Psychoneuroendocrinology 169 (2024) 107148

Contents lists available at ScienceDirect

Psychoneuroendocrinology

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

Does it need an app? – Differences between app-guided breathing and natural relaxation in adolescents after acute stress

Daniel Schleicher[a,*], Irina Jarvers[a], Martin Kocur[b,1], Stephanie Kandsperger[a], Romuald Brunner[a], Angelika Ecker[a]

[a] Department of Child and Adolescent Psychiatry and Psychotherapy, University of Regensburg, Universitätsstraße 84, Regensburg 93053, Germany
[b] Department of Media Informatics, University of Regensburg, Universitätsstraße 31, Regensburg 93053, Germany

ARTICLE INFO

Keywords:
Health App
Slow Deep Breathing
Stress
Children and Adolescents
Coping
Trier Social Stress Test

ABSTRACT

A key component of stress management and biofeedback training is the use of relaxation exercises, such as slow/deep breathing (6 breaths/minute) in heart coherence exercises (HCEs). Breathing exercises are also increasingly being integrated into smartphones as part of health apps, though their effectiveness in adolescents after acute stress has rarely been validated scientifically. The aim of the current study was to investigate the effectiveness of an app-guided HCE ($n = 36$) after an acute stress situation (Trier Social Stress Test) compared with natural relaxation ($n = 37$), among healthy adolescents (aged 11–17 years). Endocrine, autonomic, and psychological stress parameters (cortisol, alpha-amylase, heart rate, heart rate variability, mood) were examined in 73 adolescents (46 female, 27 male; $M_{age} = 13.86$, $SD_{age} = 1.87$). Significant group differences were found in heart rate variability, with higher values in the low frequency band and low-to-high frequency ratio for the HCE condition, possibly indicating improved physiological functions through the stimulation of vagal tone and baroreflex. The use of a general breathing technique (natural and app-guided) also resulted in stronger relaxation reactions in cortisol when controlling for the previous stronger stress reactivity. On the other hand, app-guided slow breathing without a long training may be experienced as more uncomfortable during relaxation. The integration of breathing exercises in health apps for adolescents appears to be useful, offering a helpful and low-threshold coping/relaxation strategy during acute stress situations. Further studies should examine the benefits of app-guided breathing exercises in both psychiatric samples and the general population across a wide age range.

1. Introduction

In recent years, the number of health apps for coping with stress has greatly increased (Wang et al., 2018), which is particularly relevant for children and adolescents due to their daily contact with digital media. Psychologically, the transactional stress model defines stress as the result of cognitive appraisal processes by comparing the "dangerousness" of stimuli and available resources (Lazarus and Folkman, 1984). Physiologically, the hypothalamic-pituitary-adrenal (HPA) and sympathetic adrenal medullary (SAM) axes are the two neuroendocrine systems that are primarily activated by experiences of stress (O'Connor et al., 2021). When the HPA axis is activated, cortisol is released from the adrenal cortex, which serves to activate bodily energy stores (O'Connor et al., 2021). The SAM axis is part of the sympathetic-autonomic nervous system, which is quickly activated for fight-or-flight responses, followed by increases in respiratory and heart rates due to release of (nor-)adrenaline (O'Connor et al., 2021). It also influences salivary glands, which promote the release of the digestion enzyme alpha-amylase (Ali and Nater, 2020).

The most common paradigm for valid investigation of acute psychosocial stress is the Trier Social Stress Test (TSST) (Kirschbaum et al., 1993) due to its social evaluation and uncontrollability components (Dickerson and Kemeny, 2004). The TSST includes a preparation phase, followed by a free speech phase (job interview) and an unexpected mental arithmetic task (calculating backward) in front of a neutral panel and a camera. Adapted versions of the TSST exist, including the TSST for Children (TSST-C, speech task: finish telling a story, arithmetic task: adjustment of difficulty to age) (Buske-Kirschbaum et al., 1997) or the

* Corresponding author.
E-mail addresses: daniel.schleicher@medbo.de (D. Schleicher), irina.jarvers@ukr.de (I. Jarvers), martin.kocur@fh-hagenberg.at (M. Kocur), stephanie.kandsperger@medbo.de (S. Kandsperger), romuald.brunner@medbo.de (R. Brunner), angelika.ecker@ukr.de (A. Ecker).
[1] Present address: Digital Media Lab, University of Applied Sciences Upper Austria, Softwarepark 11, 4232 Hagenberg, Austria.

https://doi.org/10.1016/j.psyneuen.2024.107148
Received 1 March 2024; Received in revised form 16 July 2024; Accepted 22 July 2024
Available online 2 August 2024

Modified TSST (TSST-M, focus on personality and strengths in speech task for cross-age standardization) (Yim et al., 2010). Another modification is implementation in virtual reality (Kelly et al., 2007), which shows comparable effects in stress reactivity, though the magnitude of cortisol responses is somewhat smaller than in real versions (Ecker et al., 2024; Helminen et al., 2021, 2019). The main advantages of virtual TSST versions are the reduction in personnel resources and the high standardization of the protocol (Helminen et al., 2019). At the same time, the extent to which participants can immerse themselves in the virtual environment (immersion) is relevant to the level of stress response. For example, head-mounted displays are used to create immersive virtual environments by completely replacing real visual and auditory stimuli with virtual ones (Helminen et al., 2019). This reinforces the idea or illusion of being present in the virtual world (presence) (Slater, 2018).

On the other hand, in order to successfully cope with stress, relaxation techniques are used in stress management trainings to reduce physical tension, but they usually require several weeks of training (e.g., learning mindfulness) or clinical setting (e.g., biofeedback). Here, a large number of past studies have shown positive effects on general stress levels (e.g., Hathaisaard et al., 2022), performance in critical work situations (e.g., Schlatter et al., 2022) and stress reactivity after acute stress (TSST), although the effects on physiological markers are less robust in the latter case (Morton et al., 2020). In contrast, the use of slow/deep breathing techniques has proven to be a subtle and low-threshold coping strategy (Perciavalle et al., 2017; Steffen et al., 2021; Toussaint et al., 2021). A well-known technique is heart coherence breathing, where coherence refers to an optimal state of positive thinking through the alignment of psychophysiological processes (Jasubhai, 2021; McCraty and Zayas, 2014). Instead of 9–24 breaths/minute, the aim is to achieve a breathing rate of 6 breaths/minute (inhaling and exhaling for 5 seconds each, usually 5 min) (Jasubhai, 2021; Lehrer and Gevirtz, 2014). This results in a reduction of emotional burden and improved parasympathetic activity, baroreflex function, and heart rate variability (HRV) (Jasubhai, 2021; Lehrer and Gevirtz, 2014; Lin et al., 2019; Steffen et al., 2021). This breathing technique is usually examined in long-term biofeedback units.

At the same time, heart coherence exercises (HCEs) are often integrated into health apps on smartphones for direct use in stressful situations, though relaxation effects without prolonged training should be investigated more closely. Overall, evidence-based validation studies on the functions and effectiveness of health apps are lacking (Linardon et al., 2019; Wang et al., 2018). Only a few studies have investigated the use of short app-guided breathing exercises after acute stress, with initial study results indicating higher HRV and lower alpha-amylase levels during recovery but no differences in cortisol or self-reported stress (e.g., Chelidoni et al., 2020; Hunter et al., 2019; Plans et al., 2019). These studies only focus on adults, though the learning of adaptive coping strategies via health apps for early health promotion appears to be particularly useful for children and adolescents. Direct transferability of the results from adults to adolescents is only possible to a limited extent. Some biological stress and relaxation systems are only just developing at this young age (Zavodna et al., 2015), which is why differences can result from pubertal development. In addition, sex-specific regulatory influences of the adolescent autonomic nervous system on the processing of stress should also be taken into account (Estévez-Báez et al., 2019). Finally, a different responsiveness to digital media compared to adults can also be assumed, as adolescents have grown up with them.

Therefore, this study aimed to compare the physiological and psychological relaxation responses between an app-guided HCE and the natural relaxation (NR) in adolescents after acute stress. Significantly stronger/faster relaxation responses in cortisol, alpha-amylase, heart rate, heart rate variabilities and subjective stress level after acute stress were expected for the HCE group compared to the NR group. Moreover, relaxation differences between the use of a natural breathing technique (NaBT, not app-guided, sub-sample of NR group), no breathing technique (NoBT, remaining NR group) and HCE (app-guided breathing technique) were explored. Again, significantly stronger recovery responses were expected in the stress parameters for the breathing conditions (HCE > NaBT > NoBT).

2. Material and methods

2.1. Recruitment and participants

This study was part of a comprehensive research project to validate a virtual TSST and health app for adolescents pre-registered in the German Register of Clinical Trials (DRKS00022063) since August 10, 2020 (see study protocol by Schleicher et al., 2022). The study was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and received a positive vote from the Ethics Committee of the University of Regensburg on April 22, 2020 (reference: 20-1800-101).

Recruitment took place between June 2021 and December 2022 using flyers, mailing lists, posters, and online advertising. Adolescents aged between 11 and 17 years with a sufficient understanding of German could participate. Exclusion criteria were special school attendance, psychiatric/neurological or endocrinological/immunological illnesses (current/past), psychiatric/psychotherapeutic or neurological treatment (current/past), psychotropic drugs/medication containing cortisone or glucocorticoids, pregnancy/breastfeeding, early pubertal development, and below-average intelligence. Participants received a voucher worth 40 euros if they attended all study sessions. Motivated app use resulted in an additional voucher worth 10 euros, for which a points system was programmed into the app that counted completed tasks.

