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Coupled hearts – effect of partner stress on cardiac synchronization ☆

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ABSTRACT

Physiological synchrony (PS), i.e., the alignment of physiological changes across individuals, is an established phenomenon characterizing social interactions. The degree to which interaction partners synchronize may depend on various relationship- and situation-specific factors. Stress profoundly affects behavior and cognition, but its effect on PS is still unknown. In a preregistered study, we thus investigated the effect of stress on PS in $N = 75$ romantic couples (mean age = 22.66 ±2.99, 51% female). Partners were separated upon arrival in the laboratory. In $n = 38$ dyads (*experimental condition*), one partner underwent the Socially Evaluated Cold Pressor Task (SECPT) while the other partner completed a non-stressful control task; in *control dyads*, both partners underwent the non-stressful task. After completing the intervention separately, partners were reunited and participated in a non-verbal synchronization task, a walking task, and an unstructured social interaction. PS was operationalized by calculating cross-wavelet power of partners' heart rate trajectories. We hypothesized that PS would be altered in couples with one stressed partner compared to the non-stressed control group. Across all interaction tasks, PS was lower in dyads in the experimental than in the control condition. Our findings indicate that stress disrupts PS. In the discussion, we present possible mechanisms for this effect. Our results highlight that stress is not only an intra- but also an interpersonal phenomenon affecting interpersonal physiological processes and social interactions beyond the acute stressor.

1. Introduction

Physiological synchrony (PS) is the temporal interdependence and correspondence between physiological signals of two or more individuals (daSilva & Wood, 2024; Ellamil et al., 2016; Koole & Tschacher, 2016; Mayo & Gordon, 2020; Palumbo et al., 2017; Shamay-Tsoory et al., 2019). PS has received increased research interest during the past decade (Palumbo et al., 2017), although the topic had garnered interest even earlier (West & Mendes, 2023), with seminal studies, (e.g., Levenson & Gottman, 1983) showing that PS may be an indicator of meaningful interpersonal processes. While there is an open debate about nomenclature (*physiological synchrony* versus *entrainment*, *linkage*, *interpersonal physiology*, etc.) and best analysis practices (e.g., cross-correlational versus nonlinear approaches; daSilva & Wood, 2024), the functions of PS vary (daSilva & Wood, 2024), and the mechanisms behind PS, its prerequisites, and its consequences are not well understood (Zilcha-Mano, 2024).

When two or more people interact, PS emerges when their physiological processes correspond to one another above what would be expected by chance. PS can be measured in peripheral processes, i.e., in autonomic nervous system (ANS) activity (e.g., Coutinho et al., 2021;

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Waters et al., 2014) or endocrine levels (e.g., Denk et al., 2021; Saxbe & Repetti, 2010). PS in the central nervous system, referred to as inter-brain synchrony or hyperscanning (e.g., Gvirts & Perlmutter, 2020), can also be included in the definition of PS, although it is often treated as a separate process (e.g., by Prochazkova & Kret, 2017). Measuring PS at the level of the ANS offers the ability to capture short-term changes in shared physiological processes, as the ANS adapts quickly to the (social) environment, and reacts more flexibly than endocrine systems. An advantage compared to hyperscanning procedures is that ANS measurements are typically less intrusive. The ANS is associated with emotional and social processes in the individual (Levenson, 2014) and may thus provide insights into the social connection between individuals (Coutinho et al., 2021). While individual signals constitute the building blocks of synchronized processes, PS is a higher-order phenomenon, and the psychological processes connected to individual ANS markers are not necessarily associated with the ANS markers' synchronization (see e.g., Thorson & West, 2018). For example, the parasympathetic marker high-frequency heart rate variability has been related to relaxation (Laborde et al., 2017), but whether high-frequency heart rate variability *synchrony* is likewise associated with relaxation is not yet clear. Taking into account the dyadic perspective is thus a valuable addition to studying the connection between physiology and psychological processes (Levenson, 2024). Nonetheless, the magnitude of individual processes will influence dyadic results – variation in the individual signal is the prerequisite for the emergence of synchrony in the dyad. PS is typically investigated in romantic couples, parent–child dyads, and therapists and their clients (Palumbo et al., 2017; Zilcha-Mano, 2024), but has also been found in friends (Cook, 2020), choir singers (Müller & Lindenberger, 2011), yoga groups (Quer et al., 2016), and strangers (Bizzego et al., 2019), during social interactions. Among these interaction partners, romantic relationships are one of the closest, next to parent–child relationships (Waters et al., 2014), and couples have been shown to reliably exhibit PS across different situations (Timmons et al., 2015).

Romantic relationships are especially suited for investigating PS (Timmons et al., 2015). In a developmental context, romantic relationships may be seen as a continuation of an interpersonal attachment system, where the primary attachment figures shift from caregivers to the romantic partner over the lifespan (Diamond & Fagundes, 2008). The emergence of different attachment styles during childhood influences adult attachment tendencies, which in turn guide partner-related behaviors during romantic relationships (Simpson et al., 2008; Xia et al., 2018). Young adulthood is a key life stage in which individuals begin to form their first serious romantic bonds, which have a lasting impact on individuals' development (Gala & Kapadia, 2013; Haase, 2023). Specifically, developmental outcomes related to romantic relationships are often positive, such as increased emotion regulation abilities, but can also be negative due to the profound effects of relationships going awry (Gala & Kapadia, 2013). These relationships are central in learning how to co-regulate emotions and behaviors with a partner (Butler, 2017; Butler & Randall, 2013), and can be seen as the first step to an increasing focus on interpersonal relations as partners approach middle adulthood (Haase, 2023). Romantic partners' down-regulating or up-regulating each other's emotions is often underpinned by changes in PS (Timmons et al., 2015). Navigating these novel relationship dynamics in young adulthood can be a challenging developmental task (Gala & Kapadia, 2013), making this developmental period crucial for investigating PS in romantic relationships.

