours of sleep were associated with lower RMSSD values. Marginal R^2 for the final model was 0.659.

For the PBI subscales, we found only the main effect of maternal care to significantly improve the model fit (β = −0.70, p = .046, 95 % CI [−1.38, −0.02]), indicating lower RMSSD scores to be associated with

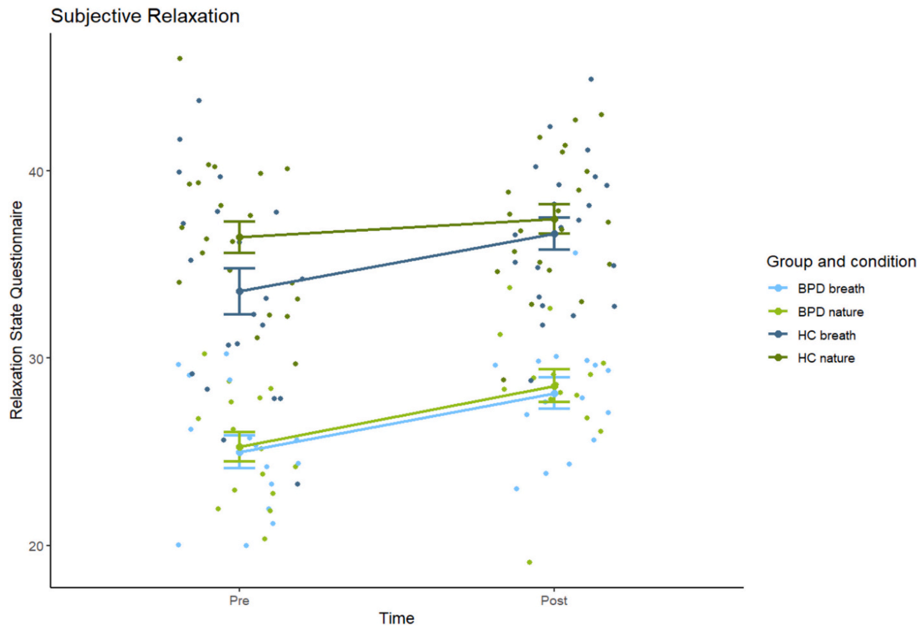

Fig. 3. Graphical representation of changes in total RSQ scores for both conditions (nature and breath) in both groups (BPD and HC) with individual data points. Error bars depict the standard error.

Table 3
Parameters of the final model for RMSSD in the total sample.

Predictors	*Estimates*	*CI*	*p value*
(Intercept)	46.69	34.88–58.50	<0.001
time	−0.78	−1.35 – -0.21	0.008
group [HC]	15.04	4.02–26.07	0.009
condition [nature]	5.13	3.19–7.08	<0.001
sleep hours current	−1.31	−2.58 – -0.05	0.043
Random effects			
σ^2	123.03		
τ_{00}	300.22		
N	42		
Observations	504		
Marginal R^2	0.34		

higher maternal care. Of the covariates, the main effects of BDI (β = −1.15, p = .006, 95 % CI [−1.91, −0.39]) and hours slept in the previous night (β = −4.07, p < .001, 95 % CI [−6.04, −2.09]) both increased the model fit significantly, with marginal R^2 = 0.513 for the final model. Higher scores of BDI and a greater number of hours slept in the previous night were associated with lower RMSSD scores.

4. Discussion

We assessed the psychophysiological relaxation response induced by a paced breathing intervention and a virtual reality nature video in patients with borderline personality disorder (BPD) and healthy controls (HC) to investigate a possible dysregulation of the relaxation response associated with BPD. We found an increase in psychological relaxation induced by both interventions, with higher psychological relaxation values in the HC group before and after both interventions. Depressive symptoms were associated with lower psychological relaxation. For physiological relaxation, we found a successful increase in vagally mediated HRV induced by the interventions in both groups. Additionally, we found higher HRV scores in the HC group during the whole experiment, and a negative effect of hours slept during the previous night on overall HRV level. These findings only partly support our hypotheses. While we found lower HRV scores in the BPD patients at all time points, we did not find differences in the relaxation response induced by the interventions.

Especially the link between more hours slept during the previous night and overall lower HRV level is noteworthy, since it is counterintuitive, with previous studies finding lower vagally mediated HRV associated with less hours slept during the last night [66–68]. However, those studies manipulated sleep duration [67,68], measured HRV after multiple nights of partial sleep deprivation [67], or measured the sleep duration with actigraphy [66,67]. or polysomnography [68]. Since we did not manipulate sleep duration, the effects observed in previous studies might be specific to situations where sleep duration is intentionally altered. Furthermore, we assessed sleep duration through self-reporting, so participants may not have accurately indicated their sleep duration. Additionally, since we did not screen for sleep duration, the greatest variability of baseline RMSSD values was linked to the middle range of sleep duration, distorting the association between RMSSD and sleep duration. Besides, there are many other factors despite sleep influencing baseline HRV [21–23].