A total of 84 adolescents took part in the study, but 11 had to be excluded due to missing feedback/motivation ($n = 7$), abnormalities in the clinical interview ($n = 3$), or difficulties with the app at home ($n = 1$). Therefore, 73 adolescents ($M_{age} = 13.86$, $SD_{age} = 1.87$) were included in the final analysis (46 female, 27 male; sex and gender overlapped for all participants). They were randomly assigned to the different relaxation conditions using a random number generator. The study consisted of a telephone screening (T0, 15–30 min) and two study appointments (T1 and T2; 2–2.5 h each; time between T1 and T2 (in days): $M = 18.62$, $SD = 14.01$, range: 3–63) at the Department of Child and Adolescent Psychiatry and Psychotherapy of the University of Regensburg at the District Hospital Regensburg. In addition, the relaxation exercise was practiced at home on two evenings between T1 and T2. The detailed procedure of the study can be found in Section 2.3. Procedure.

2.2. Interventions, paradigms, and measures

2.2.1. Questionnaires and psychological measures

Subtests (part 1, 56 items) of the Culture Fair Intelligence Test 20-R - Scale 2 (CFT 20-R) (Weiß, 2006) were used to estimate the intelligence quotient (IQ; Classifications, Series, Analogies, Matrices). The internal consistency of the CFT 20-R is high, with a Cronbach's alpha of 0.95 and retest reliability of approximately 0.80. Factorial, content, and criterion validity could be shown (Weiß, 2006).

Psychiatric diagnoses were assessed by the structured Mini-International Neuropsychiatric Interview for Children and Adolescents 6.0 (MINI-KID 6.0) (Sheehan et al., 1998). It is a reliable and valid instrument for assessing psychiatric diagnoses in childhood/adolescence, with high concordance rates with other interviews and expert diagnoses (Sheehan et al., 1998).

The Child Behavior Checklist (CBCL/6–18 R; report by guardians, 112 items, 0 = "not applicable" to 2 = "exactly/frequently applicable") and Youth Self-Report (YSR/11–18 R; self-report by adolescents, 112 items, 0 = "not applicable" to 2 = "exactly/frequently applicable") (Döpfner et al., 2014) were used to record behavioral, emotional, and somatic abnormalities. Good internal consistency (Cronbach's alpha > 0.80) and factor structure were confirmed (Döpfner et al., 2014).

Pubertal status (pre- to post-pubertal) was assessed using the Pubertal Development Scale (PDS), which contains sex-specific questions about physical changes (6 items, 1 = "not yet started" to 4 = "corresponds to adult") (Petersen et al., 1988). The PDS shows good reliability and validity for recording pubertal development (Petersen et al., 1988).

2.2.2. Stress/relaxation parameters

Subjective stress levels were assessed via ratings ("At the moment I feel stressed, tense or burdened"; 1 = "not at all" to 10 = "very much"). How helpful the exercise was perceived to be was asked using a self-created questionnaire about the app ("How helpful was the app's relaxation exercise after the presentation?"; 1 = "not at all" to 6 = "very much"). Cortisol and alpha-amylase levels were determined in the laboratory using saliva samples collected at eight time points (with regard to the start of TSST instruction: −30 min, 0 min, +5 min, +20 min, +25 min, +30 min, +40 min, +60 min, +80 min) via Salivettes® designed specifically for cortisol determination (Sarstedt, Nümbrecht, Germany). Heart rate was measured continuously before/during/after the TSST and relaxation exercises (placement of sensor: 10 min before TSST instruction, duration of recording: 50 min) using an ECG/activity sensor EcgMove 4 (movisens GmbH, Karlsruhe, Germany). Heart rate data were transformed into HRV parameters: low frequency band (LF; 0.04–0.15 Hz), high frequency band (HF; above 0.15 Hz), and low-to-high frequency ratio (LF/HF) as frequency-dependent domains and the root mean square of the successive differences of beat to beat/R-R intervals (RMSSD) as the time-dependent domain.

2.2.3. Trier social stress test

A real/in vivo TSST (TSST-IV) and virtual reality TSST (TSST-VR) were used to induce acute psychosocial stress. The distribution of both groups was approximately equal in the two relaxation conditions due to randomization (see Table 1). The protocol of both versions was almost identical: The panel consisted of one female (guiding speech task) and one male member (guiding calculation task). The neutral behaviors (facial expressions, gestures), standardized sentences, panel appearances (e.g., body shape), and room (e.g., dimensions, furnishings) were completely adapted to the real setting. Programming of the TSST-VR was achieved using the computer graphics software Daz3D and Blender. The TSST-VR was presented from a first-person perspective using the HTC Vive Pro Eye Head Mounted Display and ran using Unity3D (v. 2019.3.11f1) on a VR-compatible laptop (Dell G5 15 Notebook PC with Windows 10).

In a 5-min introductory phase, participants were told that they are applying for a student representative position and should convince the

Table 1
Descriptive statistics and characterization of the sample.

	Main analysis				Exploratory analysis						
	HCE (*n* = 36)		NR (*n* = 37)		NaBT (*n* = 15)		NoBT (*n* = 22)		Total		*N*
Sex/Gender	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	73
Female	23	63.90	23	62.20	12	80.00	11	50.00	46	63.00	
Male	13	36.10	14	37.80	3	20.00	11	50.00	27	37.00	
Age	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	73
	14.00	2.03	13.73	1.73	14.47	1.60	13.23	1.66	13.86	1.87	
School type	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	73
Mittelschule	1	2.80	1	2.70	-	-	1	4.50	2	2.70	
Realschule	6	16.70	6	16.20	2	13.30	4	18.20	12	16.40	
Gymnasium	27	75.00	28	75.70	13	86.70	15	68.20	55	75.30	
FOS/BOS	1	2.80	2	5.40	-	-	2	9.10	3	4.10	
Berufsschule	1	2.80	-	-	-	-	-	-	1	1.40	
TSST	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	73
IV	18	50.00	19	51.40	10	66.70	9	40.90	37	50.70	
VR	18	50.00	18	48.60	5	33.30	13	59.10	36	49.30	
PDS	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	73
Prepubertal	4	11.10	3	8.10	-	-	3	13.60	7	9.60	
Beginning puberty	3	8.30	3	8.10	-	-	3	13.60	6	8.20	
Pubertal	6	16.70	12	32.40	3	20.00	9	40.90	18	24.70	
Advanced puberty	19	52.80	14	37.80	11	73.30	3	13.60	33	45.20	
Postpubertal	4	11.10	5	13.50	1	6.70	4	18.20	9	12.30	
Menstruation	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	46
Yes	21	91.30	18	78.30	10	16.70	8	72.70	39	84.80	
No	2	8.70	5	21.70	2	83.30	3	27.30	7	15.20	
Hormonal contraception	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**	46
Yes	-	-	1	4.30	1	8.30	-	-	1	2.20	
No	23	100.00	22	95.70	11	91.70	11	100.00	45	97.80	
BMI	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	68
	19.77	3.87	18.78	2.72	19.66	2.32	18.20	2.85	19.26	3.34	
IQ	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	73
	107.36	14.50	108.76	13.48	110.60	13.39	107.50	13.71	108.07	13.91	
CBCL/6–18 R	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	67
Total score	16.21	14.94	15.03	13.43	11.00	9.86	17.23	14.77	15.61	14.10	
YSR/11–18 R	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	73
Total score	28.03	17.24	25.30	15.04	26.93	13.94	24.18	15.97	26.64	16.11	

Note. Sex and gender overlapped, Menstruation and hormonal contraceptives were only asked of female participants, Mittelschule: usually 9 years of elementary school, Realschule: intermediate secondary school (usually 6 years after 4 years of elementary school), Gymnasium: higher level of secondary school with general university entrance qualification (usually 8–9 years after 4 years of elementary school), FOS/BOS (Fach-/Berufsoberschule): after intermediate secondary school, with subject-specific or general university entrance qualification (usually 2–3 years after Realschule), Berufsschule: vocational school (usually 2–3 years after secondary school), TSST = Trier Social Stress Test, IV = in vivo, VR = virtual reality, PDS = Pubertal Development Scale, BMI = body mass index, IQ = Intelligence Quotient, CBCL/6–18R = Child Behavior Checklist, YSR/11–18R = Youth Self-Report, HCE = heart coherence exercise, NR = natural relaxation, NaBT = natural breathing technique (sub-sample of NR group), NoBT = no breathing technique (sub-sample of NR group), Scores for the clinical measurement instruments are in the average subclinical range.

panel of their personality and strengths. They were also informed of camera recordings for subsequent evaluation. After the panel entered the room, the preparation phase (5 min) began, during which they could mentally prepare their speech, followed by a 5-min speech task in which they talked about their strengths. Pauses were followed by standardized sentences from the panel (e.g., "You still have time. Please continue with your personal strengths."). Finally, an unexpected subtraction task (5 min) followed, which was adapted to the participant's age (e.g., for 12-year-old participants: counting backwards from 1023 in steps of 13). In case of errors, participants were informed by the panel (e.g., "Error. Please start again from 1023."). Thus, the tasks were based on both the TSST-M (speech task: talking about personality/strengths) (Yim et al., 2010) and TSST-C protocol (calculation task: adjustment of difficulty to age) (Buske-Kirschbaum et al., 1997).

2.2.4. Relaxation conditions

Using a self-programmed app, the adolescent was trained on the respective relaxation exercise on two evenings (8 p.m.) at home. The integrated development environment Android Studio was used for app implementation. The code was written in Kotlin and Java for target SDK version 29. Surveys were developed using the SurveyKit programming library version 1.1.0 published under the open-source MIT license. Sounds were taken from the Freesound database. To enhance data security, only department-internal smartphones for research purposes were used (Samsung A20e, Android Pie 9.0). All settings were kept the same, and unneeded apps/services were deactivated. A password-protected experimenter menu was used to assign/demonstrate relaxation conditions and read-out data.

