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ABSTRACT

Valid approaches to conveniently measure stress reactivity are needed due to the growing evidence of its health-impairing effects. This study examined whether the Perceived Stress Reactivity Scale (PSRS) predicts cardiovascular and psychological responses to psychosocial stressors during daily life and during a virtual reality (VR) Trier Social Stress Test (TSST). Medical students answered a standardized baseline questionnaire to assess perceived stress reactivity by the PSRS. The PSRS asks participants to rate the intensity of their typical affective responses to common stressors during daily life. They were further asked to participate in a VR-TSST and in an ecological momentary assessment (EMA) over a period of three consecutive workdays during daily life. Blood pressure and self-reported stress were repeatedly, heart rate variability (HRV) continuously measured during the VR-TSST and EMA. Furthermore, participants repeatedly assessed task demands, task control and social conflict during the EMA. Data was analysed using multilevel analysis and multiple linear regression. Results indicate that the PSRS moderates associations between blood pressure (but not HRV) and demands and control during daily life. Furthermore, the PSRS directly predicted self-reported stress, but did not moderate associations between self-reported stress and demands, control and social conflict. The PSRS did not predict physiological and self-reported stress responses to the VR-TSST. This study partly confirmed convergent validity of the PSRS to stress reactivity in daily life. Furthermore, the lack of association between the PSRS and stress responses to the VR-TSST calls for future studies to search for reliable and valid ways to assess stress reactivity.

1. Introduction

Growing scientific evidence indicates that psychosocial stress increases the risk for the development of several chronic diseases and acute cardiovascular events (Niedhammer et al., 2021; Sara et al., 2018; Seidler et al., 2022; Theorell et al., 2015). This link is often observed in the work context. Adverse psychosocial working conditions as described by established work stress models such as the job-demand-control model (Karasek, 1979) have repeatedly been shown to predict coronary heart disease, stroke, mental disorders and other stress-related diseases (Niedhammer et al., 2021; Seidler et al., 2022). The research literature thereby differentiates between stressor exposure (e.g. adverse psychosocial working conditions) and subsequent psychological, behavioural and physiological responses to those stressors, which in this study are called stress responses (Epel et al., 2018). The magnitude of acute stress response varies inter-individually and is called stress reactivity (Schlotz et al., 2011b; Schulz et al., 2005). Exaggerated stress reactivity is associated with a higher risk of hypertension and cardiovascular diseases, but also blunted stress reactivity was shown to predict poorer health outcomes (Chida & Steptoe, 2010; Hamer et al., 2012; Turner et al., 2020). Tools to reliably assess stress reactivity may thus help to identify individuals with an increased risk for cardiovascular and other

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stress-related diseases. This study therefore investigates relationships of the Perceived Stress Reactivity Scale (PSRS) as a tool to measure stress reactivity with stress responses in the Trier Social Stress Test (TSST) and with within-subject associations between psychological stress-related and physiological parameters and severity of stressor exposure in Ecological Momentary Assessment (EMA).

The TSST has repeatedly been used as a gold standard to investigate stress responses to a standardized psychosocial laboratory stressor (Kirschbaum et al., 1993). It consists of a preparation phase, followed by a speech and arithmetic math test in front of a selection committee (Kirschbaum et al., 1993). The TSST is perceived as a social-evaluative threat within an uncontrollable setting and reliably triggers typical stress responses including an increase in heart rate, blood pressure and salivary cortisol concentration (Allen et al., 2014; Dickerson & Kemeny, 2004). The magnitude of the stress response is thereby typically operationalized as the change of stress response indicators during the TSST in relation to resting levels before the TSST (Kirschbaum et al., 1993). Stress reactivity may then be defined as inter-individual differences in the magnitude of the stress response (Kirschbaum et al., 1993; Schlotz et al., 2011b; Schulz et al., 2005). In recent years, virtual reality (VR) versions of the TSST were developed to save personnel resources and increase standardization (Helminen et al., 2019; Liszio et al., 2018; Zimmer et al., 2019a). Those VR versions of the TSST have been shown to reliably induce typical stress responses even though in a smaller magnitude than the original face-to-face version (Helminen et al., 2019). However, evidence on the generalizability of cardiovascular stress responses (i.e. ecological validity) to real-life situations is still limited for the TSST (Zanstra & Johnston, 2011). For example, Henze et al. (2017) compared stress responses to the TSST with those to an oral examination in real-life and found similar cortisol responses in both settings. In contrast, Wolfram et al. (2013) compared the TSST with a graded demonstration lesson in a sample of student teachers and found no association between cortisol responses. Even less research exists in how far stress responses to the TSST resemble stress responses to more minor events, such as daily hassles.

This problem can be solved by using EMA, which allows continuous or recurrent measurement of momentary experience of stressors as well as psychological and physiological stress-related parameters as they occur in daily life (e.g. Johnston et al. (2016); Kamarck et al. (1998a); Shiffman et al. (2008)). Stressor exposure is usually collected by standardized questionnaires, most recently within mobile applications, and typically relates to important aspects of everyday life including work, education or private life (e.g. Johnston et al. (2016); Qu et al. (2020); Schmid and Thomas (2020); Schwerdtfeger and Dick (2019)). Also, psychological stress-related parameters (e.g. self-reported stress) are usually collected by standardized questionnaires, whereas physiological parameters (e.g. blood pressure, heart rate) might be measured by physiological monitoring devices, such as ambulatory ECG and blood pressure monitors (Raugh et al., 2019; Shiffman et al., 2008; Trull & Ebner-Priemer, 2013). Due to repeated measurements, within- as well as between-subject associations between stressor exposure and psychological stress-related and physiological parameters can thus be investigated by EMA using multilevel modelling (Trull & Ebner-Priemer, 2013). Recent EMA works have then operationalized stress reactivity as the inter-individual variance of the strength of the within-subject association between stressor exposure and psychological stress-related and physiological parameters (Schilling et al., 2020; Sheets & Armey, 2020; Timmons et al., 2019; Weber et al., 2022). However, operationalization of stress responses (and thus stress reactivity) in EMA research may differ from the operationalization within laboratory research using the TSST. Whereas stress responses in the TSST typically relate to within-subject differences in psychological or physiological parameters between a stress condition and a standardized quiet or neutral control condition (Kirschbaum et al., 1993), EMA research often lacks a standardized quiet or neutral control condition due to the focus on daily life. Instead, EMA works often investigate within-subject associations between stressor exposure and psychological stress-related and physiological parameters by expecting that parameters such as self-reported stress, heart rate or blood pressure increase at time points when participants report stressor exposure (Schilling et al., 2020; Sheets & Armey, 2020; Timmons et al., 2019; Weber et al., 2022). When assessing the severity of acute stressors by continuous or ordinal scales ranging from low to high stressfulness, this within-subject association thus reflects the intra-individual average change of the outcome per one point increase of the severity of stressor exposure. In this case, the within-subject association does not reflect the difference in the outcome between situations of stressor occurrence versus no stressor occurrence as in TSST research, but compares situations of higher stressor severity with lower stressor severity. This procedure is typically used to assess the influence of psychosocial working conditions on psychological stress-related and physiological parameters during daily life (Balducci et al., 2022; Bishop et al., 2003; Ilies et al., 2010; Johnston et al., 2016; Kamarck et al., 2002; Thomas et al., 2019). Regarding blood pressure, at least two out of four studies have confirmed that EMA methods are able to link demands, control and social conflict to momentary blood pressure levels during daily life (Balducci et al., 2022; Bishop et al., 2003; Kamarck et al., 2002; Thomas et al., 2019).

The PSRS was developed as a standardized questionnaire to measure perceived stress reactivity (Schlotz et al., 2011b). This questionnaire asks participants about the intensity of their typical affective responses (e.g. reacting calm, impatient or hectic) to 29 common stressors during daily life (e.g. social conflicts, high workload, task failures) and calculates a sum score with higher values representing stronger general reactivity to stress (Schlotz et al., 2011b; Schulz et al., 2005). According to stress reactivity theory, it reflects a predominantly stable disposition explaining inter-individual variance in acute physiological and psychological responses to stress (Schlotz et al., 2011b). The PSRS has been found to be predictive of mental health outcomes (Herr et al., 2018; Schlotz et al., 2011b). Compared to the (VR-) TSST and EMA, the use of PSRS is less time-consuming for participants and researchers, requires less organizational expenditure and is more participant-friendly by avoiding the experience of a laboratory stressor. A disadvantage of the PSRS is that it does not measure physiological stress responses, but a first study showed that higher values in the PSRS are associated with stronger cortisol responses to the TSST (Schlotz et al., 2011a). To the best of our knowledge, studies investigating whether the PSRS also predicts relationships between stressor exposure and psychological stress-related and physiological parameters in daily life are lacking so far. More evidence is thus needed on the convergent validity of the PSRS. We therefore aim to investigate whether the PSRS (i) predicts stress responses to the VR-TSST as a standardized laboratory stressors and (ii) moderates within-subject associations between psychological stress-related and physiological parameters and severity of stressor exposure (task demands, task control and social conflicts) in daily life as measured by EMA. Knowledge on those relationships could help to establish the PSRS as a simpler tool to measure stress reactivity as compared to the TSST or EMA.