These results suggest overall lower levels of psychophysiological relaxation parameters in BPD patients while the relaxation response appears comparable across groups. For psychological relaxation markers, previous studies found greater self-reported tension, negative affect, and less positive affect in BPD patients at baseline compared to HC [69,70]. This aligns with our finding of lower baseline subjective relaxation levels. The results for physiological relaxation show overall higher scores in the HC group but no significant differences in the relaxation response induced by the relaxation interventions. These results align with previous studies that found lower baseline HRV in BPD patients than HCs [8,71]. This not only fortifies reduced baseline PNS activity as part of the biopsychosocial model of BPD but also expands the disorder-specific knowledge, showing that the relaxation response seems to be comparable to HCs. This is noteworthy, as baseline PNS activity has been discussed as a marker of adaptability, emotional and cognitive flexibility, and being associated with executive functions and emotion regulation, which are impaired in BPD patients [72,73]. An intact relaxation response is an important resource and could allow interventions to be based upon. For example, future interventions could specifically target the relaxation response with relaxation training employing paced breathing to increase PNS activity. However, whether

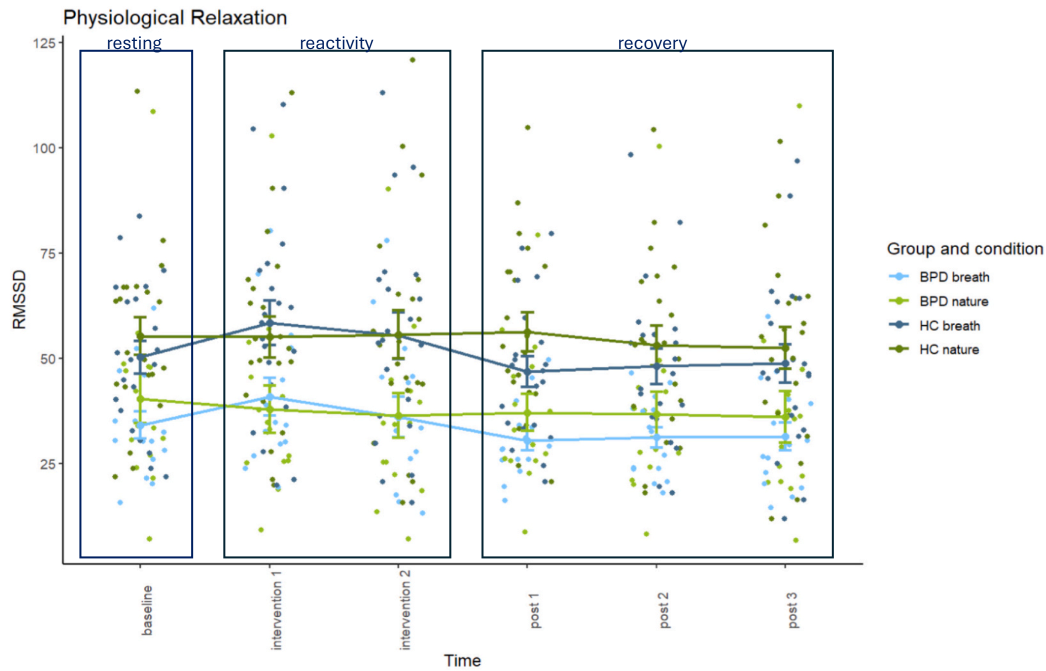

Fig. 4. Graphical representation of changes in RMSSD for both conditions (nature and breath) in both groups (BPD and HC) with individual data points. Error bars depict the standard error. Dark blue frames indicate the phases according to the Vagal Tank Theory [46]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

this would affect PNS activity not only during the intervention but also at baseline has yet to be investigated.

The driving factor of the differences in psychophysiological relaxation between BPD patients and HC seemed to be the overall differences in RMSSD levels, putting patients 15 to 20 points below HC across the entire experiment. This raises the question where those baseline differences come from, and allows future interventions to focus on improving baseline levels of BPD patients. Group interventions like a psychoeducational group and metacognitive training were found to successfully reduce baseline levels of self-reported tension, which can be interpreted as a psychological marker associated with relaxation [74,75]. To our knowledge, there is no study investigating interventions to increase baseline HRV in BPD patients at this point. However, strategies based on acceptance of emotions were found to increase HRV in BPD patients during social rejection, emphasizing that developing adaptive emotion regulation strategies should be an integral part of BPD treatment [76] which could increase baseline HRV over time. Looking at other psychopathologies, biofeedback was found to increase vagally-mediated HRV in patients with depression, either as training over four weeks without additional psychotherapy [77] or in addition to psychotherapy [78]. Similar effects were found for psychotherapy combined with breathing exercises [79]. While psychotherapy alone did not increase HRV in patients with major depressive disorder [78,80], psychotherapy was found to increase HRV in panic disorder patients [81]. These heterogeneous findings indicate disorder-specific effects of interventions, limiting the generalizability across different psychopathologies. A first study investigating the effects of a DBT intervention in adolescents with BPD found no overall changes in HRV associated with treatment, however, an increase in HRV was associated with a decrease in BPD symptomatology [82].