The tendency to synchronize physiologically not only changes across the life span (Feldman, 2017; Haase, 2023) but also depends on multiple situational factors. In adulthood, individuals have developed a trait-like tendency to "fall in sync" with others, but can deviate from this tendency given their situation-specific needs (Zilcha-Mano, 2024). The emergence of PS in a social situation does not only depend on the relationship between interaction partners (e.g., romantic partners versus strangers; Bizzego et al., 2019), but is also shaped by more immediate factors situated within a given interaction, such as the interactional context (Danyluck & Page-Gould, 2018, 2019; Järvelä et al., 2016) and task requirements (Helm et al., 2012; Wallot et al., 2016). While increased PS has been connected to social cohesion and alignment (Gvirts & Perlmutter, 2020; Koban et al., 2019; Launay et al., 2016; Shamay-Tsoory et al., 2019), increased PS does not automatically indicate a better relationship quality. For example, friends and romantic partners synchronized less than strangers under different emotional states (Bizzego et al., 2019). Within romantic couples, the association between PS and relationship quality is inconsistent (Mayo et al., 2021; Timmons et al., 2015). Instead, a picture emerges where increased PS is related to better-quality relationships in positively-valenced situations (Chen et al., 2021), whereas increased PS is associated with lower relationship satisfaction in conflict situations (Coutinho et al., 2021; Gates et al., 2015; Saxbe & Repetti, 2010). For example, Levenson and Gottman (1983) found a connection between relationship satisfaction and PS in married couples during conflict situations, but not during neutral conversations. A moderate level of PS (Timmons et al., 2015) or a balance between synchronized and decoupled states (Zilcha-Mano, 2024) may be most beneficial for maintaining good-quality (romantic) relationships. In addition to the overall valence of an interaction, situation-specific PS may be most visible in those moments when emotional states (positive or negative) are shared between individuals (Coutinho et al., 2021; Hubbard et al., 2023; Lin et al., 2024; West & Mendes, 2023). How individual and shared emotional states in romantic couples influence the emergence of PS across the lifespan remains an open question.

Past studies that have investigated the effects of emotional states on PS (e.g., Coutinho et al., 2021; Reed et al., 2013) utilized settings in which specific conversational topics could induce conflict or harmony. The advantage of such scenarios is their high ecological validity, as couple-specific conflicts are used in the paradigm. This also means that the setting is less standardized, as topics and how emotions are communicated will vary between participants. A more standardized approach might be better suited to understand which situation-specific factors influence PS. An external manipulation of the couple's arousal state could achieve a more comparable situation across individual couples. A suitable way for this is the induction of stress.

Stress can be reliably induced in the laboratory (Allen et al., 2014; Vors et al., 2018), and is associated with a well-defined physiological response (Epel et al., 2018), in contrast to emotions, which are not consistently matched to specific physiological outcomes (Siegel et al., 2018). When encountering acute stressors, especially those threatening the physical integrity of the organism, stress responses involve dynamic shifts in both the parasympathetic (PNS) and sympathetic nervous systems (SNS). While stereotypical "fight or flight" responses are marked by increased SNS activity and reduced PNS activity, stress can also elicit increased PNS activity in some contexts, such as during a freezing response (Epel et al., 2018). In a medium time frame, and especially in response to social-evaluative threats, the hypothalamic-pituitary-adrenal (HPA) axis is activated, resulting in the release of cortisol (Dickerson & Kemeny, 2004). Cortisol increases glucose availability, suppresses inflammation, and also mitigates the longer-term effects of stress by altering gene expression (Epel et al., 2018). At the same time, acute stressors result in experiencing feelings of stress (Campbell & Ehlert, 2012), which can be classified as simultaneous negative emotional valence and heightened emotional arousal (Rubin & Talarico, 2009; Russell et al., 1989; Vors et al., 2018). While physiological stress responses are flexible and shaped by individual and contextual factors, laboratory stressors offer the possibility to systematically manipulate an individual's physiological and emotional arousal state. The present study, therefore, investigates whether a stress induction also influences the physiological synchronization with a romantic partner.

A romantic partner can be affected by stress experienced by their significant other. This has been investigated in settings where one partner directly observed the other during a stressful situation in real-time (Engert et al., 2019, 2014). Witnessing someone undergo an acute stressor can lead to an empathic physiological response in the observer (Buchanan et al., 2012; Dimitroff et al., 2017; Engert et al., 2014). However, significant others can also play a role in coping with stress. Social support or social touch can mitigate acute stress responses as well as longer-term consequences of stress (Berretz et al., 2022; Cohen et al., 2015; Dreisoerner et al., 2021; Häusser et al., 2012; Løseth et al., 2022; Ocklenburg, 2024). Whether one person's stress state impacts their PS with others in subsequent interactions is less well documented. Preliminary evidence supports this notion: (Waters et al., 2014) analyzed SNS PS in mother-infant dyads after the mother had undergone a stressful social evaluation with either positive or negative feedback, or a nonstressful control condition. Upon their reunion, PS was found in the two stressful conditions but not in the control condition. PS increased during the interaction only in the negative feedback condition. Thus, even though infants did not directly witness their mother's exposure to the stressor, PS was increased following the mother's stress state. A stress induction in one partner may similarly impact a romantic couple's PS. Similarly to the (Waters et al., 2014) study, the pair's physiological concordance could be altered even after the acute stressor has ceded. While the individual's ANS functions recover quickly (ranging from seconds to minutes; Beilharz et al., 2020), remnants of the stressful situation could remain afterward (e.g., in the form of rumination; Zoccola et al., 2009), and may impact social behavior after the stressor.