Heart rate variability (HRV), heart rate and blood pressure have repeatedly been used as typical parameters to quantify cardiovascular responses to acute stressors within experimental stress research (Boesch et al., 2014; Fallon et al., 2021; Kothgassner et al., 2021; Matthews et al., 2001; Smeets et al., 2012) as well as EMA (Bowen et al., 2014; Brondolo et al., 2003; Buckley et al., 2004; Määttänen et al., 2021; Pieper et al., 2010; Schilling et al., 2020; Schwerdtfeger & Dick, 2019; Thomas et al., 2019; Wrzus et al., 2013). Experience of acute stressors is related to reduced levels of various HRV parameters such as standard deviation of NN intervals (SDNN), root mean square of successive differences (RMSSD) or high-frequency power (HF) and increased blood pressure and heart rate due to regulation by the autonomic nervous system (Kim et al., 2018; McEwen, 1998). A reduced level of various HRV parameters (e.g. SDNN, HF power, ratio of low to high frequency power (LF/HF ratio), detrended fluctuation analysis (DFA1)) have been identified as predictors to cardiovascular and all-cause mortality (Buccelletti et al., 2009; Chattipakorn et al., 2007; Jarczok et al., 2022). Furthermore, blunted HF-HRV reactivity to psychosocial laboratory stress tests has been observed in individuals with major depressive disorders (Schiweck et al., 2019). Regarding blood pressure, increased reactivity to laboratory stress tests predicts future risk of hypertension, atherosclerosis and cardiovascular mortality (Turner et al., 2020). As typical cardiovascular outcomes in the TSST and EMA and as meaningful predictors for various health-related outcomes, HRV-parameters (RMSSD, HF-HRV and LF-HRV), heart rate and blood pressure will therefore be used as primary outcomes in this study. However, the PSRS rather measures cognitive than physiological responses to stressful situations such as feeling stressed, nervous, annoyed or upset (Schlotz et al., 2011b). Furthermore, experimental research was often unable to link such cognitive responses with physiological responses to laboratory stressors such as the TSST (Campbell & Ehlert, 2012). Mixed findings regarding an association between self-reported stress and HRV parameters including RMSSD and HF-HRV were also obtained among EMA studies (Weber et al., 2022). Self-reported stress will therefore be used as a secondary outcome.

College and university students are often used as a study population in stress research (e.g. EMA stress research: Conley and Lehman (2012); Hawkley et al. (2003); Sladek et al. (2020); TSST research: Fallon et al. (2021); Henze et al. (2017); Kothgassner et al. (2021)). Medical students represent a study population that experience high stress levels due to the high workload and high social and emotional demands associated with medical studies (Kötter et al., 2015; Weber et al., 2019). High stress levels often continue during further medical training and professional life (e.g. Bragard et al. (2015); De Sio et al. (2020); Knesebeck et al. (2010)). Compared to the general population, medical students have an increased prevalence of depressive symptoms, distress and other stress-related diseases (Peng et al., 2023). Medical students are thus a suitable population to study relationships of the Perceived Stress Reactivity Scale (PSRS) with stress responses in the Trier Social Stress Test (TSST) and with within-subject associations between psychological stress-related and physiological parameters and severity of stressor exposure in Ecological Momentary Assessment (EMA).

This study will thus test the following hypotheses in a sample of medical students:

i) The PSRS will moderate associations between self-reported stress and cardiovascular parameters (RMSSD, HF-HRV, LF-HRV, heart rate, blood pressure) and task demands, task control and social conflict in daily life as being measured by EMA. Medical students scoring higher on the PSRS will have lower HRV levels (RMSSD, HF and LF) and higher blood pressure, heart rate and self-reported stress levels in association with high demands, social conflict and low control than medical students scoring lower on the PSRS.
ii) The PSRS will predict HRV (RMSSD, HF and LF), heart rate, blood pressure and self-reported stress responses to the VR-TSST. Medical students scoring higher on the PSRS will show a larger decrease in HRV levels (RMSSD, HF and LF) and a stronger increase in heart rate, blood pressure and self-reported stress than medical students scoring lower on the PSRS.

2. Methods

This study combines a baseline survey assessing self-reported perceived stress reactivity with EMA and a laboratory stress test, namely a VR version of the TSST. Prior to data collection, the study was registered at OSF (3-S Student Study: Stress, strain, stress reactivity among medical students; https://osf.io/xkrz5). The study was approved by the ethics committee of the Heinrich-Heine-University Düsseldorf (2019–714_1).

2.1. Participants

A convenience sample of medical students was recruited from a medical faculty in Germany via social media (e.g. via the Facebook website of the student body of the medical faculty, semester groups at WhatsApp). The recruitment period was one year from July 2020 to July 2021 and thus included lecture- and non-lecture periods. However, one requirement for participation in the study was that students were engaged with study-related activities during the time of data collection (i.e. lectures, exam preparation, internships). The competence-oriented curriculum of the medical faculty consists of two interdisciplinary study blocks per semester and includes hands-on-training from the first semester on (German: Modellstudiengang). Final block examinations at the end of each study block replace the written part of the first state examination. The second state examination takes place at the end of the fifth study year. We therefore excluded the tenth semester due to the specific challenge of this semester. Other inclusion criteria were i) age 18 or older and ii) being enrolled in the second to ninth semester of the human medical studies. Exclusion criteria were i) any somatic or mental health conditions that impede participation in the study, are associated with an increased health risk during participation of the VR-TSST or may contribute to cardiovascular stress reactivity (e.g. cardiovascular disease, hypertension, endocrine disorders, mental disorders, strong visual impairment, vertigo and balance disorders, epilepsy, lymphedema or other skin, bone or muscle disorders that are contraindicated for blood pressure measurements), ii) indicators for drug abuse, iii) self-reported heavy nicotine consumption (>10 cigarettes/day), iv) self-reported heavy regular alcohol consumption (usual alcohol consumption >1 time/week with >6 drinks/occasion). Furthermore, students with a hair length of less than 2 cm were excluded due to an analysis of hair cortisol (results reported elsewhere (Heming et al., 2023)). An additional exclusion criteria for analyses involving the VR-TSST was prior knowledge of the VR-TSST. After distribution of recruitment material on social media, a sample of 123 students contacted the study team to participate in the study. However, 33 students were excluded before participation due to somatic or mental health conditions ($n = 7$), enrolment in the first, tenth semester or other studies ($n = 22$) or due to short hair ($n = 4$). Furthermore 29 students were non-available after receiving participant information. One student had to be excluded after enrolment in the study due to high regular alcohol consumption (usual alcohol consumption >1 time/week with >6 drinks/occasion), leaving 60 participants for the analyses. The age in this final study sample ranged between 19 and 31 years (mean = 22.27, standard deviation = 2.13) and 70% of those participants were female.

2.2. Procedure

2.2.1. Main procedure

Participants were invited on Mondays, Tuesdays or Wednesdays between 8.30 am and 10.00 am to the study centre at the Heinrich Heine University Düsseldorf, Germany. They were asked to refrain from smoking or drinking caffeinated drinks for at least one hour before coming to the study centre. After giving written informed consent to participate in the study, participants were fitted with an ambulatory ECG-monitor and an ambulatory blood pressure monitor, were asked to remain seated for the following 30 min and to fill in the study questionnaire. They were then accompanied by a research assistant to the test room of the VR-TSST. After performing in the VR-TSST, participants were fitted with a new ECG-monitor, were asked to wear it for the following three days and to participate in the EMA-survey. The ambulatory blood pressure monitors were given to the participants to wear them during the second day of the EMA-survey. A detailed graphic description of this procedure is given in Fig. 1. To increase study participation and compliance, participants were compensated with 280€ for their time expenditure.

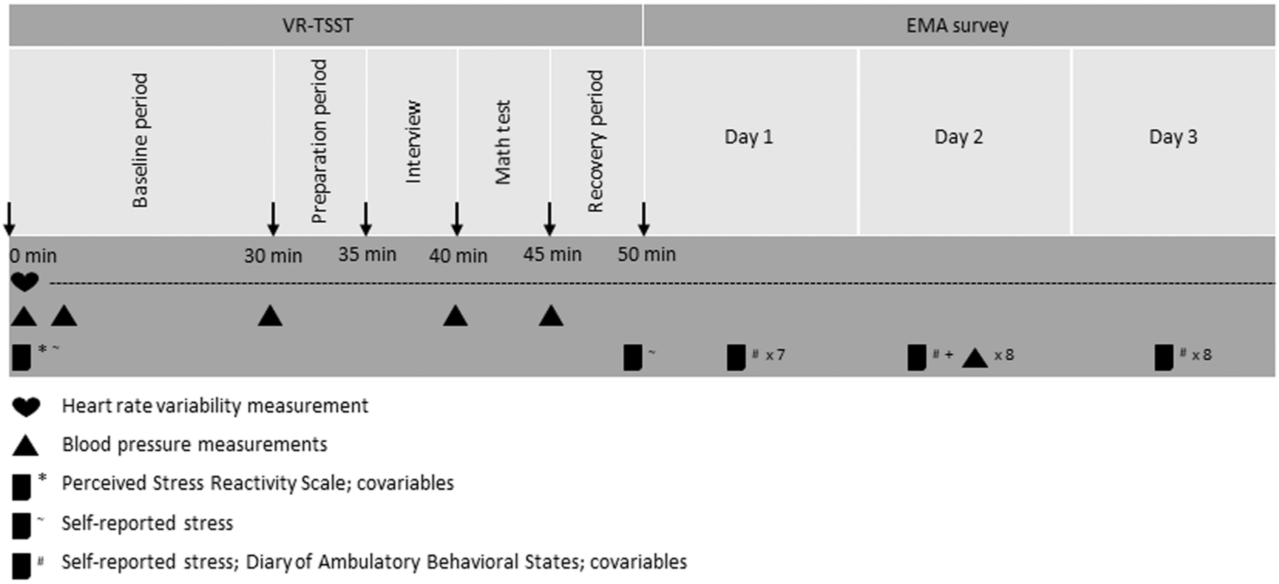

Fig. 1. Study procedure.