For healthy participants, various interventions have been shown to improve baseline HRV, for example, mindfulness training [83] and high-intensity interval training [84]. Whether these interventions are similarly effective in BPD patients has not been investigated so far. Successfully increasing baseline HRV could be beneficial for BPD patients since previous studies found baseline vagally-mediated HRV to be a predictor for clinical outcomes in BPD patients [82,85].

4.1. Associations between BPD, HRV, and ELA

In a previous study, we found that presence of ELA is associated with a blunted relaxation response in healthy participants [38], therefore we further investigated the possible effect of ELA on the psychophysiological relaxation response of BPD patients using the CTQ and PBI. Of the CTQ subscales, only physical neglect had a significant influence on RMSSD. Contrary to previous studies [86,87] we found higher physical neglect scores associated with higher RMSSD values. Additionally, having self-reported comorbidities was associated with higher RMSSD. However, only four participants did not report comorbidities, not allowing to draw firm conclusions from this result. Of the PBI subscales only maternal care significantly influenced RMSSD, being associated with lower RMSSD values. Again this contradicts previous results where higher care was associated with higher HRV [36].

While several possible explanations exist for these unexpected associations between ELA and HRV, the following explanatory approaches are speculative and warrant a thorough investigation. A closer look at the individual data points revealed noticeable outliers with RMSSD values above the mean. Such values after winsorizing could indicate undiscovered artifacts or other distortions during data collection. Additionally, there are several other factors, aside from ELA, that influence baseline HRV values [21–23]. According to the Polyvagal Theory [88], high values of vagally mediated HRV and an active PNS might also signal a shift toward a freeze response triggered by a threat, rather than accurately indicating relaxation [20,88]. Additionally, ELA was assessed retrospectively using self-report questionnaires, which may be distorted by memory effects or the negativity bias often associated with BPD. [89].

To date, few studies investigated the effects of ELA on HRV in BPD patients. For example, it was found that the severity of ELA is associated with lower vagally-mediated HRV and longer response times during an emotional working memory task [90]. However, in adolescent BPD patients, ELA did not significantly affect HRV, while still being significantly associated with clinical improvement over time (Sigrist et al., 2021; Weise et al., 2021). While these findings are inconsistent and warrant a closer investigation in the future, a close relationship between ELA and BPD has been shown consistently, with BPD patients being 13.91 times more likely to have experienced ELA than healthy participants and 3.15 times more likely than patients with other mental disorders [91]. This accords with the Biopsychosocial Model, attributing ELA an important role in the development of BPD. The biological factors associated with BPD indicated heightened impulsivity and intensity of emotions (e.g., neurological conspicuous characteristics in the prefrontal cortex and amygdala [3,6]). This biological vulnerability might explain why the association between ELA and BPD seems to be even stronger than the association between ELA and other mental diseases [91]. Experiencing ELA and especially an invalidating environment neglects to teach children how to detect and regulate their own emotions. In turn, this might lead to social difficulties and a lack of adequate emotion regulation strategies not only during childhood but also later in life [4,6]. Additionally, BPD patients show an increased focus on unpleasant emotions such as fear or anger, not only in themselves but also in others. Therefore the detection of emotions in their counterparts is shifted toward negative emotions (negativity bias; Domes et al., 2009). This might contribute to an increase in arousal and inner tension [92] with increased reactivity to stress and negative emotions and difficulties in returning to baseline afterward [4,6,93]. These findings overall indicate that the stress response seems to be altered in BPD patients. Expanding these findings, the results from the current study show that the response to relaxation interventions appears similar to those of healthy participants. Therefore, BPD seems to be associated with differences in ANS activity at baseline and during the stress response, but not with altered relaxation responses. Whether the detected changes in the ANS, namely the reduced PNS activity at baseline, is a consequence of BPD or if it is a risk factor present before the development of BPD is still unclear. Future longitudinal studies are needed to further investigate this question.