To better understand the possible role of PS between romantic partners in early adulthood, we investigated factors that may influence ANS PS in romantic couples. In contrast to previous studies, these factors were not produced by the couple's interaction directly (e.g., negative emotions induced by interpersonal conflict), but externally introduced in a more standardized approach. For this, we induced stress in one partner of a romantic couple without the other partner's knowledge and measured subsequent PS. To further standardize the interaction, participants were not allowed to talk about their emotions immediately upon reunion. Without verbalization of their stress state, any influences of stress on PS would necessarily arise through nonverbal pathways (for possible mechanisms, see Prochazkova & Kret, 2017). During the couple's interaction, we measured ANS PS at the level of the heart, i.e., cardiac synchrony. Heart rate (HR), is influenced by both SNS and PNS activity. HR, especially PNS-mediated changes in HR, has been consistently associated with social processes (Coutinho et al., 2021), but HR is also typically affected by stress (Epel et al., 2018). Thus, PS in HR seems like a suitable marker to measure the influences of stress on the dyadic interaction. As past research has shown differential results for parasympathetic and sympathetic synchrony (Danyluck & Page-Gould, 2019), we extract information about parasympathetic influences on overall HR synchrony. This can be achieved by distinguishing high-frequency changes in HR, which are associated with parasympathetic activity (Bernston et al., 1993; Quigley et al., 2024), from lower-frequency changes in HR. For this, we calculate PS using a time-frequency-based method, i.e., cross-wavelet power. Based on the quantification of synchrony using the cross-wavelet power method (Quer et al., 2016), our working definition of synchrony is the covariance of changes in HR trajectories over time between individuals. This analysis method offers a high time and frequency resolution and takes nonlinear components of HR into account (Quer et al., 2016; Rösch & Schmidbauer, 2018). We hypothesize that stress influences PS as measured by cross-wavelet power in romantic couples in a subsequent interaction.

2. Methods

2.1. Preregistration

The hypotheses and study design were preregistered prior to data collection at: https://osf.io/fk62d. The current manuscript does not cover all preregistered hypotheses. The hypothesis H1a is presented in the current report as preregistered, while the other preregistered hypotheses will be reported elsewhere.

2.2. Participants

This study has been reviewed and approved by the Institutional Review Board of the University of Konstanz (IRB 12-2017). Due to feasibility concerns, we had preregistered an expected sample size of $N = 100$ to 150 participants (50 to 75 dyads). Participants were recruited via the University of Konstanz's study recruitment system SONA (uni-konstanz.sona-systems.com), flyers, and word of mouth. Data collection took place from August 2021 to July 2022. We included romantic couples with sufficient German language skills where both partners indicated a romantic relationship with each other. Due to COVID-19-related university guidelines, at least one partner had to be enrolled at the University of Konstanz. Exclusion criteria were based on potential confounding effects on the physiological data measured in the laboratory experiment: salivary cortisol and HR. Potential participants were excluded when they indicated psychological or heart-related disorders, depressive symptoms measured as a score of > 17 on the Beck's Depression Inventory-II (Hautzinger et al., 2006; Nuevo et al., 2009), or infection with COVID-19 in the last four weeks. The final sample consisted of $N = 150$ participants, or $N = 75$ dyads (74 men and 76 women).

2.3. Socially evaluated cold pressor test

Participating dyads were pseudo-randomized into an *experimental* and a *control* condition by using a randomization algorithm (R. Core Team, 2025) to arrive at approximately the same number of dyads in each condition. In dyads in the experimental condition, stress was induced in one participant with the Socially Evaluated Cold Pressor Test (SECPT; Schwabe et al., 2008). Participants were instructed to leave their non-dominant hand in ice-cold water for three minutes while being recorded by a camera directed at their face. An experimenter acted distantly and pretended to take notes about the participants' behavior. If participants removed their hand from the ice water before the three minutes were over, the experimenter asked them to return the hand to the water for the experiment to be successful. The SECPT was shown to reliably induce stress through the combination of physical and social stress elements, leading to an increase in cortisol and self-reported feelings of stress (Allen et al., 2014). Participants undergoing the control-SECPT paradigm were instead instructed by a neutral-to-friendly acting experimenter to leave their non-dominant hand in lukewarm water for three minutes, without the pretense of being filmed or observed.

2.4. Procedure

Before testing, participants completed a prescreening questionnaire online (Qualtrics, Provo, UT, www.qualtrics.com), where they provided informed consent for participation in the screening questionnaire. Here, they indicated relationship duration and demographic variables, filled out questionnaires on parental bonding, empathy, handedness, and footedness, and were screened for exclusion criteria. Suitable participants were then invited to the laboratory. Participants were asked to abstain from eating for an hour before the experiment and to abstain from caffeine and nicotine intake as well as exercise for two hours before the experiment (Quigley et al., 2024). Upon arrival, participants were separated into two rooms. After providing informed consent and putting on HR sensors, they filled out questionnaires on state variables (compliance with abstaining from caffeine, nicotine, and exercise), relationship quality, dyadic stress coping abilities, and adult attachment style. Females furthermore provided information regarding their menstrual cycle state and the use of oral contraceptives to obtain information about their hormonal status. Participants' baseline HR was measured for five minutes while sitting with eyes open. Subsequently, HR was measured continuously throughout the experiment. In the *experimental* group, following the HR baseline ($n = 38$ dyads; 50.67%), one participant underwent a laboratory stressor, the SECPT, whereas the other, in a separate room, underwent a non-stressful control condition. In the *control-group* dyads (n=37), both participants completed the non-stressful control paradigm (control-SECPT) in separate rooms. Afterward, participants were reunited in a third room. Here, they were instructed by an experimenter who had not been involved in the SECPT paradigm, via Zoom (Zoom Video Communication, San Jose, CA) from outside the room. Both participants were instructed to sit across from each other while trying to imagine how the other person was feeling, without speaking, for three minutes (*synchronization task*). Then, participants were instructed for a gait-synchrony-related task: they were asked to walk next to each other along a predetermined course inside the room, while talking about a hypothetical vacation they would take. The walking course consisted of an irregularly shaped loop, approximately 3 × 4 m. This task lasted for ten minutes, during which couples were asked to hug every two minutes (in total five times) to assess potential laterality effects of stress (*walking task*). Afterward, participants were asked to interact freely for ten minutes (*free interaction task*). During this task, participants were permitted to sit down and free to talk about any topic of their choice. The procedure is depicted in Fig. 1.