2.2.2. VR-TSST

The VR-TSST as previously described by Liszio et al. (2018) and Liszio (2021) was used for this study. This test includes a preparation phase and an interview and math test in front of a selection committee of three virtual members. The preparation phase, interview and math test each lasted five minutes. Validity of this VR-version of the TSST was confirmed by a pilot study, which showed that salivary cortisol, the HRV parameter of standard deviation of successive differences (SDSD) and psychological stress responses were comparable to the original real-world TSST (Liszio, 2021; Liszio et al., 2018).

After the 30 min resting period, the participants were accompanied to a soundproofed test room, where a research assistant informed them that they would have a solicitation interview for a chief physician position in their favourite specialisation in front of a selection committee. They were informed that their performance would be analysed by psychologists using audio recording and that their performance would also be compared with the performance of other medical students. Participants were asked to hold a 5-minutes speech about their personal (not professional) qualification for the job without asking questions to the selection committee. Participants were then fitted with the VR-headset and were given a period of five minutes to prepare themselves for the interview.

After the preparation period, the test coordinator entered the test room and started the interview. If the participant stopped talking for more than 20 s before the interview was over or was posing questions and waiting for a response, the test coordinator initiated responses of the virtual solicitation committee including "The time is not up yet, please continue", "What is the result?", "I cannot understand you" or "Speak loud and clearly". After the interview, the math test started automatically. The virtual selection committee introduced the content of the math test and the participant was asked to begin counting backwards in steps of 13 from 1022. With each wrong calculation step, the test coordinator initiated the following reaction of the virtual solicitation committee: „The answer was wrong. Please start from the beginning". If the participant had no problems counting backwards and was making no mistakes, the test coordinator could also initiate the following reaction of the virtual solicitation committee: „Please speak with a louder voice". After the math test, the VR-headset was taken off of the participant and a 5-minute recovery period followed in which participants were asked to fill in a further study questionnaire. Then, the VR-TSST was debriefed with the participant to dissolve the stress situation.

2.2.3. EMA-survey

The EMA-Survey was performed with the PIEL Survey App (https://pielsurvey.org/, Blue Jay Ventures Pty Ltd, Australia) for three consecutive workdays. For this period, participants were asked to refrain from heavy physical activity and from alcohol consumption. The participants were instructed to install the PIEL Survey App on their personal mobile phones and upload the control file containing the EMA-survey of this study before coming to the study centre. Correct installation of the PIEL Survey App and initiation of the EMA-survey was controlled by the study team. The survey started on the same day on which the participants came to the study centre and performed in the VR-TSST. The survey run for three consecutive days. On the first day, seven and on the following two days respectively eight surveys were scheduled at semi-random time intervals of 90 min between 09:30 am and 09:45 pm. To ensure that at least 15 min lie between two surveys, those time intervals were separated by time periods of 15 min. Alongside of notifications, an alert-sound was initiated by the PIEL Survey App when a survey was due. Participants were reminded after five, ten and fifteen minutes after receiving the first notification if they had not responded yet. If participants had not responded after 20 min, the survey closed and participants were prompted when the next survey was scheduled. After answering the last EMA-survey, participants send their responses to the study team by e-Mail.

2.3. Measures

2.3.1. Task demands, task control, social conflict and covariables during EMA

The Diary of Ambulatory Behavioral States (DABS; (Kamarck et al., 1998b)) was used as a validated tool to assess task demands, task control and social conflict during EMA. The DABS thus includes important aspects of established work stress models such as the job-demand-control-support model (Kamarck et al., 1998b; Karasek, 1979). In more detail, demands were assessed by three items: (i) "required working hard", (ii) "required working fast" and (iii) "juggled several tasks at once" during the previous ten minutes. Control was assessed by two items asking participants about the last ten minutes whether (i) they could have changed activities if they had wanted to and whether (i) they had chosen to schedule their activity at this time point. To measure social conflict, participants were first asked whether they had a social interaction during the last ten minutes. If they answered „yes", three further items appeared asking about the interaction in detail. In this case, participants were asked whether (i) someone interfered with their efforts and whether (ii) they argued with someone or (iii) were treated badly by someone within the last ten minutes. On all items, participants could respond on a four point rating scale ranging from 1 = „no" to 4 = „yes". Mean scores were calculated for each scale with higher scores representing higher levels of demands, control and social conflict. If participants indicated to have had no social interaction within the last ten minutes, those situations were coded with 1 for the social conflict scale. For sensitivity analyses, a second social conflict scale was calculated in which situations with no social interactions were coded as missing. Within- and between-subject reliability was calculated according to Geldhof et al. (2014). For those reliability calculations, the original items of social conflict were used and therefore reliability estimates for the social conflict scale only relate to observations where social interactions actually took place. Within-subject reliability of demands (ω = 0.75, CI = 0.73 – 0.74) and social conflict was acceptable (ω = 0.70, CI = 0.66 – 0.73), whereas within-subject reliability of control (ω = 0.53, CI = 0.48 – 0.58) was poor. Between-subject reliability of demands was excellent (ω = 0.91, CI = 0.86 – 0.97), but questionable for control (ω = 0.69, CI = 0.47 – 0.90) and poor for social conflict (ω = 0.26, CI = −0.64 – 1.16).

During the EMA-survey also control variables were assessed including consumption of food (yes/no), alcohol (yes/no) or caffeine (yes/no) during the last hour, smoking during the last fifteen minutes (yes/no), posture (standing with high physical activity, e.g. running/standing with low physical activity, e.g. walking/sitting/lying), talking (yes/no) and physical activity (inactive/low, moderate, high) during the previous ten minutes. At the end of the surveys, participants were asked again about their current posture (standing/sitting/lying).

2.3.2. Heart rate and heart rate variability

Participants were fitted with an ambulatory ECG monitor (eMotion Faros 180°, Mega Electronics Ltd, Finland) using gel electrodes (3 M Red Dot™ Electrodes, 3 M Deutschland GmbH, Germany) in a three-lead chest configuration. The ECG was recorded with a sampling rate of 250 Hz. The HRV-Scanner (BioSign GmbH, Germany) was used to analyse the ECG recordings. In keeping with previous recommendations (Laborde et al., 2017; Malik, 1996), HRV-parameters were calculated over periods of five minutes as moving averages with a step width of one minute. For each minute, parameters averaging HRV over the surrounding five minutes were thus received from the HRV scanner. Automatic ECG detection was used. To detect and delete segments with artefacts, a plausibility control with HR_{max} = 208 – (07. X age of participant) according to previous recommendations (Tanaka et al., 2001) and HR_{min} = 45 was used as well as automatic graphic filtering using the Pointcare-Plot. If automatic artefact detection did not result in sufficient data quality, the ECGs were manually edited.

To calculate resting heart rate and HRV, a mean of the periods between 5–10 min and 25–30 min after the start of the resting period was used. The heart rate and HRV-parameters for the VR-TSST respectively contained the 5-minute periods during the interview and math test. For the EMA, the 5-minute periods before each survey were used. For this analysis, RMSSD, HF power and LF power are used as HRV-parameters. Natural log transformation was applied to all HRV parameters and heart rate (bpm) due to skewed distribution.

2.3.3. Blood pressure

Blood pressure was measured by Spacelabs OnTrak Ambulatory Blood Pressure monitor (Spacelabs Healthcare, US). Blood pressure monitors were fitted at participants' non-dominant arms. Participants were introduced to the handling of the blood pressure monitor. They were further asked to remain seated and to avoid talking during all blood pressure measurements. During the resting period and VR-TSST, measurements were manually initiated by the test coordinator: at the start and after five and 30 min of the resting period, directly after the interview and after the math test. To calculate resting blood pressure, the mean of measurements after five and 30 min was used. During the second day of the EMA, participants were asked to wear the ambulatory blood pressure monitor from waking up until going to bed. During this day, the ambulatory blood pressure monitor automatically started measurements every 120 min. Furthermore, participants were asked by the PIEL Survey App at the end of each survey to initiate an additional measurement and were reminded to remain seated and avoid talking during the measurement. For this study, only self-initiated measurements after each survey were used for analysis.

2.3.4. Self-reported stress

During the resting period and directly after performing in the VR-TSST, participants were asked to rate how stressed they feel at the moment on a visual analogue scale from 0 = "not stressed at all" to 100 = "completely stressed".

During each EMA-survey, participants were asked about how they felt during the last ten minutes on a visual analogue scale ranging from "stressed" to "relaxed". Those answers were automatically transformed to a scale from 0 = "relaxed" to 1 = "stressed" by the PIEL Survey App.

2.3.5. Perceived stress reactivity scale

Participants were asked to fill in the validated Perceived Stress Reactivity Scale (Schlotz et al., 2011b; Schulz et al., 2005) during the resting period of the VR-TSST. This scale consists of 29 items with three answer options each. Each item describes a potential stressor with three typical reactions to this situation and participants were asked which reaction they normally observe on themselves. An example item is "When I argue with other people… i) I usually calm down quickly, ii) I usually stay upset for some time, iii) It usually takes me a long time until I calm down". Those reactions were coded from one to three with one representing the weakest reaction (e.g. "I usually calm down quickly") and three representing the strongest reaction (e.g. "I usually stay upset for some time"). Then, a sum score was calculated ranging from 29 = low perceived stress reactivity to 87 = high perceived stress reactivity. The reliability of the PSRS was good with Cronbach's alpha = 0.86.