4.2. Strengths and limitations

The generalizability of our results is limited since we assessed only female participants. Nevertheless, we chose to accept this limitation because we also limited the confounding effects of sex on HRV. Structured diagnostics was not part of this study. Nonetheless, the diagnosis was considered confirmed by the treatment team in all patients. The sample consisted of young adults (23.75 ± 4.39 years for BPD patients and 22.68 ± 2.68 years for HC) since at this age most patients start their treatment for BPD. However, a previous study found the influence of ELA on HRV to increase with age (Sigrist et al., 2021), emphasizing that age is an important factor affecting HRV and should therefore be taken into account. While we imposed additional prerequisites in the HC group (no caffeine, alcohol, and nicotine four hours before the experiment, and no intensive sports 12 h before the experiment), we refrained from implementing them in the BPD group to achieve a higher number of volunteers for the study and to avoid conflicts with the individual treatment plans. During the paced breathing intervention, we did not assess the actual breathing rhythm which would have granted us additional insight, especially concerning the ability of participants to follow the rhythm given during the paced breathing intervention. Therefore it is possible that not all participants successfully followed the breathing rhythm for the duration of the intervention. Despite these limitations, we are convinced these results are noteworthy since this study also has considerable strengths. We performed an a priori power analysis to determine which sample size was required to detect a small effect (effect size $f = 0.2$) with a power of 0.9 using the tool G*Power [94]. According to this calculation, a total sample size of 36 participants, separated into two groups, would have been sufficient. To account for potential dropouts and in accordance with recommendations to assess 20 participants per cell when measuring HRV [22], we opted to include a larger sample size. Looking at the study design, we conducted a well-controlled study that conformed with the Vagal Tank Theory [46], enabling us to assess the HRV at rest, in response to the relaxation intervention and during recovery. We also followed the recommendations by Quintana and Heathers [22], employing a counterbalanced within-subjects design, including an adequate baseline and limiting possible confounding factors, while still employing a naturalistic setting. We recruited a realistic sample of BPD patients, avoiding a high selectivity by including patients with comorbid mental disorders. Therefore the results showing an intact psychophysiological relaxation response in realistic DBT patients are especially impactful for developing future interventions.

4.3. Future research

Since we found reduced overall psychophysiological relaxation markers in BPD patients but no differences in the relaxation response compared to HC future studies should focus on interventions to improve baseline levels of psychophysiological relaxation. As mentioned above, possible interventions include biofeedback training, mindfulness training, breathing exercises, high-intensity interval training, and psychotherapy with a focus on emotion regulation strategies. While there seems to be an association between ELA, BPD, and HRV the exact mechanisms not only in the development of BPD but also in the effect those factors have on the relaxation response are still unclear. Future studies are needed to add additional insights into this complex relationship. One potential avenue for future research would be to replicate the present study while addressing several of the aforementioned limitations. This could include recruiting a more diverse sample (e.g., including both male and female participants as well as older adults), enhancing the relaxation interventions (e.g., by personalizing the nature video), and refining methodological procedures (e.g., applying experimental constraints consistently across BPD and HC groups, and monitoring respiratory patterns). Since we tested the relaxation response without a previous stressor future studies should also investigate possible benefits for BPD patients to apply relaxation techniques like breathing exercises to return to baseline level after stressful situations, especially in light of findings indicating that effective recovery from stressors is impaired in BPD. A successful implementation of relaxation interventions could be especially important for BPD patients to reduce inner tension without resorting to dysfunctional strategies like suicidal behavior, non-suicidal self-harm, or impulsive behavior. Additionally, future research should investigate the potential impact of post-traumatic stress disorder (PTSD) as a comorbid diagnosis that may further impact the dysregulation of the relaxation response in individuals with BPD. Due to only two participants in our sample concurrently diagnosed with PTSD, this interaction could, however, not be adequately examined in the present study.

4.4. Conclusion

To our knowledge, this is the first study to investigate a possible dysregulation of the relaxation response associated with BPD. While we found no differences in the psychophysiological relaxation response between BPD patients and HC, we found significant differences in overall psychophysiological relaxation levels, confirming previous results. This indicates that BPD patients may not lose their ability to relax when exposed to a relaxation intervention, but instead exhibit overall lower relaxation levels. Future studies and treatment interventions should thus focus on increasing the baseline levels of psychophysiological relaxation in BPD patients. This would help to deepen our understanding of possible psychophysiological mechanisms contributing to the development of BPD. A better understanding of these mechanisms would allow for steadily improving the treatment to minimize the suffering of persons affected and their social environment, therefore increasing health and well-being.

CRediT authorship contribution statement

Raphaela J. Gaertner: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elea S.C. Klink:** Writing – review & editing. **Annika B.E. Benz:** Writing – review & editing. **Bernadette F. Denk:** Writing – review & editing. **Maria Meier:** Writing – review & editing. **Stella Wienhold:** Writing – review & editing. **Nina Volkmer:** Writing – review & editing. **Katharina E. Kossmann:** Writing – review & editing. **Jens C. Pruessner:** Writing – review & editing, Supervision, Resources, Methodology, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare no competing interests.