Saliva samples for cortisol assessment were taken at baseline, after the synchronization task, after the walking task, and after the unstructured interaction. The momentary affect of oneself as well as the estimated momentary affect of the partner were assessed after baseline, after the intervention, after the synchronization task, in the middle and after the walking task, as well as at the end of the experiment (six time points in total). Participants were video-recorded while in the third room.

2.5. Measurements

2.5.1. Physiological measures

To assess the effects of the stress induction, we measured the ANS variables HR and heart rate variability, as well as free salivary cortisol (Epel et al., 2018).

Heart rate. HR was assessed using Polar Team Pro chest strap sensors (sampling rate 1000 Hz) in combination with the Polar Team Pro dock and app (Polar Electro Oy, Kempele, Finland). Raw RR interval data were preprocessed in R (R. Core Team, 2025). Using an in-house script, we replaced outliers with best-guess estimates. For this, we first removed outliers, which we defined as subsequent RR interval values that differed by more than 30% from each other or were physiologically implausible. Secondly, the gaps in the time series were interpolated using a formula that included surrounding RR intervals, autocorrelative properties, and random error. In this way, outliers were removed without gaps in the recording. From the corrected data, HR was interpolated with a frequency of 1 Hz using the RHRV package (Le et al., 2022) in R.

Heart rate variability. As a measure of PNS activity (Bernston et al., 1993; Quigley et al., 2024), we calculated high-frequency heart rate variability (HF HRV), using the CalculatePowerBand() function of the RHRV package (Le et al., 2022) on interpolated HR data, with a window size of 60 s and no overlap between windows. We used logarithmized values in the statistical analysis.

Salivary cortisol. Cortisol was measured in four saliva samples per participant, which were collected using Salivettes (Sarstedt, Nümbrecht, Germany). Analysis of free cortisol (nmol/l) was conducted in the biochemical laboratory of the University of Konstanz. Samples were stored at −20 °C until they were analyzed using a commercially available competitive enzyme immunosorbent assay (Cortisol Saliva ELISA, RE-52611, IBL International GmbH, Hamburg, Germany). The resulting values were logarithmized and winsorized.

2.5.2. Cardiac synchrony

Cardiac synchrony was calculated for each dyad for the synchronization task, walking task, and free interaction. We used cross-wavelet power (CWP) as an indicator of cardiac synchrony (e.g., Quer et al., 2016; Wienhold et al., 2025). In our preregistration, we had planned to analyze PS using CWP, cross-correlation, or a stability and influence model, depending on the results of a preceding analysis (see Denk et al., 2024). A qualitative review including simulated data revealed the advantages of CWP compared to the other methods in question. Specifically, CWP does not require stationary or linear data and includes a high frequency and temporal resolution. By providing frequency-related information, CWP analysis can elucidate the temporality of underlying processes on which dyads synchronize. Additionally, leader–follower relationships and anti-phase synchronization are taken into account in this quantification of synchrony. To compare CWP analysis results to a more traditional approach, we also conducted a cross-correlational analysis (see Supplementary Materials).

For calculating CWP, two signals (here: HR time series) are first wavelet-transformed, i.e., the influence of different frequency bands on the signal over time is quantified. Similarities between the two transformed (i.e., band-pass-filtered) signals are determined in a second step. This analysis results in a synchrony index, called the CWP coefficient, for each frequency band and each time point (Rösch & Schmidbauer, 2018). The higher the CWP, the more the HR trajectories are synchronized, indicating increased correspondence between the two signals. CWP analysis results in a [time × frequency bands] table of coefficients. Fig. 2 shows a visualization of such a table for two different examples. Fig. 2(a) and 2(c) show two examples of HR data during the synchronization task for two different couples. Fig. 2(b) and 2(d) depict the respective resulting CWP plot. To reduce the result to a one-dimensional array, we divided the resulting continuous table into sections and extracted the maximum CWP coefficient from each. Specifically, we divided the table into 20-second intervals and into high versus low frequency bands (see the white lines in Fig. 2; Wienhold et al., 2025). In absolute HRV data, power in frequency bands between 0.15 Hz and 0.4 Hz points to PNS activity (Bernston et al., 1993). Similarly, we extracted values from the CWP matrix that correspond approximately to the HF range in HRV data to assess cardiac parasympathetic synchrony (HF CWP; period duration of 2 to 8 s). In contrast, the meaning of lower-frequency absolute values in HRV (0.04 to 0.15 Hz; Laborde et al., 2017), being a mix of sympathetic and parasympathetic activity, is ambiguous. LF HRV is further sensitive to measurement artifacts and cannot match the specificity and robustness of other HRV indicators. However, the relevance of the higher-order LF synchrony phenomenon is at this point in time unknown, and we therefore opted to explore possible effects on LF HRV synchrony in the analysis. This was termed LF CWP (period duration of 8 to 32 s). In sum, we extracted the maximum PS, which is represented as HF CWP and LF CWP time series with measurements every 20 s.

2.5.3. Affect and self-reported stress

Participants completed all questionnaires using the Qualtrics Offline App on an iPad Air (Apple Inc., Cupertino, CA).