The HCE group was instructed to sit down comfortably and breathe in the frequency of an enlarging and shrinking circle to relax (inhaling and exhaling for 5 seconds each for 5 min). A gong sounded when intervals changed. The NR group was asked to sit down comfortably, but no specific relaxation technique was provided to activate usual NR processes (5 min) (see Fig. 1).

2.3. Procedure

At T0, inclusion/exclusion criteria were reviewed with the adolescents and/or their guardians. Female participants were asked whether they were already menstruating and/or using hormonal contraceptives. If girls were menstruating and not using contraception, they were tested in the luteal phase (calculation: 15-day-period between ovulation and expected start of next menstruation).

At T1, adolescents and their guardians were informed about the study in oral and written form. Participation was voluntary, and withdrawal was possible at any time without giving reasons. Informed consent of the adolescents and guardians was required for participation. The CFT 20-R, MINI-KID 6.0, PDS, and YSR/11–18 R were then completed with the adolescents. While waiting, parents were asked to complete the CBCL/6–18 R. This was followed by practicing collection of saliva samples, explanation of the health app, and demonstration of the relaxation exercise. The allocated 5-min relaxation exercise was carried out on two evenings (8 p.m.) at home before T2. This was intended to briefly familiarize the participants with the exercise without lengthy training.

T2 always took place in the afternoon (after 1 p.m.). The 30-min acclimatization phase was followed by the TSST. The participants then performed the assigned 5-min relaxation exercise via app as practiced at home. Before the end of T2, the app evaluation was carried out. A voucher was handed out after the debriefing. At regular intervals, stress levels, saliva samples, and heart rate were assessed. An overview of the procedure is provided in Fig. 2.

2.4. Data processing and statistical analyses

To date, the few studies on the effectiveness of app-guided breathing exercises in adults after acute stress have shown moderate to strong effect sizes (Chelidoni et al., 2020; Plans et al., 2019). Assuming a medium effect size (f = 0.25), power of 0.80, and significance level of α =

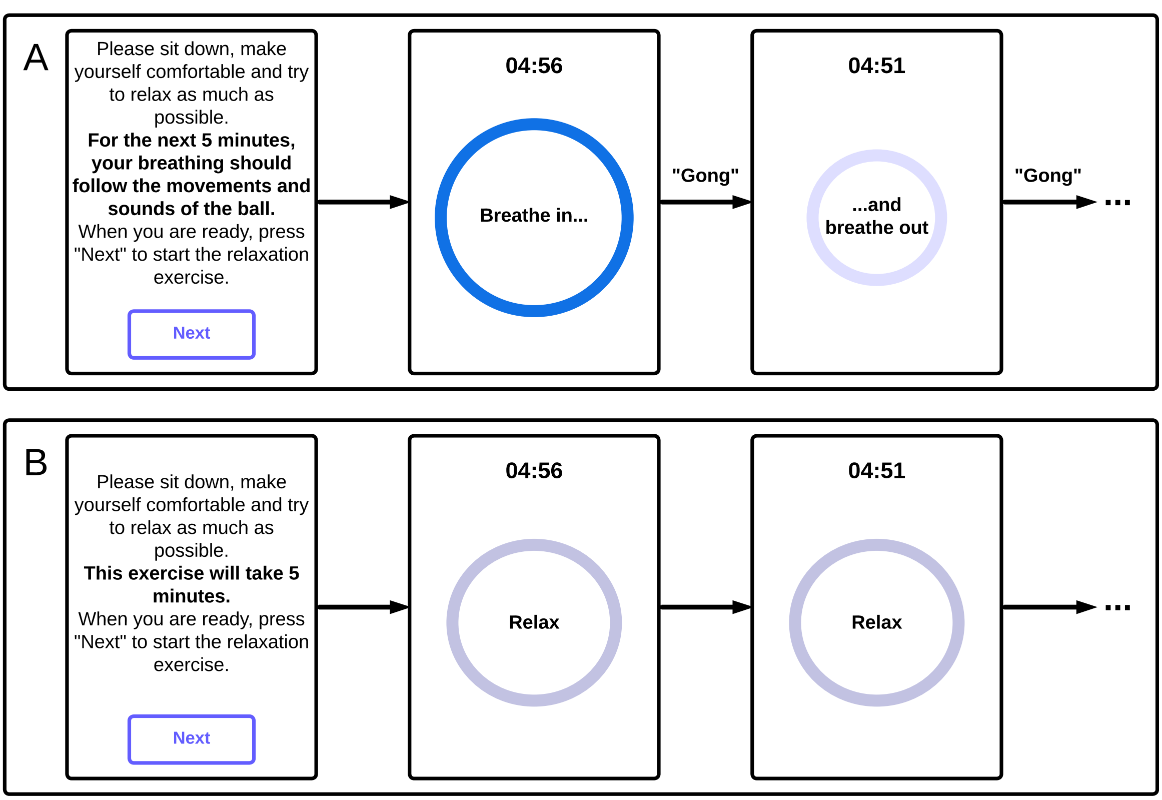

Fig. 1. Comparison of the two relaxation exercises. (A) Heart coherence exercise. (B) Natural relaxation.

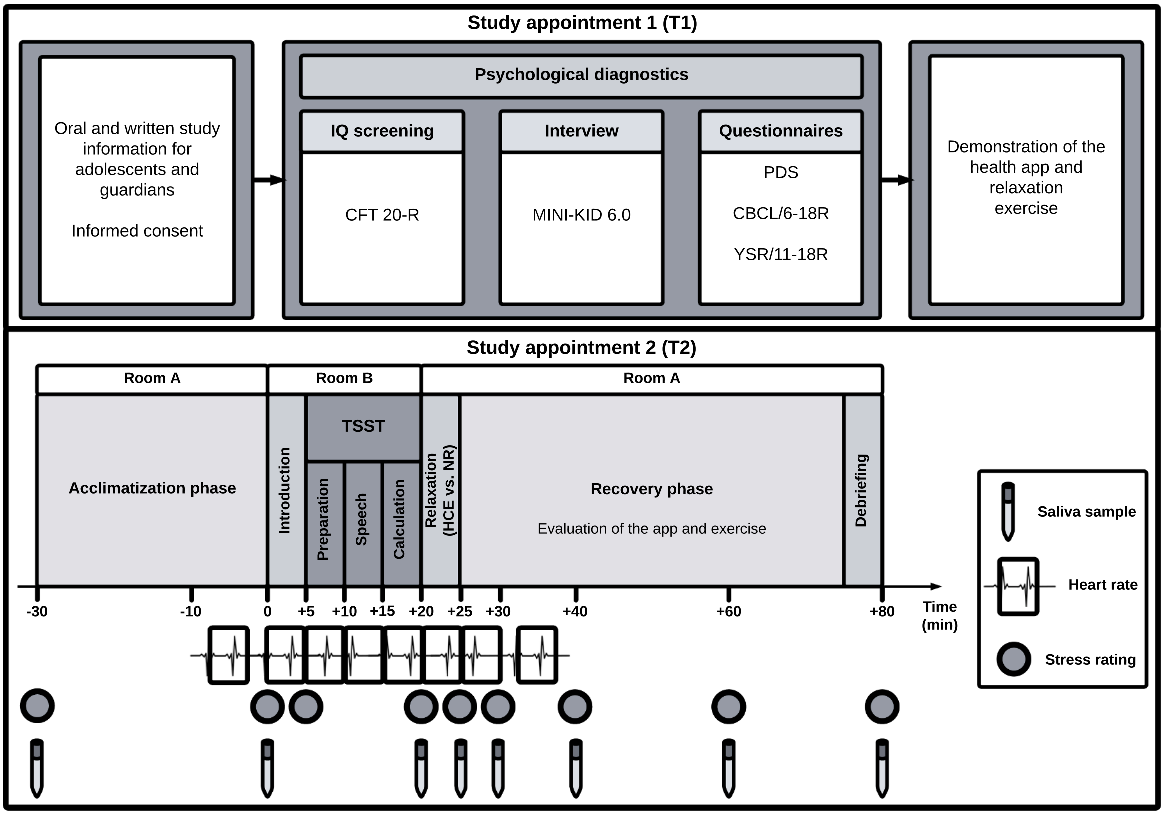

Fig. 2. Overview of the study procedure. IQ = Intelligence Quotient, CFT 20-R = Culture Fair Intelligence Test 20-R - Scale 2, MINI-KID 6.0 = Mini-International Neuropsychiatric Interview for Children and Adolescents 6.0, PDS = Pubertal Development Scale, CBCL/6–18 R = Child Behavior Checklist, YSR/11–18 R = Youth Self-Report, TSST = Trier Social Stress Test, HCE = heart coherence exercise, NR = natural relaxation. Saliva samples indicate the collection of cortisol and alpha-amylase. Heart rate stands for the measurement of heart rate and heart rate variability.

0.05, G*Power (Faul et al., 2007) was used to determine a total sample size of $N = 40$ for the planned analysis of variance (ANOVA) with repeated measures. More than 40 adolescents were included in the study because a larger sample was necessary to answer the additional main questions of the comprehensive research project to validate the virtual TSST and the health app.