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References

[1] World Health Organization. The ICD-10 classification of mental and behavioural disorders: Clinical descriptions and diagnostic guidelinesvol. 1. World Health Organization; 1992.
[2] DGPPN e. V. S3-Leitlinie Borderline-Persönlichkeitsstörung. 1.0. DGPPN e. V; 2022.
[3] Leichsenring F, Heim N, Leweke F, Spitzer C, Steinert C, Kernberg OF. Borderline personality disorder: a review. JAMA 2023;329:670–9.
[4] Linehan MM. Cognitive-behavioral treatment of borderline personality disorder. New York: Guilford; 1993.
[5] Carpenter RW, Trull TJ. Components of emotion dysregulation in borderline personality disorder: a review. Curr Psychiatry Rep 2013;15:335. https://doi.org/10.1007/s11920-012-0335-2.
[6] Crowell SE, Beauchaine TP, Linehan MM. A biosocial developmental model of borderline personality: elaborating and extending Linehan's theory. Psychol Bull 2009;135:495.
[7] Brown RL, Chen MA, Paoletti J, Dicker EE, Wu-Chung EL, LeRoy AS, et al. Emotion regulation, parasympathetic function, and psychological well-being. Front Psychol 2022;13:879166. https://doi.org/10.3389/fpsyg.2022.879166.
[8] Koenig J, Kemp AH, Feeling NR, Thayer JF, Kaess M. Resting state vagal tone in borderline personality disorder: a meta-analysis. Prog Neuropsychopharmacol Biol Psychiatry 2016;64:18–26.
[9] Geiss L, Beck B, Hitzl W, Hillemacher T, Hoesl KM. Cardiovascular autonomic modulation during metronomic breathing and stress exposure in patients with borderline personality disorder. Neuropsychobiology 2021;80:359–73.
[10] Koenig J, Rinnewitz L, Parzer P, Resch F, Thayer JF, Kaess M. Resting cardiac function in adolescent non-suicidal self-injury: the impact of borderline personality disorder symptoms and psychosocial functioning. Psychiatry Res 2017;248:117–20.
[11] Berman IS, McLaughlin KA, Tottenham N, Godfrey K, Seeman T, Loucks E, et al. Measuring early life adversity: a dimensional approach. Dev Psychopathol 2022;34:499–511.
[12] Smith KE, Pollak SD. Rethinking concepts and categories for understanding the neurodevelopmental effects of childhood adversity. Perspect Psychol Sci 2021;16:67–93.
[13] Duffy KA, McLaughlin KA, Green PA. Early life adversity and health-risk behaviors: proposed psychological and neural mechanisms. Ann N Y Acad Sci 2018;1428:151–69.
[14] Porter C, Palmier-Claus J, Branitsky A, Mansell W, Warwick H, Varese F. Childhood adversity and borderline personality disorder: a meta-analysis. Acta Psychiatr Scand 2020;141:6–20.
[15] Bloom JM, Woodward EN, Susmaras T, Pantalone DW. Use of dialectical behavior therapy in inpatient treatment of borderline personality disorder: a systematic review. Psychiatr Serv 2012;63:881–8.
[16] Linehan MM, Dexter-Mazza ET. Dialectical behavior therapy for borderline personality disorder. Clin Handb Psychol Disord Step 2008;4:365–420.
[17] Meier M, Unternaehrer E, Dimitroff SJ, Benz AB, Bentele UU, Schorpp SM, et al. Standardized massage interventions as protocols for the induction of psychophysiological relaxation in the laboratory: a block randomized, controlled trial. Sci Rep 2020;10:1–12.
[18] Bigham E, McDannel L, Luciano I, Salgado-Lopez G. Effect of a brief guided imagery on stress. Biofeedback 2014;42:28–35.
[19] Zaccaro A, Piarulli A, Laurino M, Garbella E, Menicucci D, Neri B, et al. How breath-control can change your life: a systematic review on psycho-physiological correlates of slow breathing. Front Hum Neurosci 2018;353.
[20] Del Giudice M, Ellis BJ, Shirtcliff EA. The adaptive calibration model of stress responsivity. Neurosci Biobehav Rev 2011;35:1562–92.
[21] Acharya RU, Paul Joseph K, Kannathal N, Lim CM, Suri JS. Heart rate variability: a review. Med Biol Eng Comput 2006;44:1031–51.
[22] Quintana DS, Heathers JA. Considerations in the assessment of heart rate variability in biobehavioral research. Front Psychol 2014;5:805.