Momentary affect. To assess participants' momentary affect, we utilized the Affect Grid (Russell et al., 1989), a one-item scale to measure affect as a two-dimensional construct with the dimensions valence and arousal. The Affect Grid is a 9 × 9 grid in which participants can choose one cell to indicate their current feelings. Values on each dimension range from 1 to 9 to indicate negative to positive emotional valence, and low to high arousal, respectively. We used a German translation of the Affect Grid (Wendsche et al., 2008). In addition to instructing participants to indicate their mood, we also asked participants to estimate their partners' current mood. All six ratings for the own and partner's mood took place simultaneously, except for the second measurement. The second measurement of the own mood took place directly after the stress or control paradigm in separate rooms, whereas the second

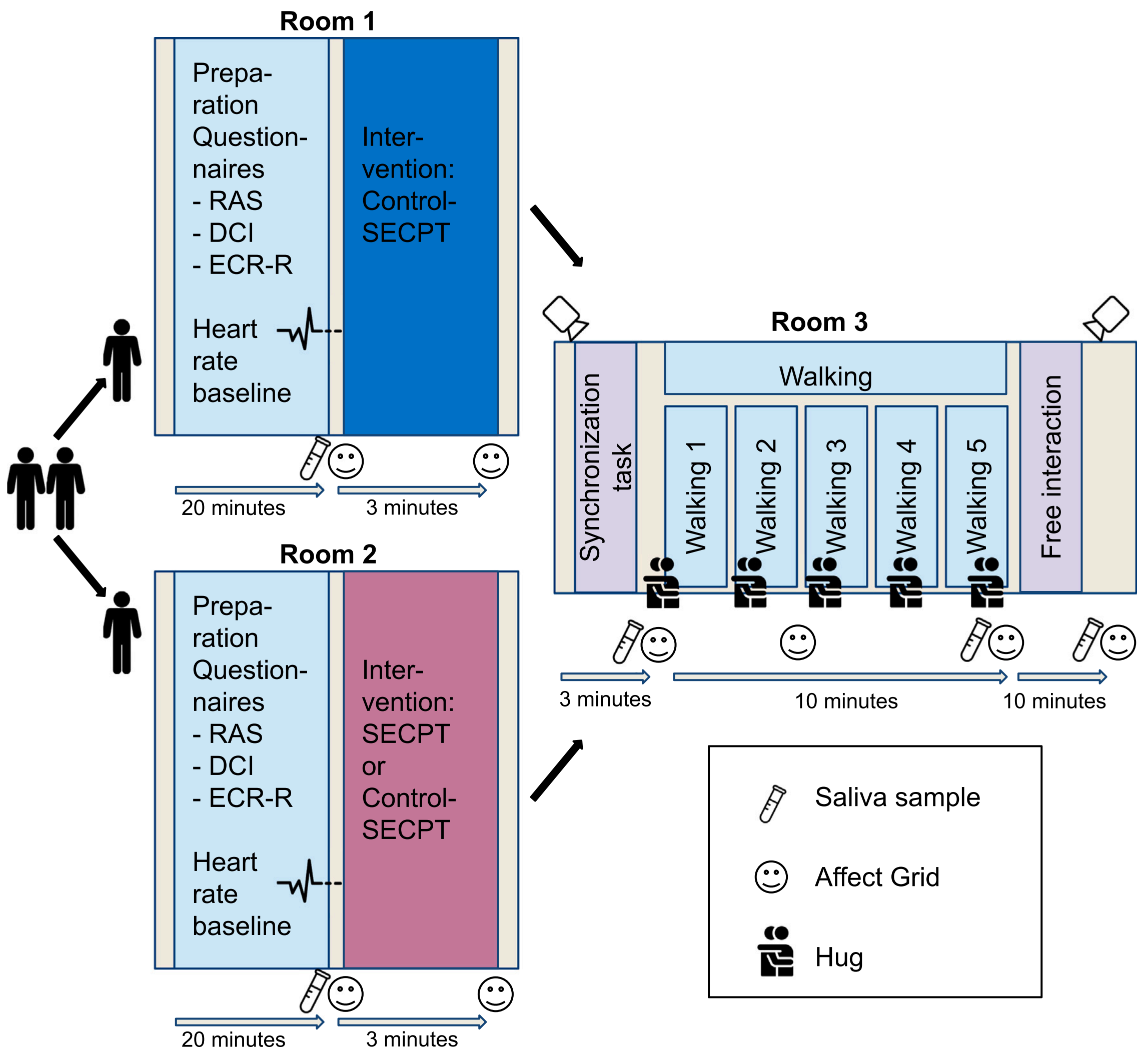


Fig. 1. Schematic depiction of the procedure of the experiment. In the first part, the partners were separated. Stress was induced in either one or none of the participants. After the intervention, partners had the opportunity to synchronize their heart rate and gait during a sitting and walking task. RAS = Relationship Assessment Scale, DCI = Dyadic Coping Inventory, ECR-R = Experiences in Close Relationships, SECPT = Socially evaluated cold pressor test.

assessment of the partner's mood took place immediately after both partners had reunited.

Perception of the intervention. To assess participants' subjective feelings directly after the stress or control intervention, we used a four-item post-treatment questionnaire with the following questions (originally in German): "How difficult was it for you to keep your hand in the water?", "How uncomfortable was the situation?", "How stressed did you feel in the situation?", and "How painful was it to keep your hand in the water?", which participants could answer on an 11-point Likert scale ranging from 0 to 100 in steps of 10. We calculated a sum score across all four times as an indicator of intervention stress and difficulty (possible range 0–400).

2.5.4. Other measures

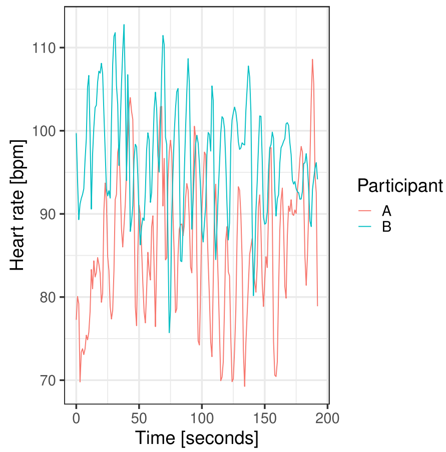
Depressive symptoms Beck's Depression Inventory II (BDI-II; Hautzinger et al., 2006) assesses subclinical and clinical symptoms of depression. Scores > 17 are assumed to indicate clinically relevant symptoms (Nuevo et al., 2009), resulting in the exclusion of the participant.

Details and sample characteristics regarding other questionnaire measures that were assessed in our study are available in the Supplementary Materials (see section A for an overview of measures, and section B for a comparison between experimental conditions).