2.3.6. Additional variables

Additional between-subject variables were gathered during the resting period of the VR-TSST by the study questionnaire. Those included the semester they were studying in, gender (female/male), age (in years) and physical activity (less than 1 h per week/1–2 h per week/3–4 h per week/5–6 h per week/> 6 h per week). Participants were asked about their height and weight, from which the BMI was calculated from. Alcohol consumption was assessed by asking participants on the number of occasions they usually drink alcohol (never/once per month or less/ 2–4 times per month/ 2–3 times per week/ 4 times per week or more) and on the amount of alcohol they usually drink per occasion (1–2 glasses/3–4 glasses/5–6 glasses/7–9 glasses/ten or more glasses with one glass accounting for 0.33 L beer, 0.25 L wine or sparkling wine or 0.02 L of spirits). Participants were asked to indicate whether they were under medical treatment or were ever having medical treatment for the following illnesses: cardiovascular diseases, endocrine disorders, mental disorders, addictive disorders, epilepsy, lymphedema or other skin, bone or muscle disorders. Furthermore, participants were asked whether they are currently suffering from the following health conditions: vision problems, vertigo or balance problems, cardiovascular problems, sensory disturbances, psychological problems or sleeping problems. In addition, participants indicated whether they were using any medication such as contraceptives. Furthermore, sense of presence regarding the VR-TSST was assessed during the recovery period of the VR-TSST with the validated group Presence Questionnaire consisting of 14 items (Schubert et al., 2001). For this study, the three subscales of spatial presence (5 items), involvement (4 items) and realness (4 items) were used. All items were rated on a 7-point rating scale from − 3 = "does not apply at all" to + 3 = "fully applies". Then, sum-scores were calculated for all three subscales with higher values representing stronger experience of presence. Within the study questionnaire during the recovery period of the VR-TSST, participants were also asked on whether someone had informed them beforehand about the contents of the VR-TSST.

2.4. Data analysis

To test the first hypothesis on whether the PSRS moderates associations between self-reported stress, cardiovascular parameters (HRV, heart rate and blood pressure) and task demands, task control and social conflict during daily life, multilevel analyses were performed with measurements $i = 1, \ldots, m_i$ (Level 1) being nested in participants $j = 1, \ldots n_j$ (Level 2). The following model was specified with a random intercept and random slopes for the predictor variables demands, control and social conflicts:

Level 1.

$\text{Outcome}_{ij} = \beta_{0j} + \beta_{1j}\text{Demands}_{ij} + \beta_{2j}\text{Control}_{ij} + \beta_{3j}\text{Social Conflict}_{ij} + \varepsilon_{ij}$.

Level 2.

$\beta_{0j} = \gamma_{00} + \gamma_{01}\text{Demands}_j + \gamma_{02}\text{Control}_j + \gamma_{03}\text{Social Conflict}_j + \gamma_{04}\text{PSRS}_j + u_{0j}$.

$\beta_{1j} = \gamma_{10} + u_{1j}$.

$\beta_{2j} = \gamma_{20} + u_{2j}$.

$\beta_{3j} = \gamma_{30} + u_{3j}$.

$\beta_{4j} = \gamma_{40}$.

The raw (blood pressure and self-reported stress) or natural log transformed (HRV) scores per measurement occasion were used as outcome variables. Demands, control and social conflict were centered around their group-mean and added at level 1 to calculate within-subject effects (β_{1j} – β_{3j}). The regression coefficients of those within-subject effects thus reflect the average intra-individual change of the outcome per one point increase of the demand, control or social conflict score. Additionally, the means of all measurements per individual were calculated for demands, control and social conflict and were then centered around their grand-mean. Those grand-mean centered variables were then added at level 2 to calculate between-subject effects (γ_{01} - γ_{03}). Also the PSRS was centered around the grand-mean and added at level 2 as a between-subject effect (γ_{04}). To assess the impact of the PSRS on the associations between self-reported stress, cardiovascular parameters (HRV, heart rate and blood pressure) and demands, control and social conflict, cross-level interactions were added. For those interaction analyses, level 2 was thus specified as:

$\beta_{0j} = \gamma_{00} + \gamma_{01}\text{Demands}_j + \gamma_{02}\text{Control}_j + \gamma_{03}\text{Social Conflicts}_j + \gamma_{04}\text{PSRS}_j + u_{0j}$.

$\beta_{1j} = \gamma_{10} + \gamma_{11}\text{PSRS}_j + u_{1j}$.

$\beta_{2j} = \gamma_{20} + \gamma_{21}\text{PSRS}_j + u_{2j}$.

$\beta_{3j} = \gamma_{30} + \gamma_{31}\text{PSRS}_j + u_{3j}$.

$\beta_{4j} = \gamma_{40}$.

For analyses regarding HRV, heart rate and blood pressure, control variables at within-subject level included recent physical activity, posture, talking, consumption of food and coffee. Control variables at between-subject level included semester, gender, use of contraceptives, BMI and physical activity. For analyses regarding self-reported stress, control variables at within-subject level included recent physical activity and at between-subject level included semester, gender, BMI and physical activity in general. Those co-variables were selected due to their potential effects on the outcomes (Kamarck et al., 1998b; Laborde et al., 2017). Measurement points in which participants indicated alcohol or nicotine consumption were excluded from analysis. Participants were excluded from analysis, if more than 33% of possible measurements were missing (four participants for the HRV-analyses and one participant for the blood pressure-analyses).

To test the second hypothesis on whether the PSRS predicts HRV, heart rate, blood pressure and self-reported stress responses to the VR-TSST, linear regression models for each outcome were calculated. In those models, resting values and the PSRS were used as independent variables and measurements during or after the interview and math test were used as dependent variables. Analyses regarding HRV, heart rate and blood pressure were controlled for semester, BMI, gender, use of contraceptives, physical activity. Analysis regarding self-reported stress was controlled for semester, BMI, gender and physical activity.

Due to the knowledge gap on whether HRV parameters need to be adjusted for heart rate, recommendations of de Geus et al. (2019) were followed on this issue. HRV parameters were transformed by using the coefficient of variation (CV) as recommended (de Geus et al., 2019). Natural log transformation was then applied to those parameters due to skewed distributions. Multilevel analyses and linear regression analyses were repeated by using those transformed HRV parameters as outcomes.

Sensitivity analyses were performed by using a second social conflict scale in which all situations with no social interactions were coded as missing. For those sensitivity analyses, only results regarding social conflict will be interpreted.

Statistical significance was assumed at a p-level $< .05$. Benjamin-Hochberg adjusted p-values (referred to as q-values) were calculated for the within- and between-subject effects of demands, control, social conflict, PSRS and cross-level interactions to adjust for the inflation of Type I error due to multiple testing. All analyses were conducted with R version 4.1.3 (The R Foundation for Statistical Computing).

2.5. Sample size calculations

The required sample size to investigate the effect of PSRS on stress responses during the VR-TSST was calculated with G*Power 3.1.9.7. For a two-tailed test using a significance level of $\alpha = 0.05$, a power of $\beta = 0.80$, seven predictors and an assumed medium effect size of $f^2 = 0.15$, a required sample size of 55 participants was obtained for linear multiple regression analyses. To the best of our knowledge, no comparable studies assessing the relationship between the PSRS and HRV, blood pressure, heart rate and self-reported stress to the VR-TSST exist to derive an effect size for sample size calculations. However, as small effect sizes might not be sufficient to use the PSRS as a predictive tool for health relevant stress reactions, a medium effect size was chosen for sample size calculation. The required sample size for the multilevel-models to investigate the effects of PSRS on the association between self-reported stress, cardiovascular parameters and demands, control and social conflict during daily life was obtained from a previous simulation study. This study found that group sizes of 50 participants are sufficient to accurately estimate regression coefficients and standard errors in a two-level-model (Maas & Hox, 2005).

3. Results

3.1. Description of study sample

In total, 61 students participated in the study. One participant had to be excluded due to high regular alcohol consumption (usual alcohol consumption > 1 time per week with >6 drinks/occasion) resulting in 60 participants being included in the analyses. A compliance rate of 95.5% was reached for the EMA, meaning that on average 22.2 surveys of possible 23 surveys were answered per participant. However, two further participants were excluded from all HRV and heart rate-analyses due to a large number of ventricular ectopic beats. Furthermore, four participants had to be excluded from HRV and heart rate analyses of the EMA part and six participants from HRV and heart rate analyses of the VR-TSST part due to technical problems with the ambulatory ECG monitor. Additionally, HRV and heart rate measurements with insufficient data quality were excluded from remaining participants, leaving 21.2 surveys per participants with sufficient HRV and heart rate data quality for data analyses of the EMA part. One participant had to be excluded from blood pressure analyses of the EMA part due to technical problems with the ambulatory blood pressure monitor. One participant further indicated prior knowledge about the contents of the TSST and was therefore excluded from VR-TSST-analyses. Description of the study sample is given in Table 1.