[23] Shaffer F, Ginsberg JP. An overview of heart rate variability metrics and norms. Front. Public Health 2017:258.
[24] Kromenacker BW, Sanova AA, Marcus FI, Allen JJ, Lane RD. Vagal mediation of low-frequency heart rate variability during slow yogic breathing. Psychosom Med 2018;80:581–7.
[25] Szulczewski MT. Training of paced breathing at 0.1 Hz improves CO2 homeostasis and relaxation during a paced breathing task. PloS One 2019;14:e0218550.
[26] Benson H. The relaxation response. New York: William Morrow & Co. Inc; 1975. p. L975.
[27] Steghaus S, Poth CH. Assessing Momentary States of Relaxation: The Relaxation State Questionnaire. 2021.
[28] Farrow MR, Washburn K. A review of field experiments on the effect of forest bathing on anxiety and heart rate variability. Glob Adv Health Med 2019;8 (2164956119848654).
[29] Gladwell VF, Brown DK, Barton JL, Tarvainen MP, Kuoppa P, Pretty J, et al. The effects of views of nature on autonomic control. Eur J Appl Physiol 2012;112:3379–86.
[30] Jo H, Song C, Miyazaki Y. Physiological benefits of viewing nature: a systematic review of indoor experiments. Int J Environ Res Public Health 2019;16:4739.
[31] Payne MD, Delphinus E. A review of the current evidence for the health benefits derived from forest bathing. Int J Health Wellness Soc 2019:9.
[32] Song C, Ikei H, Park B-J, Lee J, Kagawa T, Miyazaki Y. Psychological benefits of walking through forest areas. Int J Environ Res Public Health 2018;15:2804. https://doi.org/10.3390/ijerph15122804.
[33] Ulrich RS. Aesthetic and affective response to natural environment. Behav. nat. environ. Springer; 1983. p. 85–125.
[34] Gaertner RJ, Kossmann KE, Benz AB, Bentele UU, Meier M, Denk BF, et al. Relaxing effects of virtual environments on the autonomic nervous system indicated by heart rate variability: a systematic review. J Environ Psychol 2023:102035.
[35] Liszio S, Graf L, Masuch M. The relaxing effect of virtual nature: immersive technology provides relief in acute stress situations. Annu Rev Cyberther Telemed 2018;16:87–93.
[36] Benz AB, Gaertner RJ, Meier M, Unternaehrer E, Scharndke S, Jupe C, et al. Nature-based relaxation videos and their effect on heart rate variability. Front Psychol 2022:13.
[37] Matsui T, Kakisaka K, Shinba T. Impaired parasympathetic augmentation under relaxation in patients with depression as assessed by a novel non-contact microwave radar system. J Med Eng Technol 2016;40:15–9.
[38] Gaertner RJ, Burkart M, Richter L, Schnell P, Finkhäuser M, Klink ES, et al. Early life adversity blunts the subjective and physiological relaxation response in healthy adults. Sci Rep 2024;14:27992.
[39] Bernstein DP, Stein JA, Newcomb MD, Walker E, Pogge D, Ahluvalia T, et al. Development and validation of a brief screening version of the childhood trauma questionnaire. Child Abuse Negl 2003;27:169–90.
[40] Parker G, Tupling H, Brown LB. A parental bonding instrument. Br J Med Psychol 1979;52(1):1–10.
[41] Widiger TA, Costa PT, Association AP. Personality disorders and the five-factor model of personality. JSTOR; 2013.
[42] Quintana DS, Alvares GA, Heathers JAJ. Guidelines for reporting articles on psychiatry and heart rate variability (GRAPH): recommendations to advance research communication. Transl Psychiatry 2016;6:e803.
[43] Bureau M, Hirsch E, Vigevano F. Epilepsy and videogames. Epilepsia 2004;45:24–6.
[44] Noordam R, van den Berg ME, Niemeijer MN, Aarts N, Hofman A, Tiemeier H, et al. Antidepressants and heart-rate variability in older adults: a population-based study. Psychol Med 2016;46:1239–47.
[45] Malaspina D, Dalack G, Leitman D, Corcoran C, Amador XF, Yale S, et al. Low heart rate variability is not caused by typical neuroleptics in schizophrenia patients. CNS Spectr 2002;7:53–7.