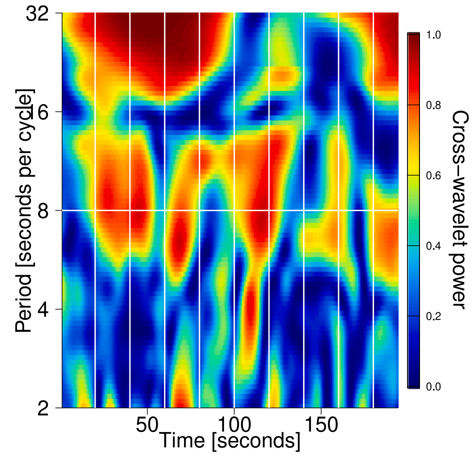
2.6. Statistical analysis

Statistical analyses were conducted in R version 4.5.2 (R. Core Team, 2025), using RStudio version 2025.05.1 (RStudio Team, 2020). We used the nlme package (Pinheiro et al., 2023) for multilevel regression models. Figures were created using the ggplot2 package (Wickham, 2016). The level of significance was set to alpha = 0.05.

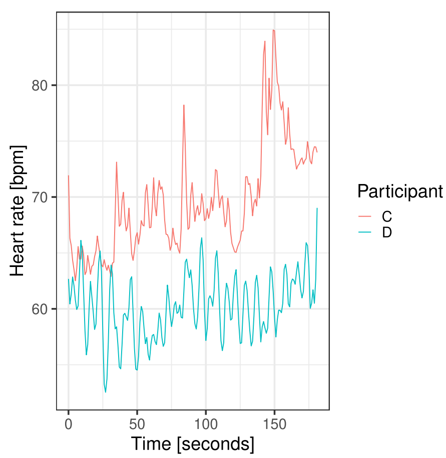
To test whether the SECPT had successfully induced stress, we conducted manipulation checks comparing HR, HF HRV, salivary cortisol, emotional valence, emotional arousal, and perception of the intervention scores between stressed and non-stressed participants. Here, we differentiated between participants who underwent the SECPT themselves with partners who underwent the nonstressful control-SECPT (*Stress/partner-control*), participants who underwent the nonstressful control-SECPT with partners who were exposed to the SECPT (*Control/partner-stress*), and participants who underwent the nonstressful control-SECPT with likewise non-stressed partners (*Control/partner-control*). For all repeated measures, we conducted multilevel mixed models, with the independent variables measurement point and experimental condition, random intercepts and slopes per participant, and random intercepts per dyad. Perception of the intervention scores was only measured once and was compared between the experimental conditions (SECPT or control-SECPT) using a two-sample *t*-test. We did not take into account the partner's experimental condition for this



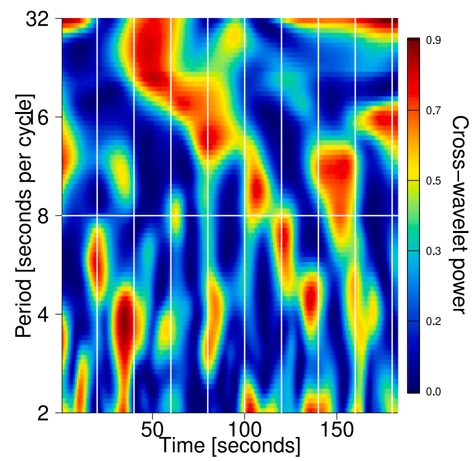
(a) Example for heart rate trajectories for dyad A B (in the control condition) during the synchronization task.



(b) Resulting cross-wavelet power plot for dyad A B.



(c) Example for heart rate trajectories for dyad C D (in the stress condition) during the synchronization task.



(d) Resulting cross-wavelet power plot for dyad C D.

Fig. 2. Examples for measured heart rate data and resulting synchrony data. Synchrony was measured as cross-wavelet power (CWP). CWP plots show time on the x-axis and the frequency bands on the y-axis (here, the y-axis shows period = 1/frequency). The color indicates the amount of synchronization. Resulting values were aggregated by splitting the plot into high and low frequencies, and extracting the maximum value for each 20-second segment.

measure, as the perception of the intervention was only measured once, before reuniting with the partner.

Our hypothesis stated that cardiac synchrony was influenced by stress in the dyad. We calculated two multilevel mixed models, one to predict HF CWP and one to predict LF CWP (with outcome variables assessed in 20-second intervals). Each model included a random intercept for each dyad, random slopes across time points within each phase of the experiment, and random slopes across the experimental phases. As fixed effects, we included the experiment phase (synchronization task, walking task, and free interaction), the time within each phase (in steps of 20 s), the experimental condition, and interaction terms between phase and experimental condition. Regression coefficients and their significance compared to a null effect were determined for fixed effects using the nlme package summary function. The model equation and code are available in the Supplementary Material, section C. To avoid overfitting, we excluded non-significant variables from the final model and report the results of a model with significant variables only. The models containing a more extensive list of all factors are shown in the Supplementary Materials (Section C).

We explored additional effects of other variables, such as questionnaire scores, on HF CWP and LF CWP, the results of which are detailed in the Supplementary Material, section D.

2.6.1. Covariates

The resulting value for CWP is related to the absolute values of the individual trajectories (Rösch & Schmidbauer, 2018). To control for the absolute values statistically, we included individuals' HF HRV per experimental phase into the HF CWP and LF CWP models. We further controlled for HF HRV at baseline to account for individuals' ANS activation at rest. To control for the ANS reactivity to different experimental phases, we additionally included the area under the curve with respect to the ground (AUCg) for HF HRV. The AUCg is a measure for overall reactivity including baseline levels (see Pruessner et al., 2003).