Analog data were double-coded by an independent coder to 30 %. However, six guardians did not complete the CBCL/6–18 R, and one person did not indicate how helpful they found the exercise. Transfer from sensor, storage and preprocessing of heart rate as well as the transformation into HRV were carried out using UnisensViewer version 1.16.46.0 and Data Analyzer version 1.13.5 (FZI, movisens GmbH, Karlsruhe, Germany). Heart rate and HRV (output interval: 1 min) were averaged in eight T2 time intervals (5 min each): baseline (beginning), TSST introduction, preparation, speech, calculation, during and after relaxation, and baseline (end). An exact time log, kept by the experimenter at T2, served as a marker for the time intervals. Due to technical errors followed by missing data ($n = 3$, none of the intervals could be computed) and outliers (Tukey's method, $n = 2$), heart rate/HRV data had to be excluded in advance. Saliva samples were stored at −20°C until analyzed by Dresden LabService GmbH, Germany. Intra- and inter-assay coefficients of variation were between 1.2 % and 2.0 %. Recovery values (difference between maximum/last TSST response and relaxation response during/after relaxation) were determined for all parameters as a measure of relaxation strength. Specific parameter characteristics were considered, including the latency of the cortisol response. Some recovery values could not be calculated due to missing measurements: alpha-amylase (NR, $n = 3$), LF and LF/HF (HCE, $n = 9$; NR, $n = 6$).

As NR participants could also have used a breathing technique on their own (not app guided), this was queried afterward, as it is difficult to control in advance and cannot be prohibited. Adolescents in the NR group ($n = 15$) who described a breathing strategy (e.g., more calmly/deeper/slower) were assigned to a separate group for exploratory analyses. Thus, we had three groups for exploratory analyses, the NR group without breathing technique (NoBT, $n = 22$), the NR group with a natural breathing technique (NaBT, $n = 15$) and the HCE group ($n = 36$). All HCE participants stated that they had performed the HCE and had not used any other relaxation strategy.

Statistical analyses were carried out using IBM SPSS Statistics Version 28.0 (IBM Corp., Armonk, NY). Equivalence tests (two one-sided tests procedure, Welch's t-tests of independent samples) were carried out for demographic data using the TOSTER package, with a mean effect size of Cohen's $d = 0.70$ (Lakens, 2017). Repeated measures ANOVAs with post hoc t-tests were used to analyze stress (over entire T2) and relaxation responses (from last stress response to T2 end). Due to the lack of a normal distribution, data were log-transformed to allow an approximation. Preliminary analyses revealed correlations of cortisol and alpha-amylase with PDS, and of HF and LF/HF with age, and they ultimately served as covariates. Intermediate subject factors were app condition (HCE vs. NR), preceding TSST condition (TSST-VR vs. TSST-IV), and sex due to possible influences on stress responses. Variables with significant effects were always included in further analyses. If the assumption of sphericity was violated, corrections were made according to Greenhouse-Geisser. To analyze differences in relaxation strengths and exercise evaluation between groups (HCE vs. NR, NoBT vs. NaBT vs. HCE), Mann-Whitney U and Kruskal-Wallis-H tests were used to compare recovery values and evaluations due to the lack of a normal distribution and robustness towards unequal or smaller sample sizes. For variables with significant differences between the three groups (NoBT, NaBT, HCE), post-hoc tests and linear regressions were computed, controlling for maximum increase. The false discovery rate (FDR) (Benjamini and Hochberg, 1995) was used to correct for multiple comparisons. Cohen's d and the partial eta-square (η^2) were used as measures of effect size. The effect sizes can be interpreted as small (d = 0.20, $\eta^2 = 0.01$), medium ($d = 0.50$, $\eta^2 = 0.10$), or large ($d = 0.80$, $\eta^2 = 0.25$) (Vacha-Haase and Thompson, 2004). The significance level was set to $\alpha = 0.05$.

3. Results

3.1. Sample

A total of 73 participants between the ages of 11 and 17 years (46 females and 27 males) were included in the analysis (see Table 1 and Table S1 in Supplementary Material for descriptive overview). Equivalence tests showed that no variable was significantly different between the HCE and NR groups ($p > 0.420$ for all). Moreover, both groups were

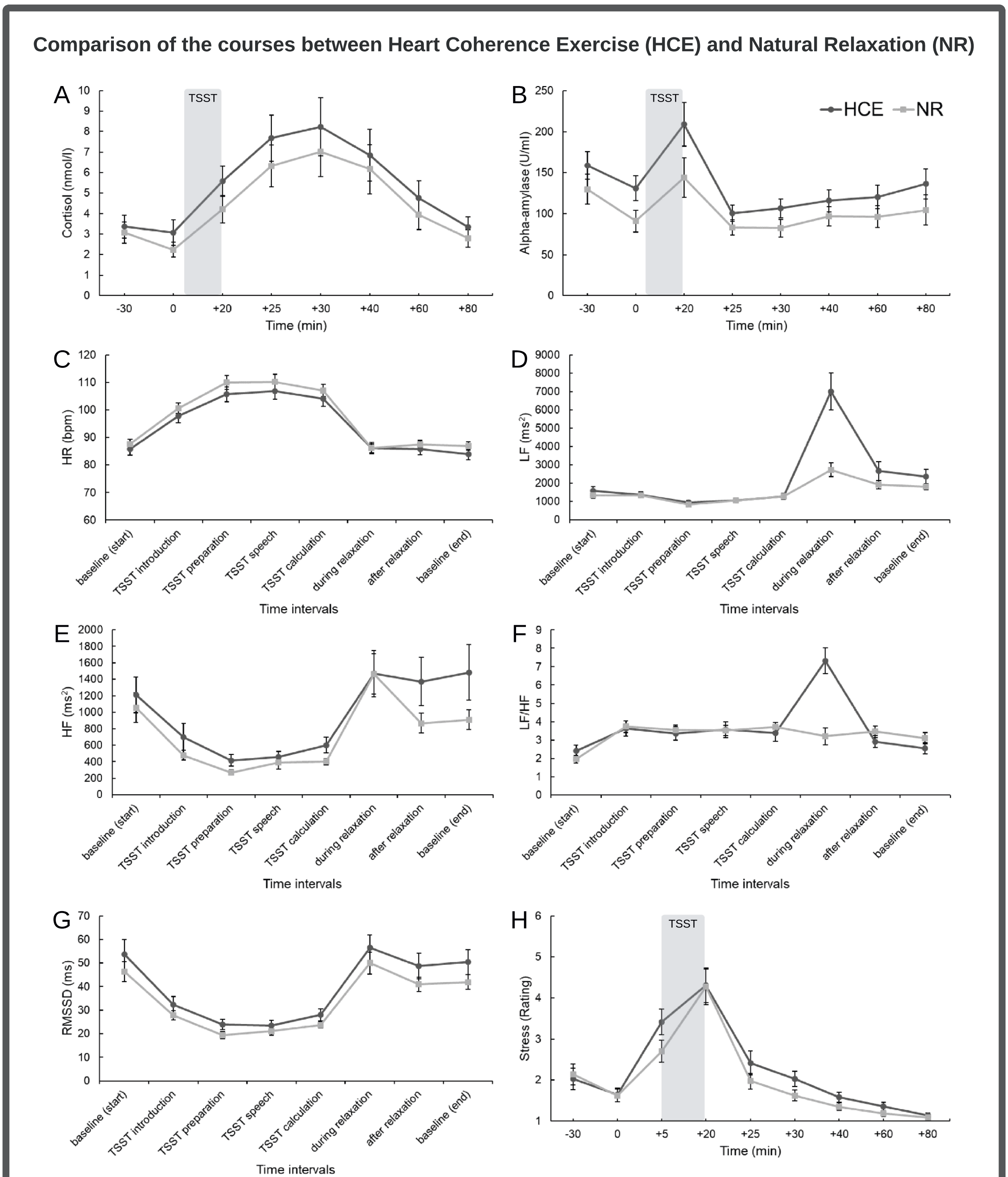

Fig. 3. Comparison of the courses between heart coherence exercise (HCE) and natural relaxation (NR). TSST = Trier Social Stress Test, HR = heart rate, bpm = beats per minute, LF = low frequency band, HF = high frequency band, LF/HF = low-to-high frequency ratio, RMSSD = root mean square of the successive differences of beat to beat/R-R intervals. Stress rating from 1 = "not at all" to 10 = "very". Error bars indicate standard error.

equivalent in all variables: age (t(68.60) = −2.37, p = 0.010), sex (t(71.00) = −2.84, p = 0.003), PDS (t(70.50) = −2.84, p = 0.003), IQ (t(70.30) = 2.56, p = 0.006), CBCL (t(63.80) = −2.52, p = 0.007), YSR (t(69.20) = −2.27, p = 0.013). NoBT, NaBT and HCE did not differ significantly in age, sex, PDS, IQ, CBCL, or YSR (all $p > 0.101$).

3.2. Comparison of heart coherence exercise and natural relaxation (main analyses)

Fig. 3 provides an overview of changes in the parameters for HCE and NR over T2. To investigate relaxation reactions between both groups, parameters had to show stress reactions caused by the TSST. In repeated measures ANOVAs across T2, we found significant main/interaction effects for time with all variables (see Table S2 in Supplementary Material).

Relaxation reactions were analyzed using repeated measures ANOVAs (from last stress reaction to T2 end). Results are given in Table 2.

Due to significant effects of app condition on alpha-amylase, LF, LF/HF, and stress rating, post-hoc t-tests were carried out. Significant differences were found in alpha-amylase at +30 min (HCE: M = 4.49, SD = 0.62; NR: M = 4.15, SD = 0.76; t(69) = 2.08, p = 0.041, d = 0.49) and +60 min (HCE: M = 4.60, SD = 0.62; NR: M = 4.23, SD = 0.91; t(70) = 2.04, p = 0.045, d = 0.48). Before relaxation, significant differences were found at each time point with higher values for HCE (all $t > 2.06$, all $p < 0.043$, d = [0.48; 0.63]). Significant differences in LF (HCE: M = 8.54, SD = 0.87; NR: M = 7.61, SD = 0.87; t(59) = 4.15, $p < 0.001$, d = 1.06) and LF/HF (HCE: M = 1.86, SD = 0.55; NR: M = 0.87, SD = 0.80; t(54.97) = 5.63, $p < 0.001$, d = 1.42) were found only during relaxation. There were no significant differences in stress ratings at any time (all $p > 0.136$).