3.2. *Results regarding the perceived stress reactivity scale and ecological momentary assessment*

Correlation analyses between the PSRS and person-mean values of demands, control, social conflict and all outcome variables are shown in the Supplemental material (Table S1). Results of multilevel analyses predicting HRV, heart rate, blood pressure and self-reported stress during daily life with unadjusted and Benjamin-Hochberg adjusted p-levels are given in Table 2. When using Benjamin-Hochberg adjusted p-levels, no between-subject or within-subject associations were found between HRV parameters and control, social conflicts or the PSRS. Only demands were positively associated with LF-HRV at the between-subject level. No moderation of the associations between demands, control, social conflict and HRV were observed by the PSRS (see Table S2 in supplementary material for interaction analyses). Similar results were obtained when using CV-transformed HRV parameters (see Table S3 in supplementary material).

Demands, control and social conflict were not associated with heart rate. There was also no moderation by the PSRS.

Regarding blood pressure, there were also no between-subject or within-subject associations observed for demands, control, social conflict and the PSRS when using the Benjamin Hochberg adjusted p-levels. However, significant interactions between demands and the PSRS on systolic ($b=-0.35$, $SE=0.10$, $p < .001$, $q=.004$) and diastolic blood pressure ($b=-0.44$, $SE=0.11$, $p < .001$, $q=.001$) occurred. As depicted in Figs. 2 and 3, situations with high demands were associated with increased blood pressure among individuals scoring low on the PSRS. Among individuals scoring high on the PSRS, situations of high demands were associated with decreased blood pressure. Furthermore, an interaction between control and PSRS ($b=-0.12$, $SE=0.06$, $p = .04$, $q=.308$) on systolic blood pressure suggests that situations of high control are associated with decreased systolic blood pressure among individuals with high and medium levels of the PSRS but not among individuals with low levels of the PSRS (Fig. 4). However, the interaction was not significant when using Benjamin-Hochberg adjusted p-values.

Regarding self-reported stress, within-subject associations occurred with demands, control and social conflict. In more detail, high demands, low control and social conflicts were associated with increased levels of self-reported stress. No interactions between demands, control, social conflict and PSRS were observed.

Only minor changes in the results for social conflict were obtained when using a social conflict scale in which all observations with no social interactions were coded as missing (see Table S4 and S5 in supplementary material). This included a significant interaction between the PSRS and social conflict on heart rate ($b=-0.003$, $SE=0.001$, $p = .028$, $q=.196$). However, this interaction was not significant after adjusting for multiple tests using the Benjamin-Hochberg procedure.

Table 1
Description of study sample (n = 60).

	N (%)	M (SD)	Range (min-max)
gender			
• female	42 (70%)		
• male	18 (30%)		
semester			
• 1	3 (5%)		
• 2-3	6 (10%)		
• 4-5	18 (30%)		
• 6-7	12 (20%)		
• 8	21 (35%)		
physical activity			
• < 1 h/wk	2 (3%)		
• 1-2 h/wk	20 (33%)		
• 3-4 h/wk	24 (40%)		
• 5-6 h/wk	10 (17%)		
• > 6 h/wk	4 (7%)		
age (years)		22.27 (2.13)	19-31
BMI (kg/m^2)		22.60 (3.56)	17.76 – 37.55
perceived stress reactivity scale (29-87)		57.82 (8.64)	40-80

Notes: n = number, M = mean, SD = standard deviation

3.3. *Results regarding the Perceived Stress Reactivity Scale and stress responses during the VR-TSST*

Levels of HRV, heart rate, blood pressure, self-reported stress and experience of presence before and during the VR-TSST are shown in Table 3. All HRV parameters decreased and heart rate and blood pressure increased during the interview of the VR-TSST compared to resting levels. Similar results regarding RMSSD, HF-HRV, heart rate and blood pressure were obtained for the math test of the VR-TSST but differences to resting levels were less pronounced. LF-HRV was higher during the math test than during baseline. Self-reported stress levels were higher after the VR-TSST than before. Correlation analyses between the PSRS and outcome variables during and after the interview and math test are shown in the supplemental material (Table S6 and Table S7).

Results of multiple linear regressions to model associations between the PSRS and HRV, heart rate and blood pressure responses to the interview are given in Table 4. Table 5 summarizes results of multiple linear regressions predicting HRV, heart rate, blood pressure and self-reported stress responses to the math test of the VR-TSST. Results indicate that the PSRS was not related to any of the observed responses to the interview or math test. Similar results were obtained when using CV transformed HRV parameters (see Table S8 in supplementary material).

4. Discussion

This study tested the hypotheses that the PSRS moderates associations between self-reported stress, cardiovascular parameters and task demands, task control and social conflict during daily life and predicts stress responses to a VR version of the TSST. The results indicate that the PSRS only moderates associations with blood pressure but does not moderate associations with HRV parameters including RMSSD, HF and LF, heart rate or self-reported stress during daily life. Contrary to the hypothesis, results further suggest that blood pressure, HRV (RMSSD, HF and LF), heart rate and self-reported stress responses to the VR-TSST are not predicted by the PSRS.

Individuals scoring high on the PSRS experienced increased systolic blood pressure levels after periods with low demands and low control. However, results regarding control were not significant when using Benjamin-Hochberg adjusted p-values and therefore need to be interpreted carefully. On the one hand, the results indicate that perceived stress reactivity corresponds to associations between blood pressure and task control as hypothesized. On the other hand, further studies are needed to confirm that those results were not just pure chance. We also expected that high perceived stress reactivity leads to increased blood pressure levels in situations of high demands. However, our results demonstrate that demands were associated with lower blood pressure among individuals scoring high on the PSRS. This result leaves room for interpretation and needs further exploration. A possible explanation could be that dysregulation of the autonomic nervous system due to chronic stress (McEwen, 1998; Ulrich-Lai & Herman, 2009) might have caused this counterintuitive result. High correlation between perceived

Table 2
Multilevel-analysis predicting heart rate variability, blood pressure and self-reported stress during daily life.

	ln RMSSD (ms)	ln HF (ms^2)	ln LF (ms^2)	ln heart rate (bpm)	systolic blood pressure (mmHg)	diastolic blood pressure (mmHg)	self-reported stress
Between-subject variables							
• semester[a]	0.01 (0.03)	0.00 (0.05)	0.01 (0.04)	-0.00 (0.01)	-0.45 (0.52)	0.08 (0.43)	-0.02 (0.01) *
• gender (vs. male)	-0.27 (0.14)*	-0.51 (0.28)$^{+}$	-0.50 (0.20) **	0.13 (0.04) **	-11.11 (2.82)* *	-0.87 (2.35)	-0.06 (0.04)
• use of contraceptives (vs. no)	0.10 (0.13)	0.28 (0.26)	0.04 (0.18)	-0.06 (0.04)	2.02 (2.65)	-1.10 (2.21)	-
• BMI (kg/m^2)	0.01 (0.01)	0.03 (0.03)	0.01 (0.02)	0.00 (0.00)	0.44 (0.30)	-0.37 (0.26)	-0.00 (0.00)
• physical activity[a, c]	0.12 (0.05) *	0.13 (0.10)	0.12 (0.07)$^{+}$	-0.01 (0.01)	-2.36 (1.04) *	-2.28 (0.84)**	-0.00 (0.02)
• demands[a]	0.25 (0.13)$^{+}$	0.50 (0.26)$^{+}$	**0.55 (0.18)****	-0.04 (0.04)	4.48 (3.40)	-0.02 (2.82)	0.09 (0.04)*
• control[a]	0.25 (0.12) *	0.57 (0.24) *	0.35 (0.17) *	-0.06 (0.04)$^{+}$	5.77 (2.67)*	3.76 (2.23)$^{+}$	-0.01 (0.04)
• social conflict[a]	1.23 (0.59) *	2.67 (1.17) *	0.84 (0.83)	-0.12 (0.17)	-5.50 (9.79)	-16.27 (8.40)$^{+}$	0.35 (0.14)*
• PSRS[a]	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	-0.00 (0.00)	0.02 (0.13)	0.11 (0.11)	0.01 (0.00) * *
Within-subject variables							
• physical activity[b, d]	-0.13 (0.02) ***	-0.33 (0.05) ***	-0.19 (0.05) ***	0.06 (0.01) ***	0.94 (0.65)	1.48 (0.72)*	0.00 (0.01)
• posture (lying vs. sitting)	0.12 (0.05) *	0.17 (0.11)	-0.12 (0.10)	-0.06 (0.01) ***	-1.22 (1.55)	-1.43 (1.68)	-
• posture (standing low activity vs. sitting)	-0.30 (0.03) ***	-0.64 (0.08) ***	-0.21 (0.07) **	0.11 (0.01) ***	6.59 (1.41)* **	2.01 (1.57)	-
• posture (standing high activity vs. sitting)	-0.68 (0.09) ***	-1.65 (0.22) ***	-1.35 (0.19) ***	0.25 (0.03) ***	-	-	-
• meal (vs. yes)	0.06 (0.03) *	0.06 (0.06)	0.04 (0.05)	-0.03 (0.01) ***	-0.86 (0.79)	1.66 (0.85)	-
• coffee (vs. yes)	-0.04 (0.04)	-0.13 (0.09)	-0.06 (0.08)	-0.00 (0.01)	0.73 (1.12)	1.04 (1.21)$^{+}$	-
• talking (vs. yes)	-0.07 (0.03) **	-0.14 (0.06) *	-0.27 (0.05) ***	-0.01 (0.01)	-1.84 (0.85)*	-0.90 (0.92)	-
• demands[b]	0.01 (0.03)	0.04 (0.05)	0.03 (0.04)	-0.01 (0.01)	-1.06 (0.85)	1.53 (1.00)	**0.16 (0.01) *** **
• control[b]	0.03 (0.02) *	0.04 (0.04)	0.01 (0.03)	0.01 (0.01)	-0.73 (0.49)	-0.90 (0.58)	**-0.05 (0.01) *** **
• social conflict[b]	-0.05 (0.04)	-0.02 (0.09)	-0.02 (0.08)	0.01 (0.01)	2.12 (1.07)*	-0.89 (2.37)	**0.08 (0.02) *** **
Model							
• AIC	1414.72	3213.09	2932.84	-1352.20	3158.41	3266.67	-180.56
• BIC	1571.00	3368.41	3088.71	-1195.78	3281.22	3389.75	-55.87
• Log Likelihood	-676.36	-1575.55	-1435.42	707.10	-1549.20	-1603.34	114.28
• Number of observations	1143	1108	1128	1148	443	447	1333
• Number of participants	54	54	54	54	59	59	60