Several health-related and demographic factors are known to influence HR, HF HRV, and cortisol (Laborde et al., 2017; Strahler et al., 2017). While modulators of cardiac synchrony are not as well-investigated, influences on HR and HF HRV may also impact their synchronization. We thus included relevant characteristics in each statistical model. Specifically, age, sex, health behaviors, and health outcomes have been associated with both HF HRV (Laborde et al., 2017) and cortisol (Strahler et al., 2017). We thus include the variables age, sex, smoking (yes/no), body mass index (BMI), medication, and self-rated physical health as covariates. Medication was categorized.

Table 1
Sample characteristics (N = 150).

Variable	Mean (SD) or %	Stress condition	Control condition	Group comparison
Sex female[a]	50.67%	52.63%	50.00%	$\chi^2(1) = 0.01$ $p = .926$
Gender[b]	0.00 ±4.74	0.33 ±4.86	−0.11±4.71	$t(62.25) = 0.49$ $p = .624$
Age	22.66 ±2.99	22.39 ±3.98	22.75±2.58	$t(47.96) = -0.51$ $p = .609$
Student	92.00%	86.84%	93.75%	$\chi^2(1) = 1.02$ $p = .312$
Relationship duration[c]	27.11 ±23.98	28.30 ±24.46	26.71 ±23.91	$t(62.70) = 0.35$ $p = .730$
Medication[d]	19.33%	18.42%	19.64%	$\chi^2(1) < 0.01$ $p = 1$
Smoking[e]	13.33%	13.16%	13.40%	$\chi^2(1) < 0.01$ $p = 1$
Physical health[f]	8.29 ±1.23	8.37 ±1.22	8.27 ±1.24	$t(65.16) = -0.44$ $p = .663$

[a] Self-reported sex assigned at birth, response options were male, female, diverse, and no response, but only the response options male and female were chosen.
[b] Feelings of belonging to a gender from −5 for male to +5 for female.
[c] Relationship duration was given in months.
[d] Self-reported use of any medication.
[e] Self-reported nicotine consumption of any kind.
[f] Self-reported physical health, possible range 1–10.

Most participants (n = 121) indicated taking no medication. Other participants indicated taking hormonal contraception (n = 23), which might have a blunting effect on HPA axis reactivity (Gervasio et al., 2022). Three participants indicated taking severe medications that might have physiological and psychological effects, i.e., an antidepressant, ADHD medication (methylphenidate), or heart medication. These participants were allocated to a *severe* category. Since these numbers were very small and would not allow meaningful interpretation when analyzed statistically, we grouped these three participants together. We then ran the analysis with and without these participants to explore whether they had an effect on the main result. Here, we did not observe significant changes in the main effects. Three other participants reported the use of other medications and were allocated to an *'other'* category (e.g., eye medication, antihistamines).

With synchrony outcomes being dyadic, we included minimum and maximum values of all variables mentioned above as separate variables into the analysis for continuous variables, and the combination of partners' levels for discrete variables. For example, if one partner's HF HRV during the baseline was 5 (log-value) and the other partner's was 7, the variable *Minimum Baseline HF HRV* would be 5, whereas the variable *Maximum Baseline HF HRV* would be 7 for this dyad, such that both values were included for each dyad. For the discrete variable smoking, possible levels were yes – yes, yes – no, and no – no. For PS-related models, the combination of the medication types in each dyad was used. We did not include the gender combination into the model, as almost all dyads consisted of one man and one woman. Continuous variables were centered.

2.6.2. Exploratory analysis

Stress effects on individual physiological variables depend on sex and gender (Domes et al., 2024; Pruessner, 2018). Likewise, stress effects on PS may depend on the sex or gender of the stressed person. We therefore assess the effects of the experimental condition combined with the sex of the stressed person. In the models for HF CWP and LF CWP detailed above, we thus exchanged the variable *condition* with a variable consisting of the levels *Control condition – no stressed partner*, *Experimental condition – female stressed partner*, and *Experimental condition – male stressed partner*.

3. Results

3.1. Sample characteristics

We assessed N = 75 couples and as such N = 150 participants (50.67% female) in our study. Table 1 gives an overview of relevant sample characteristics. Participants were on average 22.66 years old (range 18 to 41; *SD = 2.99*), and had an average relationship duration of 27.11 months (range 1 to 92; *SD = 23.98*). 96% of the relationships were heterosexual.

3.2. Manipulation checks

3.2.1. Physiological measures

Fig. 3 depicts the trajectories of HR, HF HRV, and salivary cortisol across the experiment. For HR and HF HRV, $n = 144$ participants were included in the analysis. Due to bad data quality, defined as ≥ 10% of data being either outliers or interpolated, n = 6 participants were excluded. Model specifications and additional results are presented in detail in the Supplementary Materials, section C.

A multilevel model for HR, including experimental condition (i.e., *Stress/partner-control, Control/partner-stress, or Control/partner-control*), phase, random intercepts and slopes for participants, random intercepts for dyads, and relevant covariates, showed a significant interaction between experimental phase and condition. Compared to *Control/partner-control* participants, *Stress/partner-control* participants showed higher HR during the intervention (b = 6.93, p < .001). *Control/partner-stress* participants did not differ from *Control/partner-control* participants during the intervention (b = 0.12, p = .907). On average, *Stress/partner-control* participants' HR increased by 5.36 beats per minute (bpm; SD = 6.60) from the baseline (average HR during the stress induction = 84.86 bpm, SD = 10.04), whereas *Control/partner-control* participants' HR decreased by, on average, 1.48 bpm (SD = 4.26; average HR = 78.98 bpm, SD = 11.82). In *Control/partner-stress* participants, HR decreased by 1.47 bpm (SD = 3.64; average HR = 75.96, SD = 11.19). In contrast, HR decreases from baseline were greater in the *Stress/partner-control* compared to the *Control/partner-control* condition during the subsequent synchronization task (b = −2.88, p = .047), with an average HR of 76.91 bpm