Next, we compared recovery values for alpha-amylase, LF, and LF/HF. Though no differences were found in the recovery values for alpha-amylase (HCE: M_{rank} = 38.11, NR: M_{rank} = 32.74, U = 518.00, z = −1.11, r = 0.13, p = 0.269), there were differences in the recovery values for maximum stress to relaxation during exercise for LF (HCE: M_{rank} = 21.86, NR: M_{rank} = 39.28, U = 199.00, z = −3.83, r = 0.49, $p < 0.001$) and LF/HF (HCE: M_{rank} = 19.38, NR: M_{rank} = 41.53, U = 127.00, z = −4.87, r = 0.62, $p < 0.001$). Similar results were found for values of LF (HCE: M_{rank} = 19.93, NR: M_{rank} = 37.84, U = 160.00, z = −4.03, r = 0.53, $p < 0.001$) and LF/HF (HCE: M_{rank} = 17.52, NR: M_{rank} = 39.94, U = 95.00, z = −5.04, r = 0.66, $p < 0.001$) from last stress response (TSST calculation) to relaxation during exercise. No significant differences in recovery values up to the time after the exercise were found (all $p > 0.127$).

Finally, in the rating of how helpful the exercise was perceived, there were no differences between HCE and NR (HCE: M = 4.80, SD = 1.35; NR: M = 4.46, SD = 1.68; U = 590.50, z = −0.67, r = 0.08, p = 0.504).

Other effects beyond app condition were examined. More advanced puberty (higher PDS values) resulted in higher cortisol and alpha-amylase values. TSST-IV resulted in stronger cortisol reactivities compared to TSST-VR (all $t > 4.81$, all $p < 0.001$, d = [1.13; 1.19]). Higher LF/HF values were obtained for older adolescents and female participants in TSST-IV. Higher stress ratings were obtained for female participants from +25 min to +60 min (all $t < -2.30$, all $p < 0.025$, d = [-0.94; −0.49]). The interaction "Time × App × TSST" could not be confirmed in post-hoc t-tests.

3.3. Comparison of breathing technique and no breathing technique (exploratory analyses)

When comparing NoBT, NaBT and HCE, there were significant differences in recovery values from maximum stress to relaxation during exercise for LF (z = 14.70, η^2 = 0.25, $p < 0.001$, NaBT > HCE, NoBT > HCE, NoBT = NaBT) and LF/HF (z = 24.16, η^2 = 0.40, $p < 0.001$, NaBT > HCE, NoBT > HCE, NoBT = NaBT), similar for recovery values from

Table 2
Results of repeated measures ANOVAs investigating relaxation responses in all parameters.

	Sum of squares	df	Mean of squares	F	p	Partial η^2
Cortisol (HCE, n = 36; NR, n = 37)						
Time	**1.42**	**1.79**	**0.79**	**6.17**	**.004**	**0.08**
Time * PDS	**1.08**	**1.79**	**0.60**	**4.66**	**.014**	**0.06**
Time * App	0.06	1.79	0.03	0.24	.765	0.00
Time * TSST	**1.41**	**1.79**	**0.79**	**6.13**	**.004**	**0.08**
Time * App * TSST	0.32	1.79	0.18	1.37	.257	0.02
Error (Time)	15.68	121.82	0.13			
PDS	**36.24**	**1**	**36.24**	**12.74**	**<.001**	**0.16**
App	6.11	1	6.11	2.15	.147	0.03
TSST	**87.55**	**1**	**87.55**	**30.78**	**<.001**	**0.31**
App * TSST	3.68	1	3.68	1.29	.259	0.02
Error	193.38	68	2.84			
Alpha-amylase (HCE, n = 36; NR, n = 34)						
Time	2.45	4.01	0.61	1.85	.119	0.03
Time * PDS	0.53	4.01	0.13	0.40	.808	0.01
Time * App	0.14	4.01	0.03	0.11	.981	0.00
Time * Sex	1.07	4.01	0.27	0.81	.519	0.01
Time * App * Sex	0.20	4.01	0.05	0.15	.962	0.00
Error (Time)	85.81	260.71	0.33			
PDS	**12.95**	**1**	**12.95**	**6.72**	**.012**	**0.09**
App	**8.73**	**1**	**8.73**	**4.54**	**.037**	**0.07**
Sex	2.95	1	2.95	1.53	.220	0.02
App * Sex	0.55	1	0.55	0.29	.595	0.00
Error	125.17	65	1.93			
HR (HCE, n = 30; NR, n = 35)						
Time	**2.03**	**1.81**	**1.12**	**286.54**	**<.001**	**0.82**
Time * App	0.01	1.81	0.01	1.47	.235	0.02
Error (Time)	0.45	114.30	0.00			
App	0.04	1	0.04	0.75	.389	0.01
Error	3.30	63	0.05			
LF (HCE, n = 27; NR, n = 31)						
Time	**36.79**	**2.41**	**15.28**	**55.24**	**<.001**	**0.50**
Time * App	**7.56**	**2.41**	**3.14**	**11.35**	**<.001**	**0.17**
Error (Time)	37.30	134.88	0.28			
App	4.00	1	4.00	2.41	.126	0.04
Error	93.01	56	1.66			
HF (HCE, n = 27; NR, n = 31)						
Time	**27.34**	**2.17**	**12.60**	**31.98**	**<.001**	**0.36**
Time * App	0.93	2.17	0.43	1.09	.345	0.02
Error (Time)	47.87	121.52	0.39			
App	1.04	1	1.04	0.32	.575	0.01
Error	183.64	56	3.28			
LF/HF (HCE, n = 27; NR, n = 31)						
Time	0.56	2.27	0.25	1.35	.265	0.03
Time * Age	0.36	2.27	0.16	0.85	.442	0.02
Time * App	**15.77**	**2.27**	**6.95**	**37.55**	**<.001**	**0.43**
Time * Sex	0.39	2.27	0.17	0.92	.412	0.02

(continued on next page)

Table 2 (*continued*)

	Sum of squares	df	Mean of squares	*F*	*p*	Partial η^2
Time * TSST	0.66	2.27	0.29	1.57	.211	0.03
Time * App * Sex	0.10	2.27	0.44	2.38	.090	0.05
Time * App * TSST	0.74	2.27	0.33	1.76	.172	0.04
Time * Sex * TSST	0.88	2.27	0.39	2.10	.120	0.04
Time * App * Sex * TSST	0.29	2.27	0.13	0.69	.524	0.01
Error (Time)	20.57	111.16	0.19			
Age	**12.54**	**1**	**12.54**	**19.12**	**<.001**	**0.28**
Sex	0.40	1	0.40	0.61	.440	0.01
App	0.50	1	0.50	0.76	.388	0.02
TSST	0.29	1	0.29	0.44	.513	0.01
App * Sex	0.08	1	0.08	0.12	.726	0.00
App * TSST	0.33	1	0.33	0.51	.479	0.01
Sex * TSST	**4.46**	**1**	**4.46**	**6.79**	**.012**	**0.12**
App * Sex * TSST	2.21	1	2.21	3.36	.073	0.06
Error	32.13	49	0.66			
RMSSD (HCE, *n* = 27; NR, *n* = 32)						
Time	**16.08**	**2.25**	**7.17**	**76.03**	**<.001**	**0.57**
Time * App	0.02	2.25	0.01	0.07	.949	0.00
Error (Time)	12.06	127.95	0.09			
App	0.64	1	0.64	0.71	.404	0.01
Error	51.21	57	0.90			
Stress (HCE, *n* = 36; NR, *n* = 37)						
Time	**57.98**	**2.79**	**20.82**	**111.35**	**<.001**	**0.63**
Time * App	0.22	2.79	0.08	0.41	.728	0.01
Time * TSST	0.75	2.79	0.27	1.44	.234	0.02
Time * Sex	**1.49**	**2.79**	**0.53**	**2.86**	**.042**	**0.04**
Time * App * TSST	**2.89**	**2.79**	**1.04**	**5.55**	**.002**	**0.08**
Time * App * Sex	0.48	2.79	0.17	0.91	.430	0.01
Time * TSST * Sex	0.16	2.79	0.06	0.30	.809	0.01
Time * App * TSST * Sex	0.18	2.79	0.06	0.34	.782	0.01
Error (Time)	33.85	181.02	0.19			
Sex	**7.58**	**1**	**7.58**	**9.88**	**.003**	**0.13**
App	0.76	1	0.76	0.99	.323	0.02
TSST	2.51	1	2.51	3.27	.075	0.05
App * TSST	0.41	1	0.41	0.53	.470	0.01
App * Sex	0.43	1	0.43	0.57	.455	0.01
TSST * Sex	0.00	1	0.00	0.01	.944	0.00
App * TSST * Sex	0.00	1	0.00	0.01	.942	0.00
Error	49.87	65	0.77			

Note. Significant results are in bold, App (Heart Coherence Exercise vs. Natural Relaxation), TSST = Trier Social Stress Test (virtual vs. real version), ANOVA = analysis of variance, T2 = second study date, PDS = Pubertal Development Scale (pubertal status from pre- to post-pubertal), HR = heart rate, LF = low frequency band, HF = high frequency band, LF/HF = low-to-high frequency ratio, RMSSD = root mean square of the successive differences of beat to beat or R-R intervals, "Stress" refers to the stress level rating.

last stress response. Furthermore, there was a significant difference in cortisol recovery ($z = 12.94$, $\eta^2 = 0.18$, $p = 0.002$, HCE > NoBT, NaBT > NoBT, HCE = NaBT; Fig. 4) and subjective stress recovery ($z = 6.23$, $\eta^2 = 0.09$, $p = 0.044$, NaBT > NoBT, HCE = NaBT, HCE = NoBT; Fig. 4). To control for different cortisol increases between groups, a linear regression was calculated with group (HCE and NaBT as dummy variables), maximum cortisol level, and significant factors in the ANOVAs (TSST, PDS) as predictors. The model was significant ($F(5,67) = 4.17$, $p = 0.002$), and both group variables (NaBT, HCE) were significant (positive) predictors (Table S3 in Supplementary Material). A second regression was computed to predict subjective stress increase with group, subjective stress right after the TSST and significant factors in the ANOVAs (TSST, sex) as predictors. The model was significant ($F(5,67) = 23.66$, $p < .001$), and only being in the HCE group was a significant (negative) predictor (Table S3 in Supplementary Material). We also found a significant difference in the rating of how helpful the exercise was perceived (HCE: $M = 4.80$, $SD = 1.35$; NaBT: $M = 5.27$, $SD = 1.10$; NoBT: $M = 3.91$, $SD = 1.80$; $z = 6.66$, $\eta^2 = 0.09$, $p = 0.036$, NaBT > NoBT, HCE = NaBT, HCE = NoBT).