PSRS = Perceived Stress Reactivity Scale; ln = natural log transformation; RMSSD = root mean square of successive differences; HF = high frequency, LF = low frequency; [a] variables were centered around their grand mean; [b] variables were centered around their group mean; [c] general physical activity ranging from 1 = "< 1 h/week" to 5 = "> 6 h/week"; [d] current physical activity ranging from 1 = "inactive/low" to 3 = "high"; p values: + <.10, * <.05, ** < .01, *** <.001; bold: significant Benjamin-Hochberg adjusted p-values < .05

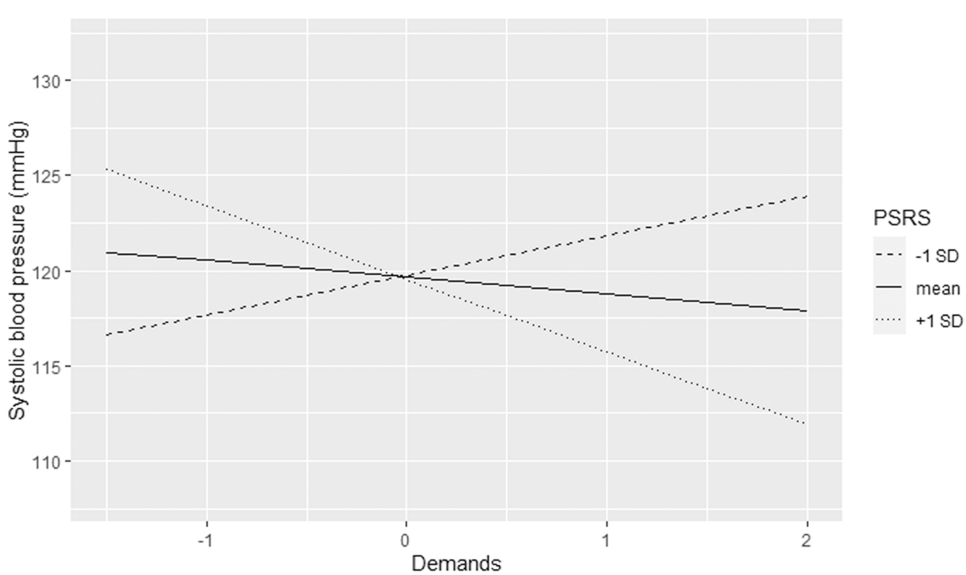

Fig. 2. Interaction between demands and the Perceived Stress Reactivity Scale (PSRS) on systolic blood pressure (mmHg).

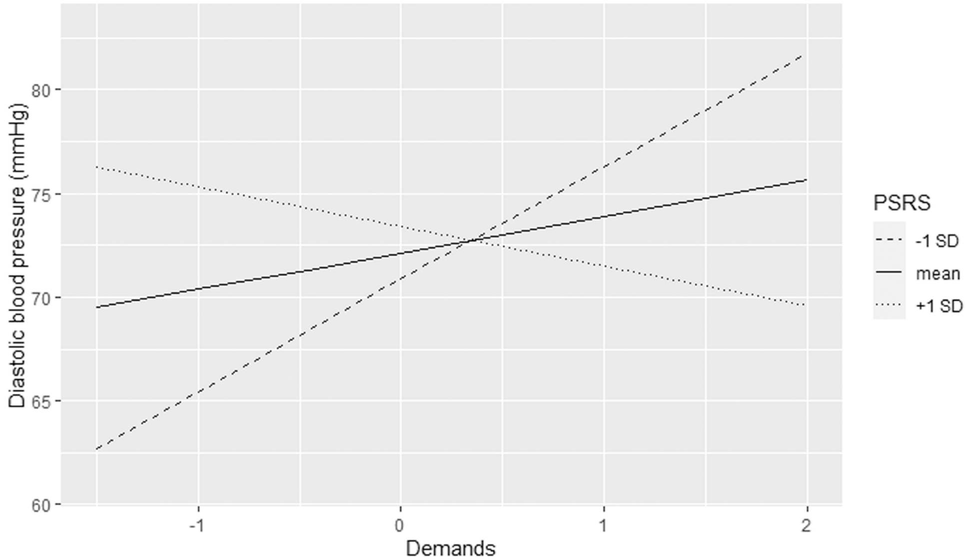

Fig. 3. Interaction between demands and the Perceived Stress Reactivity Scale (PSRS) on diastolic blood pressure (mmHg).

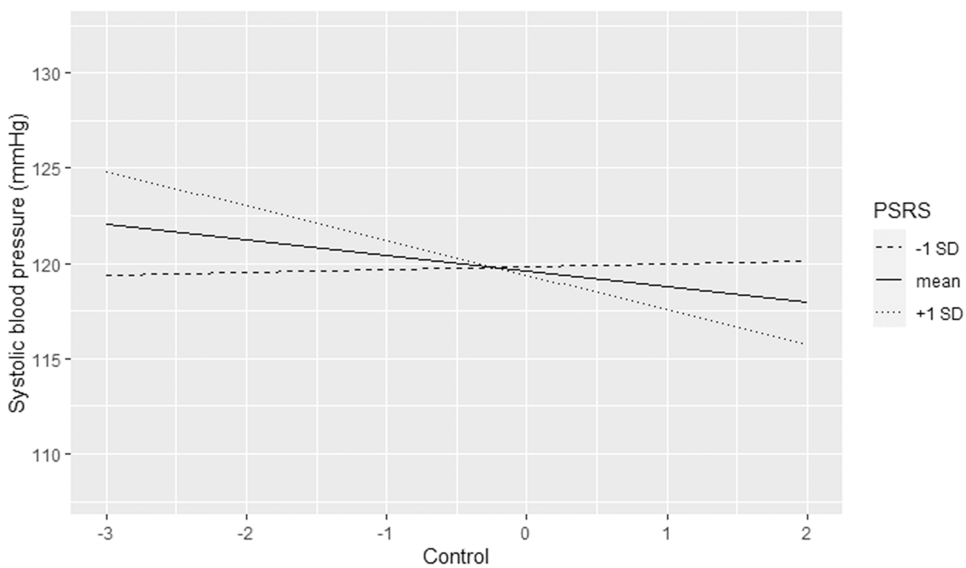

Fig. 4. Interaction between control and the Perceived Stress Reactivity Scale (PSRS) on systolic blood pressure (mmHg).

stress reactivity and chronic stress has been acknowledged by previous research (Jackowska et al., 2018; Limm et al., 2010; Schlotz et al., 2011b). It is thus conceivable that constant time and performance pressure had led to chronic stress among students reporting high perceived stress reactivity. Chronic stress might have then caused dysregulation of physiological stress response systems leading to habituation effects and thus blunted physiological stress reactivity (McEwen, 1998; Ulrich-Lai & Herman, 2009). Previous laboratory stress research supports this hypothesis, because chronic stress seems to be related to cardiovascular hypo-reactivity during laboratory stress tests (Matthews et al., 2001). It might further be possible that students reporting high perceived stress reactivity have used more avoidant coping strategies and behavioural disengagement in response to high demands (Britton et al., 2019a). Previous research indicates that those strategies lead to blunted physiological stress reactivity (Ginty et al., 2020; Keogh et al., 2023). A freezing stress response may further explain reduction of blood pressure levels during high demands. However, a freezing response is also related to heart rate deceleration (Roelofs, 2017) and this was not the case in this study. Heart rate was neither directly related to demands nor was this relationship moderated by the PSRS.

Contrary to our expectations, situations of high demands and social conflicts were neither directly related to HRV (RMSSD, HF and LF) and heart rate at the within-subject level during daily life nor was the relationship moderated by the PSRS. High study demands and social conflicts have been identified as important stressors for university students (Schmidt et al., 2018; Schmidt et al., 2015; Weber et al., 2019) and our results further confirm that they are related to increased levels of self-reported stress. One might have therefore expected that high levels of demands and social conflict could lead to a stress response of the autonomic nervous system (Kim et al., 2018) and that this could lead into a within-subject association of demands and social conflict with those HRV parameters and heart rate. A lack of association might thus hint to an incongruence between psychological and physiological stress responses. Also previous laboratory research confirms that self-reported and physiological stress responses often fail to match (Campbell & Ehlert, 2012). Personality traits and psychological states with rather positive connotations (e.g. self-esteem, happiness, active coping) were discussed as reasons for this mismatch (Campbell & Ehlert, 2012),

Table 3
Descriptive results of the VR-TSST.