[46] Laborde S, Mosley E, Mertgen A. Vagal tank theory: the three rs of cardiac vagal control functioning–resting, reactivity, and recovery. Front Neurosci 2018;12:458.
[47] Annerstedt M, Jönsson P, Wallergård M, Johansson G, Karlson B, Grahn P, et al. Inducing physiological stress recovery with sounds of nature in a virtual reality forest—results from a pilot study. Physiol Behav 2013;118:240–50.
[48] Snell TL, McLean LA, McAsey F, Zhang M, Maggs D. Nature streaming: contrasting the effectiveness of perceived live and recorded videos of nature for restoration. Environ Behav 2019;51:1082–105.
[49] Gollehon J, Troia B. Awesome breathing. Pacer Timer; 2022.
[50] Russo MA, Santarelli DM, O'Rourke D. The physiological effects of slow breathing in the healthy human. Breathe 2017;13:298–309.
[51] Laborde S, Mosley E, Thayer JF. Heart rate variability and cardiac vagal tone in psychophysiological research–recommendations for experiment planning, data analysis, and data reporting. Front Psychol 2017;8:213.
[52] Altini M. Heart rate variability logger. 2022.
[53] Koppold A, Ruge J, Hecker T, Lonsdorf T. The many faces of early life adversity-content overlap in validated assessment instruments as well as in fear and reward learning research. 2023.
[54] Wingenfeld K, Spitzer C, Mensebach C, Grabe HJ, Hill A, Gast U, et al. Die deutsche version des childhood trauma questionnaire (CTQ): erste befunde zu den psychometrischen kennwerten. PPmP-Psychother Psychosom Med Psychol 2010: 442–50.
[55] Benz AB, Kloker LV, Kuhlmann T, Meier M, Unternaehrer E, Bentele UU, et al. Psychometric properties of a German translation of the parental bonding instrument. Psychother Psychosom Med Psychol 2021;72:34–44.
[56] Wolf M, Limberger MF, Kleindienst N, Stieglitz R-D, Domsalla M, Philipsen A, et al. Kurzversion der Borderline-Symptom-Liste (BSL-23): Entwicklung und Überprüfung der psychometrischen Eigenschaften. PPmP - Psychother Psychosom Med Psychol 2009;59:321–4. https://doi.org/10.1055/s-0028-1104598.
[57] Beck AT, Steer RA, Brown G. Beck depression inventory–II. Psychol Assess 1996. https://doi.org/10.1037/t00742-000.
[58] Pietsch K, Hoyler A, Frühe B, Kruse J, Schulte-Körne G, Allgaier A-K. Früherkennung von Depressionen in der Pädiatrie: Kriteriumsvalidität des Beck Depressions-Inventar Revison (BDI-II) und des Beck Depressions-Inventar–Fast Screen for Medical Patients (BDI-FS). PPmP - Psychother Psychosom Med Psychol 2012;62:418–24. https://doi.org/10.1055/s-0032-1314869.
[59] Kemp AH, Quintana DS, Gray MA, Felmingham KL, Brown K, Gatt JM. Impact of depression and antidepressant treatment on heart rate variability: a review and meta-analysis. Biol Psychiatry 2010;67:1067–74.
[60] Wang Y, Zhao X, O'Neil A, Turner A, Liu X, Berk M. Altered cardiac autonomic nervous function in depression. BMC Psychiatry 2013;13:187.
[61] R Core Team. R: A language and environment for statistical computing. 2022.
[62] Posit Team. RStudio: integrated development environment for R. 2022.
[63] Rodriguez-Linares L, Vila X, Lado M, Mendez A, Otero A, Garcia C. RHRV: Heart rate variability analysis of ECG data. 2022.
[64] Bliese P. multilevel: Multilevel functions. 2022.
[65] Kassambara R. ggpubr: "ggplot2" based publication ready plots. 2022.
[66] Castro-Diehl C, Diez Roux AV, Redline S, Seeman T, McKinley P, Sloan R, et al. Sleep duration and quality in relation to autonomic nervous system measures: the multi-ethnic study of atherosclerosis (MESA). Sleep 2016;39:1927–40.
[67] Dettoni JL, Consolim-Colombo FM, Drager LF, Rubira MC, Cavasin De Souza SBP, Irigoyen MC, et al. Cardiovascular effects of partial sleep deprivation in healthy volunteers. J Appl Physiol 2012;113:232–6. https://doi.org/10.1152/japplphysiol.01604.2011.
[68] Schlagintweit J, Laharnar N, Glos M, Zemann M, Demin AV, Lederer K, et al. Effects of sleep fragmentation and partial sleep restriction on heart rate variability during night. Sci Rep 2023;13:6202.
[69] Ebner-Priemer UW, Welch SS, Grossman P, Reisch T, Linehan MM, Bohus M. Psychophysiological ambulatory assessment of affective dysregulation in borderline personality disorder. Psychiatry Res 2007;150:265–75.
[70] Willis F, Kuniss S, Kleindienst N, Lis S, Naoum J, Jungkunz M, et al. Stress reactivity and pain-mediated stress regulation in remitted patients with borderline personality disorder. Brain Behav 2018;8:e00909. https://doi.org/10.1002/brb3.909.
[71] Maiß C, Engemann L, Kern K, Flasbeck V, Mügge A, Lücke T, et al. Cardiac parasympathetic activity in female patients with borderline personality disorder predicts approach/avoidance behavior towards angry faces. Biol Psychol 2021; 163:108146.
[72] Pham T, Lau ZJ, Chen SH, Makowski D. Heart rate variability in psychology: a review of HRV indices and an analysis tutorial. Sensors 2021;21:3998.
[73] Thayer JF, Åhs F, Fredrikson M, Sollers III JJ, Wager TD. A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. Neurosci Biobehav Rev 2012;36:747–56.