4. Discussion

When analyzing the differences in physiological and psychological relaxation reactions between the HCE and NR groups after acute stress, a mixed picture emerged depending on the parameter examined. General relaxation responses were found in cortisol, heart rate, HRV, and stress rating; only alpha-amylase did not show a clear recovery. Differences between HCEs and NR during relaxation were only seen in LF and LF/HF, with a peak in the HCE group, which indicates different activation processes. Past studies have also reported higher HRV with slow breathing (e.g., Chelidoni et al., 2020), though the findings are contradictory depending on the HRV parameter (Lin et al., 2014). Though the HF is mostly associated with spontaneous breathing at rest due to modulation by the parasympathetic system, the LF has been predominantly linked to sympathetic activity and LF/HF to the balance between both systems, with higher values representing sympathetic dominance (Billman, 2013b; Lin et al., 2014). However, there is increasing evidence that the LF is modulated by both nervous systems and the baroreflex, and that LF/HF is influenced by a complex interaction of (para)sympathetic, vagal, and respiratory processes (Billman, 2013a, 2013b; Lin et al., 2014). At 6 breaths/minute, there is a high respiratory sinus arrhythmia (RSA) amplitude, meaning short-term suppression of parasympathetic activity during inhalation (heart rate increase) and restoration of vagal/parasympathetic activity during exhalation (heart rate reduction) (Lehrer et al., 2000; Lin et al., 2014). When breathing at this rate in resonant frequency, improvements in mood, oxygen saturation, vagal tone, blood pressure, and baroreflex sensitivity can be observed, with increases in RSA and the LF (Bernardi et al., 2002; Chaitanya et al., 2022; Joseph et al., 2005; Lehrer et al., 2000; Lin et al., 2014; Steffen et al., 2017). Therefore, high LF values (resulting in increased LF/HF) indicate improvements in cardiovascular-respiratory function (Billman, 2013a; Lin et al., 2014), but also in psychological processes (Chaitanya et al., 2022; Steffen et al., 2017). In our study, we also found higher LF/HF values for older adolescents and girls, but only with TSST-IV. Sex differences could be due to different group sizes and responsiveness to stressor types (social evaluation by real vs. virtual panel). However, sex-specific regulatory effects of the autonomic nervous system in adolescence, as well as age in general due to the rapid/strong physical changes during puberty, on LF/HF should also be taken into account (Estévez-Báez et al., 2019). Another possible reason for the age differences could be the final developmental phase for establishing sympatho-vagal balance in this stage of life (Zavodna et al., 2015).

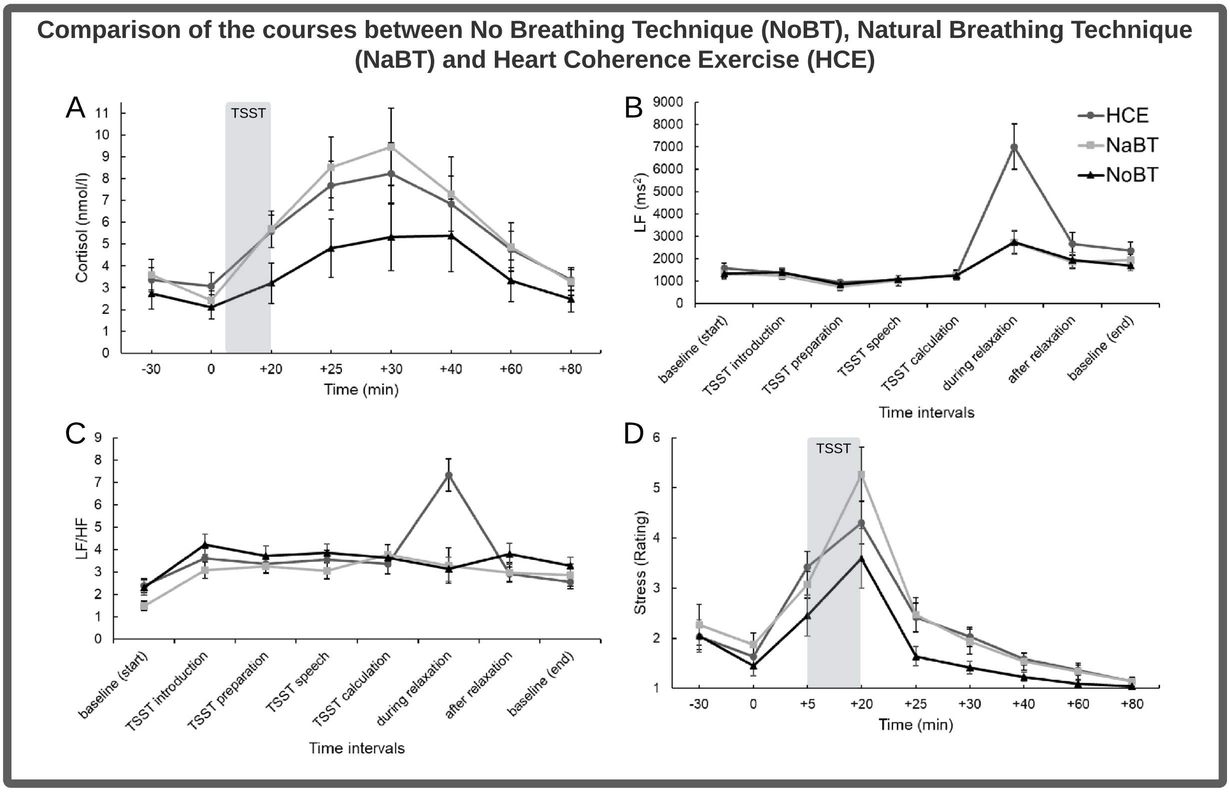

Fig. 4. Comparison of the courses between no breathing technique (NoBT), natural breathing technique (NaBT) and app-guided heart coherence breathing (HCE). TSST = Trier Social Stress Test, LF = low frequency band, LF/HF = low-to-high frequency ratio. For clarity, only parameters with significantly different recovery values are presented. Error bars indicate standard error.

Overall, there are only a few studies on sex- and age-specific differences in coping with stress in adolescence/puberty, which is why further studies on these relationships are necessary.

Although we did not find differences in relaxation strength between HCE and NR for alpha-amylase, the main effects were in regard to the PDS and app. With regard to the PDS, increased alpha-amylase reactivity in later puberty during stressful situations results from maturation processes and increases in sensitivity to social evaluation (Sumter et al., 2010; van den Bos et al., 2014). The app effect, with significantly higher alpha-amylase levels for HCE at all time points before and isolated time points after relaxation, could indicate a sampling and/or anticipation effect. As all participants were informed in advance that a speech must be given, the HCE group may have increasingly suspected a stressful situation due to the specific breathing instructions. They may also have implicitly developed a "pressure to perform" due to social desirability, resulting in higher tension and increased alpha-amylase levels.

Overall, there were no differences in cortisol, heart rate, HF, RMSSD, or stress rating between the HCE and NR groups. This supports previous studies showing a mixed picture with higher HRV (Chelidoni et al., 2020; Plans et al., 2019), lower alpha-amylase levels, and no differences in cortisol and mood (Hunter et al., 2019). Cortisol also exhibited increased reactivity in advanced puberty due to maturation processes (Sumter et al., 2010; van den Bos et al., 2014) and in TSST-IV. Despite comparable stress responses between real and virtual TSSTs, cortisol usually shows stronger reactivity in real conditions (Ecker et al., 2024; Helminen et al., 2021, 2019). First, a stress-reducing safety effect can be discussed due to the low threshold VR context (Ecker et al., 2024). Second, the TSST-IV could have been assessed as more threatening, which is why more energy from the body is required for fight-or-flight responses. Girls had higher subjective stress levels, which supports previous assumptions that they may express their internalizing feelings/behaviors more strongly than boys (Sanchis-Sanchis et al., 2020).