	Baseline M (SD)	Interview M (SD)	Math test M (SD)
Total study sample			
RMSSD (ms)	45.07 (25.16)	34.36 (21.49)	42.54 (24.43)
HF (ms^2)	811.01 (747.86)	569.42 (507.36)	799.10 (690.60)
LF (ms^2)	1365.7 (1080.58)	1307.58 (1088.20)	1941.9 (1828.86)
heart rate (bpm)	77.20 (10.48)	91.91 (15.44)	83.72 (14.16)
diastolic blood pressure (mmHg)	73.77 (9.17)	79.99 (10.77)	78.9 (10.11)
systolic blood pressure (mmHg)	117.16 (11.31)	129.26 (15.36)	126.01 (14.95)
self-reported stress (range 0 - 100)	33.27 (30.34)		48.51 (30.93)
spatial presence (range −15 – 15)			4.63 (5.04)
involvement (range −12 – 12)			-2.05 (5.08)
realness (range −12 – 12)			-2.78 (3.71

Notes: RMSSD = root mean square of successive differences; HF = high frequency, LF = low frequency; M = mean, SD = standard deviation

because they were shown to be associated with a downregulation of physiological stress responses (Chida & Hamer, 2008). Another explanation for the lack of association between demands, social conflict and HRV might further relate to the large amount of other HRV predictors. Even though most important variables were statistically controlled for in the analysis (e.g. age, gender physical activity, position, talking (Laborde et al., 2017)), other confounders could have been missed (e.g. genetic factors, respiration, relaxation skills involving slow and deep breathing (Beda et al., 2007; Laborde et al., 2022; Nolte et al., 2017)). Last but not least, our results add to the inconclusive literature base of previous EMA studies. While four studies found no association between time-domain indices of HRV and self-reported stress (Määttänen et al., 2021; Pieper et al., 2010; Schmid & Thomas, 2020; Wrzus et al., 2013), two others found negative association between levels of RMSSD and SDNN and stress in daily life among healthy individuals (Schwerdtfeger & Dick, 2019; Simon et al., 2021). Mixed results were also found for HF-HRV (Dennis et al., 2016; Simon et al., 2021).

We have also investigated stress responses to a VR version of the TSST. As expected, blood pressure, heart rate and self-reported stress increased and RMSSD and HF-HRV decreased during the VR-TSST. However, the PSRS did not predict the magnitude of those cardiovascular and self-reported stress responses. Those findings partly confirm results of a similar study by Britton et al. (2019b), which specifically investigated the effect of the PSRS subscale of reactivity to social evaluation on HF-HRV and self-reported stress responses to the socially evaluated cold pressure test. In this study, perceived reactivity to social evaluation predicted perceived stressfulness of the task, but not changes in HF-HRV (Britton et al., 2019b). One should however consider that our analyses calculated PSRS effects on residualized changes of self-reported stress levels during the VR-TSST, whereas Britton et al. (2019b) did not control for baseline levels of self-reported stress. Our findings are in contrast to results of another previous study by Schlotz et al. (2011a), which found that the PSRS predicts the cortisol response to the TSST. Important differences in study design, outcome measure and analysis need to be mentioned. First, the previous study included a study population of male students, whereas in our study most participants were female. Previous research described sex differences in stress responses with men showing stronger cortisol responses to the TSST than women (Allen et al., 2014). Second, cortisol levels peak after 20–40 min after stressor exposure (Dickerson & Kemeny, 2004) and Schlotz et al. (2011a) thus evaluated cortisol trajectories over a time frame of 90 min. In contrast, cardiovascular measures change immediately after stressor exposure (Allen et al., 2014; Fallon et al., 2021) and we have therefore analysed immediate responses during or directly after the VR-TSST. Third, cortisol levels correspond to the stress response of the hypothalamic-pituitary-adrenal (HPA) axis, whereas blood pressure, heart rate and HRV rather represent stress responses of the autonomic nervous system (Allen et al., 2014; Kim et al., 2018). Furthermore and as described above, only a minority of previous studies found a correlation

Table 4
Linear Regression Model predicting heart rate variability and blood pressure response to the interview of the VR-TSST.

	ln RMSSD (ms)	ln HF power (ms^2)	ln LF power (ms^2)	ln heart rate (bpm)	systolic BP (mmHg)	diastolic BP (mmHg)
	B (SE)	B (SE)	B (SE)	B (SE)	B (SE)	B (SE)
baseline	0.690 (0.115) ***	0.466 (0.155) **	0.400 (0.172) *	0.758 (0.146) ***	1.076 (0.12)***	0.940 (0.107)***
PSRS	0.009 (0.007)	0.014 (0.018)	0.02 (0.015)	-0.002 (0.002)	-0.105 (0.14)	-0.041 (0.113)
F (df, df)	6.91 (7, 43) ***	2.82 (7, 40)*	1.68 (7,42)	6.71 (7, 43)***	18.42 (7,51)***	13.16 (7,51)***
Adj R^2	0.453	0.213	0.089	0.444	0.676	0.595
Number of participants	51	48	50	51	59	59

Notes: PSRS = Perceived Stress Reactivity Scale; Log = natural log transformation; RMSSD = root mean square of successive differences; HF = high frequency, LF = low frequency BP = blood pressure; models are controlled for semester, BMI, gender, use of contraceptives, physical activity; B= unstandardized regression coefficient, SE = standard error; p values: + <.10, * <.05, ** < .01, *** <.001

Table 5
Linear Regression Model predicting heart rate variability, blood pressure and self-reported stress response to the math tests of the VR-TSST.

	ln RMSSD[1] (ms)	ln HF power[1] (ms^2)	ln LF power[1] (ms^2)	ln heart rate[1] (bpm)	systolic BP[1] (mmHg)	diastolic BP[1] (mmHg)	self-reported stress[2]
	B (SE)	B (SE)	B (SE)	B (SE)	B (SE)	B (SE)	B (SE)
baseline	0.772 (0.101) ***	0.611 (0.124)***	0.352 (0.150) *	0.930 (0.123)***	0.991 (0.125) ***	0.888 (0.098)***	0.426 (0.13) **
PSRS	0.010 (0.006)	0.007 (0.015)	0.012 (0.013)	-0.001 (0.002)	0.008 (0.154)	-0.025 (0.104)	0.24 (0.47)
F (df, df)	10.79 (7,43) ***	5.23 (7,41)***	1.84 (7,41)	11.43 (7, 43)***	14.06 (7,51) ***	13.94 (7,51)***	3.89 (6,52)**
Adj R^2	0.578	0.382	0.110	0.593	0.612	0.657	0.230
Number of participants	51	51	51	51	59	59	59

PSRS = Perceived Stress Reactivity Scale; Log = natural log transformation; RMSSD = root mean square of successive differences; HF = high frequency, LF = low frequency, BP = blood pressure; [1] models are controlled for semester, BMI, gender, use of contraceptives, physical activity; [2] model is controlled for semester, BMI, gender, use of contraceptives, physical activity B= unstandardized regression coefficient, SE = standard error; p values: + <.10, * <.05, ** < .01, *** <.001

of self-reported stress and cortisol responses in laboratory stress research (Campbell & Ehlert, 2012). In addition to personality traits and psychological states, also methodological issues including the one-time measurements of self-reported stress before and after the TSST (Campbell & Ehlert, 2012) could explain disparate findings regarding self-reported stress in this study and physiological responses described by Schlotz et al. (2011a). Last but not least, we have assumed a medium effect size for the association between the PSRS and stress responses during the VR-TSST within our sample size calculations. The power might have therefore been too low to find associations with smaller effect sizes.

On the one hand, the lack of association between the PSRS and self-reported stress and cardiovascular responses to the VR-TSST might hint to problems of ecological validity of the VR-TSST. Whereas the PSRS assesses typical reactions to a set of potential stressors that could realistically and repeatedly occur during daily life (Schlotz et al., 2011b; Schulz et al., 2005), the TSST reflects a very specific stressor that would normally not occur during daily life. Therefore, usual secondary appraisal of the described stressors in the PSRS might not apply to the TSST. This possibility has been investigated in detail by Schlotz et al. (2011a). Within this study, the PSRS was related to secondary appraisal of the TSST (i.e. evaluation of personal coping resources), but secondary appraisal did not influence cortisol responses to the TSST. The authors explained their findings by recognizing that typical coping resources including competences and locus of control are not relevant for the TSST due the novelty, unpredictability, uncontrollability of its tasks (Schlotz et al., 2011a). The VR-version of the TSST might have further impaired realistic representation of a real-life situation. This was reflected by the moderate levels of the sense of presence that our participants reported in regard to the VR-TSST. Levels of involvement were weaker, but levels of spatial presence and realness were similar compared to a prior study reporting sense of presence in regard to another VR version of the TSST (Zimmer et al., 2019b). One might therefore conclude that cardiovascular and self-reported stress responses to the VR-TSST do not reflect perceived stress responses to everyday life stressors. Ecological validity of the TSST has also been repeatedly questioned by other researchers, who found mixed evidence on whether stress responses to the TSST mirror stress responses in daily life (De Calheiros Velozo et al., 2022; Henze et al., 2017; Wolfram et al., 2013). On the other hand, the lack of association between the PSRS and self-reported stress and cardiovascular responses to the VR-TSST might question convergent validity of the PSRS. In this context, our finding on the relationship between the PSRS and self-reported stress during EMA need to be taken into account as well. Individuals scoring high on the PSRS generally experienced more stress in their daily life. On the one hand, this association might have been found by pure chance, because the Benjamin-Hochberg adjusted p-value was not significant anymore. On the other hand, a true effect would confirm results of a previous validation study using cross-sectional data of the PSRS and self-reported stress (Limm et al., 2010; Schlotz et al., 2011b). However, our results indicate that the PSRS does not moderate the relationship between self-reported stress and psychosocial stressors such as high demands, low control and social conflict. This was unexpected, because the PSRS specifically measures perceived stress responses to work overload, social conflicts or social evaluation (Schlotz et al., 2011b). One possible explanation is that the PSRS is rather an indicator of psychological stress levels in general than stress reactivity. However, one should also keep in mind that our EMA approach only considered task demands, task control and social conflicts and that other stressors could have been missed.