[74] Ridolfi ME, Rossi R, Occhialini G, Gunderson JG. A clinical trial of a psychoeducation group intervention for patients with borderline personality disorder. J Clin Psychiatry 2019;81:16069.
[75] Schilling L, Moritz S, Kriston L, Krieger M, Nagel M. Efficacy of metacognitive training for patients with borderline personality disorder: preliminary results. Psychiatry Res 2018;262:459–64.
[76] Dixon-Gordon KL, Turner BJ, Rosenthal MZ, Chapman AL. Emotion regulation in borderline personality disorder: an experimental investigation of the effects of instructed acceptance and suppression. Behav Ther 2017;48:750–64.
[77] Park SM, Jung HY. Respiratory sinus arrhythmia biofeedback alters heart rate variability and default mode network connectivity in major depressive disorder: a preliminary study. Int J Psychophysiol 2020;158:225–37.
[78] Caldwell YT, Steffen PR. Adding HRV biofeedback to psychotherapy increases heart rate variability and improves the treatment of major depressive disorder. Int J Psychophysiol 2018;131:96–101.
[79] Chien H, Chung Y, Yeh M, Lee J. Breathing exercise combined with cognitive behavioural intervention improves sleep quality and heart rate variability in major depression. J Clin Nurs 2015;24:3206–14. https://doi.org/10.1111/jocn.12972.
[80] Neyer S, Witthöft M, Cropley M, Pawelzik M, Lugo RG, Sütterlin S. Reduction of depressive symptoms during inpatient treatment is not associated with changes in heart rate variability. PloS One 2021;16:e0248686.
[81] Garakani A, Martinez JM, Aaronson CJ, Voustianiouk A, Kaufmann H, Gorman JM. Effect of medication and psychotherapy on heart rate variability in panic disorder. Depress Anxiety 2009;26:251–8. https://doi.org/10.1002/da.20533.
[82] Weise S, Parzer P, Fürer L, Zimmermann R, Schmeck K, Resch F, et al. Autonomic nervous system activity and dialectical behavioral therapy outcome in adolescent borderline personality pathology. World J Biol Psychiatry 2021;22:535–45.
[83] Kirk U, Axelsen JL. Heart rate variability is enhanced during mindfulness practice: a randomized controlled trial involving a 10-day online-based mindfulness intervention. PloS One 2020;15:e0243488.
[84] Navarro-Lomas G, Dote-Montero M, Alcantara JMA, Plaza-Florido A, Castillo MJ, Amaro-Gahete FJ. Different exercise training modalities similarly improve heart rate variability in sedentary middle-aged adults: the FIT-AGEING randomized controlled trial. Eur J Appl Physiol 2022;122:1863–74. https://doi.org/10.1007/s00421-022-04957-9.
[85] Sigrist C, Reichl C, Schmidt SJ, Brunner R, Kaess M, Koenig J. Cardiac autonomic functioning and clinical outcome in adolescent borderline personality disorder over two years. Prog Neuropsychopharmacol Biol Psychiatry 2021;111:110336.
[86] Sigrist C, Mürner-Lavanchy I, Peschel SK, Schmidt SJ, Kaess M, Koenig J. Early life maltreatment and resting-state heart rate variability: a systematic review and meta-analysis. Neurosci Biobehav Rev 2021;120:307–34.
[87] Thurston RC, Carson MY, Koenen KC, Chang Y, Matthews KA, von Känel R, et al. The relationship of trauma exposure to heart rate variability during wake and sleep in midlife women. Psychophysiology 2020;57:e13514.
[88] Porges SW. The polyvagal theory: phylogenetic contributions to social behavior. Physiol Behav 2003;79:503–13.
[89] Domes G, Schulze L, Herpertz SC. Emotion recognition in borderline personality disorder—a review of the literature. J Pers Disord 2009;23:6–19.
[90] Krause-Utz A, Walther J-C, Kyrgiou AI, Hoogenboom W, Alampanou M, Bohus M, et al. Severity of childhood maltreatment predicts reaction times and heart rate variability during an emotional working memory task in borderline personality disorder. Eur J Psychotraumatol 2022;13:2093037.
[91] Cattane N, Rossi R, Lanfredi M, Cattaneo A. Borderline personality disorder and childhood trauma: exploring the affected biological systems and mechanisms. BMC Psychiatry 2017;17:1–14.
[92] Kramer L, Sander C, Bertsch K, Gescher DM, Cackowski S, Hegerl U, et al. EEG-vigilance regulation in borderline personality disorder. Int J Psychophysiol 2019; 139:10–7.
[93] Glaser J-P, Van Os J, Mengelers R, Myin-Germeys I. A momentary assessment study of the reputed emotional phenotype associated with borderline personality disorder. Psychol Med 2008;38:1231–9.
[94] Faul F, Erdfelder E, Buchner A, Lang A-G. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav Res Methods 2009;41: 1149–60. https://doi.org/10.3758/BRM.41.4.1149.

Glossary

ANS: Autonomic Nervous System
BPD: Borderline Personality Disorder
CTQ: Childhood Trauma Questionnaire
DBT: Dialectic Behavioral Therapy
ELA: Early Life Adversity
HC: Healthy Controls
HRV: Heart Rate Variability
PBI: Parental Boning Instrument
PNS: Parasympathetic Nervous System
RMSSD: Root Mean Square of Successive Differences
RSQ: Relaxation State Questionnaire
SNS: Sympathetic Nervous System
VR: Virtual Reality