As 15 participants in the NR group also used a general breathing strategy, the relaxation responses between HCE, NaBT and NoBT were exploratively analyzed. Results were comparable regarding LF and LF/HF, as only the HCE group showed a clear peak during the exercise. Furthermore, HCE and NaBT showed higher cortisol and subjective stress recovery values, but also stronger stress reactivities due to the TSST in advance. Reasons for the stronger reactivities could be the smaller group sizes or possible anticipation effects (in the sense: “It will be a stressful situation on the second study date,… 1) HCE: …I have therefore been assigned an app-guided breathing technique.” or 2) NaBT: …I therefore have to think about a relaxation technique.”). It is also conceivable that adolescents with generally higher stress reactivity are more likely to use breathing techniques to cope with stress. The latter assumption is also supported by the fact that adolescents in the NaBT group rated the exercise as significantly more helpful, as they had possibly already experienced that it was supportive and a safety net/anchor for them in times of stress. However, when controlling for stress reactivity using the maximum values, the two breathing technique groups (HCE, NaBT) predict a stronger recovery response in cortisol. For subjective stress levels, unexpectedly, the HCE group predicted smaller improvements in mood. As these are purely exploratory analyses and preliminary results, it can therefore only be speculated whether cortisol recovery is less dependent on specific breathing strategies compared to HRV, and more dependent on the use of breathing as a coping strategy in general. Maybe the knowledge/availability of a breathing strategy could have increased the feeling of safety/self-efficacy, followed by a stronger cortisol recovery.

The smaller recovery values in subjective stress in the HCE group could result from the fact that slow breathing is seen as unpleasant/difficult to perform, particularly at the start of training (Lin et al., 2014). As participants only learned the exercise on two evenings due to the research question, they may have focused too much on inhalation, which can sometimes increase physical tension (Toussaint et al., 2021).

Although only relaxation differences in LF and LF/HF for HCE were found, missing differences in other parameters could have resulted from study limitations. First, the results can only be discussed for healthy children and adolescents. This may be associated with little variance in data, which is why small effects do not emerge. Another limitation is that the use of a (natural) breathing strategy in NR could not be prevented/forbidden, and a real or virtual TSST was used for stress induction, which was taken into account in the statistical analyses and the counterbalanced group allocation. Both TSST versions contained the important components of social evaluation and uncontrollability for successful stress induction (Dickerson and Kemeny, 2004), which was the basis for investigating relaxation responses in both study groups. It should also be noted that practicing the HCE in advance on two evenings at home could have had an effect on the stress situation on T2. Despite the short training time, general positive effects of the exercise on the stress response cannot be ruled out. In addition, participants may also have performed the HCE for themselves without being asked during the TSST preparation in order to calm themselves down in advance without this being noticed by the study management.

The major strengths of the study were the comprehensive characterization of the relatively large sample, investigation of coping processes via breathing in children and adolescents, and measurement of various stress parameters (i.e., cortisol, alpha-amylase, heart rate, HRV, and mood). In the future, it would be important to investigate clinical samples with a broad spectrum of psychiatric disturbances, dysfunctional coping strategies (e.g., self-injurious behaviors), and deviating physiological reactivities (e.g., stronger cortisol awakening responses) (Reichl et al., 2016). Furthermore, comparisons with other active control groups (e.g., mindfulness, imagination, and body-oriented relaxation) would be useful. It would also be conceivable to extend the variables (e.g., skin conductance, neuronal activity, positive emotions, such as feeling happy or balanced). In addition, respiration rate should be included as a control variable in the future.

In summary, we were able to demonstrate that performing an app-guided HCE results in increased frequency-dependent HRV parameters (LF, LF/HF) compared to NR responses in adolescents after acute stress. These changes can be explained by stimulation of vagal tone and baroreflex using slow breathing, which addresses cardiovascular-respiratory functions. These results can make an important contribution to discussions of modulation pathways of LF and LF/HF (Billman, 2013b; Lin et al., 2014). Furthermore, the effects of slow breathing on HRV can be confirmed not only for young adults (Chaitanya et al., 2022) or patients with physical illnesses (Bernardi et al., 2002; Joseph et al., 2005), but also for healthy adolescents. In this age range, additional variables (e.g., stressor type, gender, puberty) should be considered when analyzing relaxation reactions. The use of a breathing technique also resulted in stronger recovery in cortisol (but also stronger preceding stress reactivities), possibly due to the knowledge of an effective coping strategy and feeling of self-efficacy. This is further supported by the evaluation that the use of an already known natural breathing technique was rated as being more helpful. Though the specific breathing strategy/pattern itself illustrates improvements in HRV, psychological components of the exercises (e.g., possible re-evaluation of the situation through self-efficacy/confidence) appear to have more influence on cortisol. Nevertheless, it should be noted that performing a slow app-guided breathing technique without a long training period may be subjectively perceived as unpleasant during relaxation.

5. Conclusion

In our study, the answer to the question “Does it need an app?” for practicing helpful coping strategies, such as breathing exercises for children and adolescents, was “Yes.” The integration of breathing exercises as quickly learned, always available, and low-threshold "coping tools" in health apps for children and adolescents seems to be useful especially on a respiratory and cardiovascular level – possibly also due to the high level of acceptance of digital media in this age range. Further research should be conducted to determine whether app-guided exercises are really helpful in reducing stress and preventing stress-related psychiatric disorders in all age groups.

Ethics statement and consent to participate

This study was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and was approved by the Ethics Committee of the University of Regensburg (reference number: 20-1800-101, date of ethical approval: 22 April 2020). Informed consent was obtained from all participants and their accompanying parent/guardian.

Funding

This study was financed by the Department of Child and Adolescent Psychiatry and Psychotherapy, University of Regensburg, under the direction of Prof. Dr. Romuald Brunner. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Daniel Schleicher: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Angelika Ecker:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Martin Kocur:** Writing – review & editing, Software, Resources, Methodology. **Irina Jarvers:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation. **Romuald Brunner:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Stephanie Kandsperger:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of Competing Interest

No conflict

Acknowledgements

We would like to thank Colin Nash for programming the health app with the integrated relaxation exercises and our research assistants for helping collect and pre-process the data. Moreover, many thanks to the participants and their parents/guardians for their motivated participation in the study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2024.107148.

References

Ali, N., Nater, U.M., 2020. Salivary alpha-amylase as a biomarker of stress in behavioral medicine. Int. J. Behav. Med. 27, 337–342. https://doi.org/10.1007/s12529-019-09843-x.

Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc.: Ser. B (Methodol.) 57, 289–300.

Bernardi, L., Porta, C., Spicuzza, L., Bellwon, J., Spadacini, G., Frey, A.W., Yeung, L.Y.C., Sanderson, J.E., Pedretti, R., Tramarin, R., 2002. Slow breathing increases arterial baroreflex sensitivity in patients with chronic heart failure. Circulation 105, 143–145. https://doi.org/10.1161/hc0202.103311.

Billman, G.E., 2013a. The effect of heart rate on the heart rate variability response to autonomic interventions. Front. Physiol. 4, 222. https://doi.org/10.3389/fphys.2013.00222.