4.1. Strengths and limitations

Important strengths of this study include the combination of the PSRS, VR-TSST and EMA and the rare opportunity to compare those research approaches within one single study sample. The study thereby benefits from a dense sampling scheme and high compliance rate during EMA as well as high standardization of the TSST protocol due to VR.

Limitations include the convenience sampling, which could have led to a selection bias. On the one hand, especially students perceiving high levels of stress might have felt appealed by our call for study participation. On the other hand, students perceiving high levels of stress might have had limited time resources to participate and therefore especially students perceiving lower levels of stress might have been included in our study. Furthermore, female participants were overrepresented. This could have influenced our study results, because gender and chronic stress are predictors for perceived and physiological stress reactivity (Allen et al., 2014; Jackowska et al., 2018; Limm et al., 2010; Matthews et al., 2001; Schlotz et al., 2011b). Our analyses, however, were controlled for gender and use of oral contraceptives. In addition, the study sample was small and only students of one German medical school were included which limits generalizability of study results. However, sampling occasions during EMA are likely representative for the daily life of this study sample due to frequent assessments and the high compliance rate.

Limitations of the EMA are the low within- and between subject reliability scores for control and the low between-subject reliability score for social conflict. Those between-subject reliability scores were unexpected in light of the high between-subject Cronbach's alpha scores within a previous study (Kamarck et al., 1998b). However, the within-subject reliability score for control was similar to this study (Kamarck et al., 1998b). It needs to be mentioned that a small number of items and low inter-correlations naturally reduce Cronbach's alpha levels (Cortina, 1993), but that intensive sampling schemes during EMA call for short measurement scales to reduce participant's burden. Therefore scales need to be reduced by items which measure very similar topics of the same construct. At the same time, items need to be retained that together are able to sufficiently cover the broad constructs of demands, control and social conflict. Low inter-correlations might thus be expected. Furthermore, one might question the approach of coding situations with no social interactions as 1 in the social conflict scale. Situation with no social interactions are thereby coded on the same level as having social interactions with low social conflict. Sensitivity analyses were therefore repeated with a social conflict score in which situations with no social interactions were coded as missing. In those sensitivity analyses, some between- and within-subject associations changed, but the main results remained the same with finding few evidence for interactions between the PSRS and social conflict on the outcomes.

The temporal alignment of blood pressure measurements during the EMA also needs some further thoughts. Blood pressure measurements took place directly at the end of the EMA surveys. This time point was chosen to reduce effects of physical activity prior to the EMA survey on blood pressure, because participants were asked to get seated when answering the EMA survey. Blood pressure measurements might thus reflect recovery measurements in situations where high demands, low control or social conflicts did not persist over the period of answering the EMA survey. However, the questions on demands, control and social conflict referred to a period of only ten minutes and therefore the chances are high that those situations were still ongoing during blood pressure measurements.

Furthermore and as explained in the introduction, operationalization of stress responses and stress reactivity within EMA differs from the typical operationalization within laboratory research using the TSST. The TSST aims to evoke a maximal stress response and compares psychological stress-related and physiological parameters after stressor exposure with a standardized quiet condition (Kirschbaum et al., 1993). Our EMA approach however samples experiences during daily life without using a standardized quiet condition and without necessarily capturing situations that are comparable with the TSST regarding stressor severity. The within-subject associations between stressors severity and psychological stress-related and cardiovascular outcomes in the EMA analyses therefore do not resemble the stress response in the VR-TSST. This could explain the different findings that some significant moderations of the within-subject associations by PSRS in the EMA-part occurred but that the PSRS had no predictive value on stress responses in the VR-TSST part. More specifically, those disparate finding could have occurred, because the PSRS aims to measure stress reactivity regarding typical situations during everyday life and not regarding a new and rather extreme stressor as the TSST (Schlotz et al., 2011b; Schulz et al., 2005). In addition, one might expect that within-subject associations in the EMA-part might be stronger if they would compare psychological stress-related and cardiovascular parameters during situations with high stressor severity with a standardized quiet condition as in the VR-TSST and that this could influence moderation effects by the PSRS.

Although most important confounders were controlled for in the analyses, others might have been missed. Especially respiration is often discussed to influence HRV parameters. HF-HRV was only found to reflect vagal tone when respiratory rate lies between nine and 24 cycles per minute, hence interpretation of changes in HF-HRV during situations in which respiration rate lies outside those boundaries is not recommended (Laborde et al., 2017). In accordance to those issues, relaxation skills involving slow and deep breathing are associated with increased levels of HRV parameters such as RMSSD and – in most instances – HF-HRV (Laborde et al., 2022; Zaccaro et al., 2018). The lack of control for respiration might thus be discussed as a limitation of this study. However, respiration rate is highly associated with physical activity, posture and talking (Bernardi et al., 2000; Sandercock & Brodie, 2006), variables that are statistically controlled for in the EMA analyses and are standardized during the VR-TSST. It thus seems unlikely that controlling for respiration rate would significantly change results of the analyses. In addition, current recommendations discourage from routine control for respiration under spontaneous breathing in stress research (Laborde et al., 2017). Regarding potential effects of relaxation skills involving slow and deep breathing, the adoption of those techniques during stress could have contributed to the non-significant within-subject associations as well as to the positive between-subject associations of demands, social conflict and HRV- parameters including RMSSD and HF-HRV in the EMA analyses. Furthermore, if the PSRS is related to the use of those techniques, we cannot exclude the possibility that this might have contributed to the cross-level interaction effects of the EMA analysis as well as to the non-significant findings of the VR-TSST analysis regarding HRV parameters including RMSSD and HF-HRV. This is hypothetically though, because to the best of our knowledge no study has yet examined associations between relaxation skills and the PSRS. Last but not least, evidence exists that the main proportion of changes in blood pressure and HF-HRV during the TSST relates to the need of talking during the tasks (Grimley et al., 2019). This could have also contributed the non-significant findings.

We have experienced some technical problems with our ambulatory ECG monitors and therefore had to exclude some participants from analyses. However, technical problems occurred in an unsystematic pattern and therefore no systematic bias is expected.

4.2. Implications

Stress reactivity is discussed as a risk factor for cardiovascular and mental disorders (Turner et al., 2020). Identification of individuals at risk with high stress reactivity thus seems to be important, because they might especially benefit from stress management interventions. However, our study results suggest that typical approaches to assess relationships between stressor exposure and relevant outcomes are not interchangeable with one another and further research is needed on reliable and valid methods to measure stress reactivity. Future research might test in how far the PSRS, stress responses in the TSST and within-subject associations between stressor exposure and psychological stress-related and physiological parameters in EMA differ in their prediction of stress-related diseases. In accordance to previous research (Herr et al., 2018; Kamarck et al., 2012; Schlotz et al., 2011b; Turner et al., 2020), it is conceivable that the PSRS is useful to predict the risk for mental disorders, but that physiological measurements in combination with the TSST or EMA could be more useful to predict the risk for cardiovascular diseases including hypertension. In this sense, also reference values on normal, blunted and exaggerated stress reactivity are needed, but to the best of our knowledge only reference values for blunted heart rate and blood pressure reactivity to the TSST have been reported so far (O' Riordan et al., 2023). VR versions of laboratory stress tests and questionnaires on perceived stress reactivity offer opportunities to increase standardization and thereby possibilities to deduce reference values. Furthermore, first approaches exist to use a combination of 24 h HRV assessments and personal diaries as a communication tool to demonstrate personal stressors, resources and stress responses (Jarczok et al., 2021; Jarczok et al., 2019). This EMA approach might complement standardized assessment of stress reactivity at a more qualitative level.

5. Conclusions

This study investigated the predictive value of the PSRS for (i) associations between self-reported psychosocial stressors and psychological stress-related and physiological parameters in daily life as measured by EMA and ii) psychological stress-related and physiological responses to the VR-TSST as a standardized laboratory stressor. Even though the PSRS, EMA and VR-TSST have all been extensively used by previous research to assess inter-individual variation in the relationship between stressor exposure and subsequent changes in psychological and physiological parameters, this study was only partly able to confirm a relationship between those methods. Reasons might include a mismatch between psychological and physiological stress responses, unreliable measurement of physiological parameters with EMA or problems either related to the convergent validity of the PSRS or to the ecological validity of the VR-TSST. Those findings call for future studies to search for reliable and valid ways to assess stress reactivity.

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CRediT authorship contribution statement

Weber Jeannette: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Heming Meike:** Visualization, Formal analysis, Data curation. **Angerer Peter:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Apolinário-Hagen Jennifer:** Writing – review & editing, Methodology, Conceptualization. **Liszio Stefan:** Software, Methodology.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2024.108762.

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