Billman, G.E., 2013b. The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. Front. Physiol. 4, 26. https://doi.org/10.3389/fphys.2013.00026.
Buske-Kirschbaum, A., Jobst, S., Wustmans, A., Kirschbaum, C., Rauh, W., Hellhammer, D., 1997. Attenuated free cortisol response to psychosocial stress in children with atopic dermatitis. Psychosom. Med. 59, 419.
Chaitanya, S., Datta, A., Bhandari, B., Sharma, V.K., 2022. Effect of resonance breathing on heart rate variability and cognitive functions in young adults: a randomised controlled study. Cureus 14, e22187. https://doi.org/10.7759/cureus.22187.
Chelidoni, O., Plans, D., Ponzo, S., Morelli, D., Cropley, M., 2020. Exploring the effects of a brief biofeedback breathing session delivered through the biobase app in facilitating employee stress recovery: randomized experimental study. JMIR mHealth uHealth 8, e19412.
Dickerson, S.S., Kemeny, M.E., 2004. Acute stressors and cortisol responses: a theoretical integration and synthesis of laboratory research. Psychol. Bull. 130, 355–391. https://doi.org/10.1037/0033-2909.130.3.355.
Döpfner, M., Plück, J., Kinnen, C., 2014. CBCL/6-18R, TRF/6-18R, YSR/11-18R. Deutsche Schulalter-Formen der Child Behavior Checklist von Thomas M. Achenbach, Göttingen: Hogrefe.
Ecker, A., Jarvers, I., Kocur, M., Kandsperger, S., Brunner, R., Schleicher, D., 2024. Multifactorial stress reactivity to virtual TSST-C in healthy children and adolescents-It works, but not as well as a real TSST-C. Psychoneuroendocrinology 160, 106681. https://doi.org/10.1016/j.psyneuen.2023.106681.
Estévez-Báez, M., Carricarte-Naranjo, C., Jas-García, J.D., Rodríguez-Ríos, E., Machado, C., Montes-Brown, J., Leisman, G., Schiavi, A., Machado-García, A., Luaces, C.S., Pié, E.A., 2019. Influence of heart rate, age, and gender on heart rate variability in adolescents and young adults. Adv. Exp. Med. Biol. 1133, 19–33. https://doi.org/10.1007/5584_2018_292.
Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39, 175–191. https://doi.org/10.3758/BF03193146.
Hathaisaard, C., Wannarit, K., Pattanaseri, K., 2022. Mindfulness-based interventions reducing and preventing stress and burnout in medical students: a systematic review and meta-analysis. Asian J. Psychiatry 69, 102997. https://doi.org/10.1016/j.ajp.2021.102997.
Helminen, E.C., Morton, M.L., Wang, Q., Felver, J.C., 2019. A meta-analysis of cortisol reactivity to the Trier Social Stress Test in virtual environments. Psychoneuroendocrinology 110, 104437. https://doi.org/10.1016/j.psyneuen.2019.104437.
Helminen, E.C., Morton, M.L., Wang, Q., Felver, J.C., 2021. Stress reactivity to the trier social stress test in traditional and virtual environments: a meta-analytic comparison. Psychosom. Med. 83, 200–211. https://doi.org/10.1097/PSY.0000000000000918.
Hunter, J.F., Olah, M.S., Williams, A.L., Parks, A.C., Pressman, S.D., 2019. Effect of brief biofeedback via a smartphone app on stress recovery: randomized experimental study. JMIR Serious Games 7, e15974. https://doi.org/10.2196/15974.
Jasubhai, S., 2021. Effect of quick coherence technique on psychophysiological coherence, heart rate, stress, anxiety, depression and feeling state in young adults in India. J. Psychol. Neurosci. 3, 1–9. https://doi.org/10.47485/2693-2490.1042.
Joseph, C.N., Porta, C., Casucci, G., Casiraghi, N., Maffeis, M., Rossi, M., Bernardi, L., 2005. Slow breathing improves arterial baroreflex sensitivity and decreases blood pressure in essential hypertension. Hypertension 46, 714–718. https://doi.org/10.1161/01.HYP.0000179581.68566.7d.
Kelly, O., Matheson, K., Martinez, A., Merali, Z., Anisman, H., 2007. Psychosocial stress evoked by a virtual audience: relation to neuroendocrine activity. Cyber Behav.: Impact Internet, Multimed. Virtual Real. Behav. Soc. 10, 655–662. https://doi.org/10.1089/cpb.2007.9973.
Kirschbaum, C., Pirke, K.M., Hellhammer, D.H., 1993. The 'Trier Social Stress Test'—a tool for investigating psychobiological stress responses in a laboratory setting. NPS 28, 76–81. https://doi.org/10.1159/000119004.
Lakens, D., 2017. Equivalence tests: a practical primer for t tests, correlations, and meta-analyses. Soc. Psychol. Personal. Sci. 8, 355–362. https://doi.org/10.1177/1948550617697177.
Lazarus, R.S., Folkman, S., 1984. Stress, appraisal, and coping. Springer, New York, 445 pp.
Lehrer, P.M., Gevirtz, R., 2014. Heart rate variability biofeedback: how and why does it work? Front. Psychol. 5, 756. https://doi.org/10.3389/fpsyg.2014.00756.
Lehrer, P.M., Vaschillo, E., Vaschillo, B., 2000. Resonant frequency biofeedback training to increase cardiac variability: rationale and manual for training. Appl. Psychophysiol. Biofeedback 25, 177–191. https://doi.org/10.1023/A:1009554825745.
Lin, I.-M., Fan, S.-Y., Yen, C.-F., Yeh, Y.-C., Tang, T.-C., Huang, M.-F., Liu, T.-L., Wang, P.-W., Lin, H.-C., Tsai, H.-Y., Tsai, Y.-C., 2019. Heart rate variability biofeedback increased autonomic activation and improved symptoms of depression and insomnia among patients with major depression disorder. Clin. Psychopharmacol. Neurosci.: Off. Sci. J. Korean Coll. Neuropsychopharmacol. 17, 222–232. https://doi.org/10.9758/cpn.2019.17.2.222.
Lin, I.-M., Tai, L.Y., Fan, S.Y., 2014. Breathing at a rate of 5.5 breaths per minute with equal inhalation-to-exhalation ratio increases heart rate variability. Int. J. Psychophysiol.: Off. J. Int. Organ. Psychophysiol. 91, 206–211. https://doi.org/10.1016/j.ijpsycho.2013.12.006.
Linardon, J., Cuijpers, P., Carlbring, P., Messer, M., Fuller-Tyszkiewicz, M., 2019. The efficacy of app-supported smartphone interventions for mental health problems: a meta-analysis of randomized controlled trials. World Psychiatry 18, 325–336. https://doi.org/10.1002/wps.20673.
McCraty, R., Zayas, M.A., 2014. Cardiac coherence, self-regulation, autonomic stability, and psychosocial well-being. Front. Psychol. 5, 1090 https://doi.org/10.3389/fpsyg.2014.01090.
Morton, M.L., Helminen, E.C., Felver, J.C., 2020. A systematic review of mindfulness interventions on psychophysiological responses to acute stress. Mindfulness 11, 2039–2054. https://doi.org/10.1007/s12671-020-01386-7.
O'Connor, D.B., Thayer, J.F., Vedhara, K., 2021. Stress and health: a review of psychobiological processes. Annu. Rev. Psychol. 72, 663–688. https://doi.org/10.1146/annurev-psych-062520-122331.
Perciavalle, V., Blandini, M., Fecarotta, P., Buscemi, A., Di Corrado, D., Bertolo, L., Fichera, F., Coco, M., 2017. The role of deep breathing on stress. Neurol. Sci. 38, 451–458. https://doi.org/10.1007/s10072-016-2790-8.
Petersen, A.C., Crockett, L., Richards, M., Boxer, A., 1988. A self-report measure of pubertal status: reliability, validity, and initial norms. J. Youth Adolesc. 17, 117–133.
Plans, D., Morelli, D., Sütterlin, S., Ollis, L., Derbyshire, G., Cropley, M., 2019. Use of a biofeedback breathing app to augment poststress physiological recovery: randomized pilot study. JMIR Form. Res. 3, e12227.
Reichl, C., Heyer, A., Brunner, R., Parzer, P., Völker, J.M., Resch, F., Kaess, M., 2016. Hypothalamic-pituitary-adrenal axis, childhood adversity and adolescent nonsuicidal self-injury. Psychoneuroendocrinology 74, 203–211. https://doi.org/10.1016/j.psyneuen.2016.09.011.
Sanchis-Sanchis, A., Grau, M.D., Moliner, A.-R., Morales-Murillo, C.P., 2020. Effects of age and gender in emotion regulation of children and adolescents. Front. Psychol. 11, 946. https://doi.org/10.3389/fpsyg.2020.00946.
Schlatter, S.T., Thérond, C.C., Guillot, A., Louisy, S.P., Duclos, A., Lehot, J.-J., Rimmelé, T., Debarnot, U.S., Lilot, M.E., 2022. Effects of relaxing breathing paired with cardiac biofeedback on performance and relaxation during critical simulated situations: a prospective randomized controlled trial. BMC Med Educ. 22, 422. https://doi.org/10.1186/s12909-022-03420-9.
Schleicher, D., Ecker, A., Kocur, M., Jarvers, I., Nash, C., Götz, L., Otto, A.H., Kandsperger, S., Brunner, R., 2022. Psychosocial stress induction in vivo vs. in virtuo and the influence of a health app on the acute stress reaction in youths: a study protocol for a randomized controlled trial. Trials 23, 847. https://doi.org/10.1186/s13063-022-06758-z.
Sheehan, D.V., Lecrubier, Y., Sheehan, K.H., Amorim, P., Janavs, J., Weiller, E., Hergueta, T., Baker, R., Dunbar, G.C., 1998. The Mini-International Neuropsychiatric Interview (MINI): the development and validation of a structured diagnostic psychiatric interview for DSM-IV and ICD-10. J. Clin. Psychiatry.
Slater, M., 2018. Immersion and the illusion of presence in virtual reality. Br. J. Psychol. (London, England: 1953) 109, 431–433. https://doi.org/10.1111/bjop.12305.
Steffen, P.R., Austin, T., DeBarros, A., Brown, T., 2017. The impact of resonance frequency breathing on measures of heart rate variability, blood pressure, and mood. Front. Public Health 5, 222. https://doi.org/10.3389/fpubh.2017.00222.
Steffen, P.R., Bartlett, D., Channell, R.M., Jackman, K., Cressman, M., Bills, J., Pescatello, M., 2021. Integrating breathing techniques into psychotherapy to improve HRV: which approach is best? Front. Psychol. 12, 624254 https://doi.org/10.3389/fpsyg.2021.624254.
Sumter, S.R., Bokhorst, C.L., Miers, A.C., van Pelt, J., Westenberg, P.M., 2010. Age and puberty differences in stress responses during a public speaking task: do adolescents grow more sensitive to social evaluation? Psychoneuroendocrinology 35, 1510–1516. https://doi.org/10.1016/j.psyneuen.2010.05.004.
Toussaint, L., Nguyen, Q.A., Roettger, C., Dixon, K., Offenbächer, M., Kohls, N., Hirsch, J., Sirois, F., 2021. Effectiveness of progressive muscle relaxation, deep breathing, and guided imagery in promoting psychological and physiological states of relaxation. Evid. -Based Complement. Altern. Med. 2021, 5924040 https://doi.org/10.1155/2021/5924040.
Vacha-Haase, T., Thompson, B., 2004. How to estimate and interpret various effect sizes. J. Couns. Psychol. 51, 473–481. https://doi.org/10.1037/0022-0167.51.4.473.
van den Bos, E., Rooij, M., de, Miers, A.C., Bokhorst, C.L., Westenberg, P.M., 2014. Adolescents' increasing stress response to social evaluation: pubertal effects on cortisol and alpha-amylase during public speaking. Child Dev. 85, 220–236. https://doi.org/10.1111/cdev.12118.
Wang, K., Varma, D.S., Prosperi, M., 2018. A systematic review of the effectiveness of mobile apps for monitoring and management of mental health symptoms or disorders. J. Psychiatr. Res. 107, 73–78. https://doi.org/10.1016/j.jpsychires.2018.10.006.
Weiß, R., 2006. Grundintelligenztest Skala 2-Revision (CFT 20-R). Hogrefe.
Yim, I.S., Quas, J.A., Cahill, L., Hayakawa, C.M., 2010. Children's and adults' salivary cortisol responses to an identical psychosocial laboratory stressor. Psychoneuroendocrinology 35, 241–248. https://doi.org/10.1016/j.psyneuen.2009.06.014.
Zavodna, E., Hruskova, J., Budinskaya, K., Novakova, Z., Hrstkova, H., Brazdova, L., Honzikova, N., 2015. The development of LF/HF ratio and its dependence on the mean heart rate in children and adolescents. 2015 Computing in Cardiology Conference (CinC). IEEE.