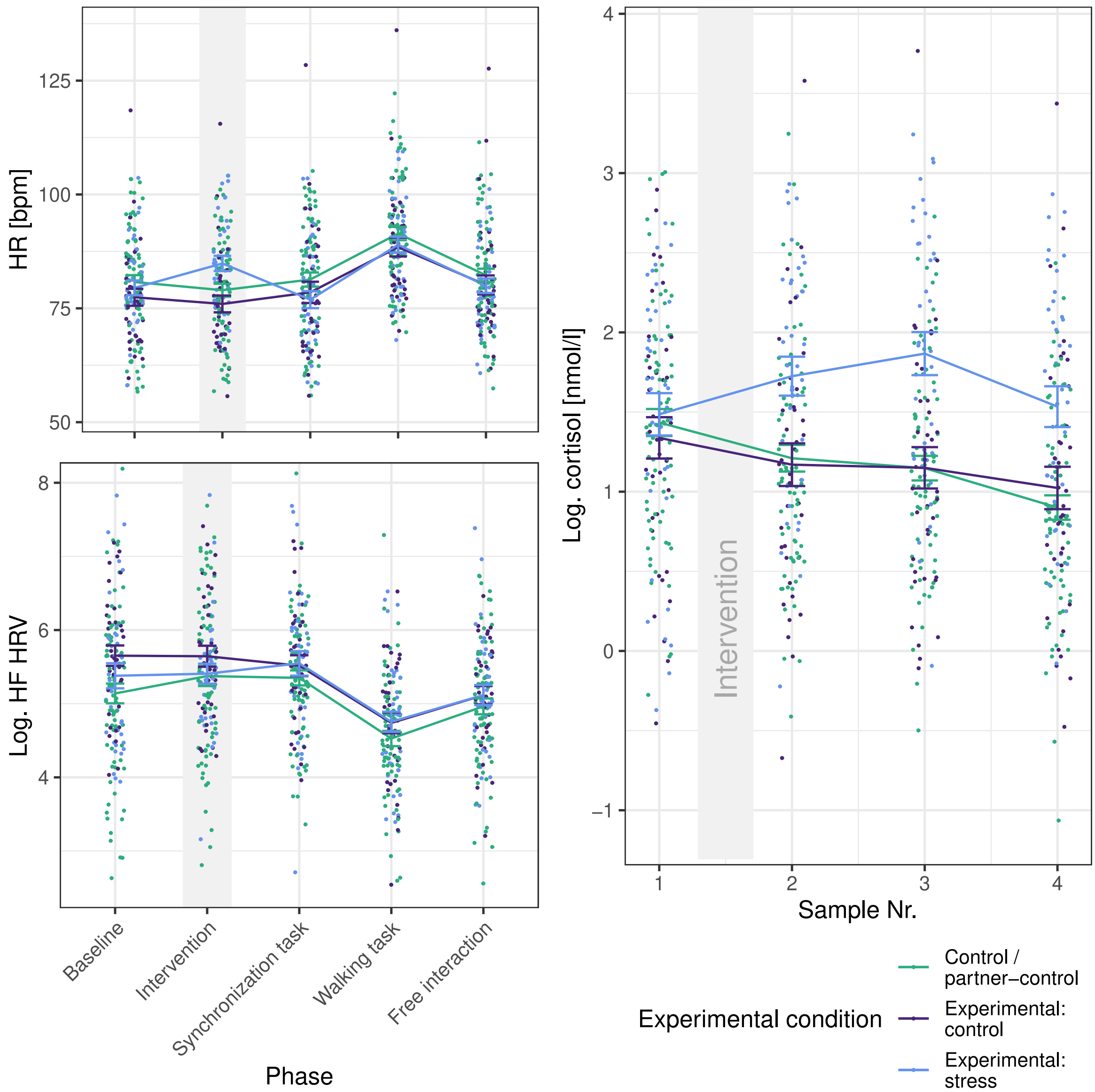


Fig. 3. HR (top left), HF HRV (bottom left), and salivary cortisol (right) trajectories by experimental condition over time; mean and standard error. The gray rectangle indicates the intervention (SECPT or control-SECPT). Participants in the control-SECPT condition are divided into those with a stressed versus a nonstressed partner.

(SD = 11.38) in *Stress/partner-control* participants, an average HR of 81.31 bpm (SD = 12.95) in *Control/partner-control* participants, and average HR of 78.50 bpm (SD = 14.22) in *Control/partner-stress* participants (see Fig. 3). Potential covariates were nonsignificant except for age ($\beta = -0.98$, $p = .008$).

For HF HRV, a multilevel model including experimental condition, experiment phase, an interaction between phase and condition, and random intercepts for participant and dyad, as well as random slopes per participant, showed no significant decrease in HF HRV for *Stress/partner-control* participants during the intervention ($b = -0.18$, $p = .228$) compared to *Control/partner-control* participants. However, *Control/partner-stress* participants showed decreased HF HRV compared to *Control/partner-control* participants during the synchronization task ($b = -0.33$, $p = .038$) and during the unstructured interaction task ($b = -0.34$, $p = .040$; see Fig. 3). HF HRV was generally higher in female compared to male participants ($\beta = 0.03$, $p = .040$).

For cortisol, winsorizing was applied to two values of one participant. A multilevel model including experimental condition, measurement point (1–4), random intercepts and slopes per participant, and random intercepts per dyad, showed a significant interaction between time point and the *Stress/partner-control* compared to the *Control/partner-control* condition ($b = 0.19$, $p < .001$), where cortisol was increased for *Stress/partner-control* participants for all time points after the intervention (2–4; see Fig. 3). An interaction effect between time and the *Control/partner-stress* compared to the *Control/partner-control* condition did not reach significance ($b = 0.07$, $p = .056$). The covariates included in the model were not significantly associated with cortisol values.

3.2.2. Psychological measures

Fig. 4 shows emotional valence and arousal trajectories. A multilevel model with emotional valence as the dependent variable, and experimental condition, measurement point, random intercepts and slopes per participant, and random intercepts per dyad as independent variables, showed a significant condition and measurement point interaction. Valence values were significantly lower in the *Stress/partner-control* condition compared to the *Control/partner-control* condition

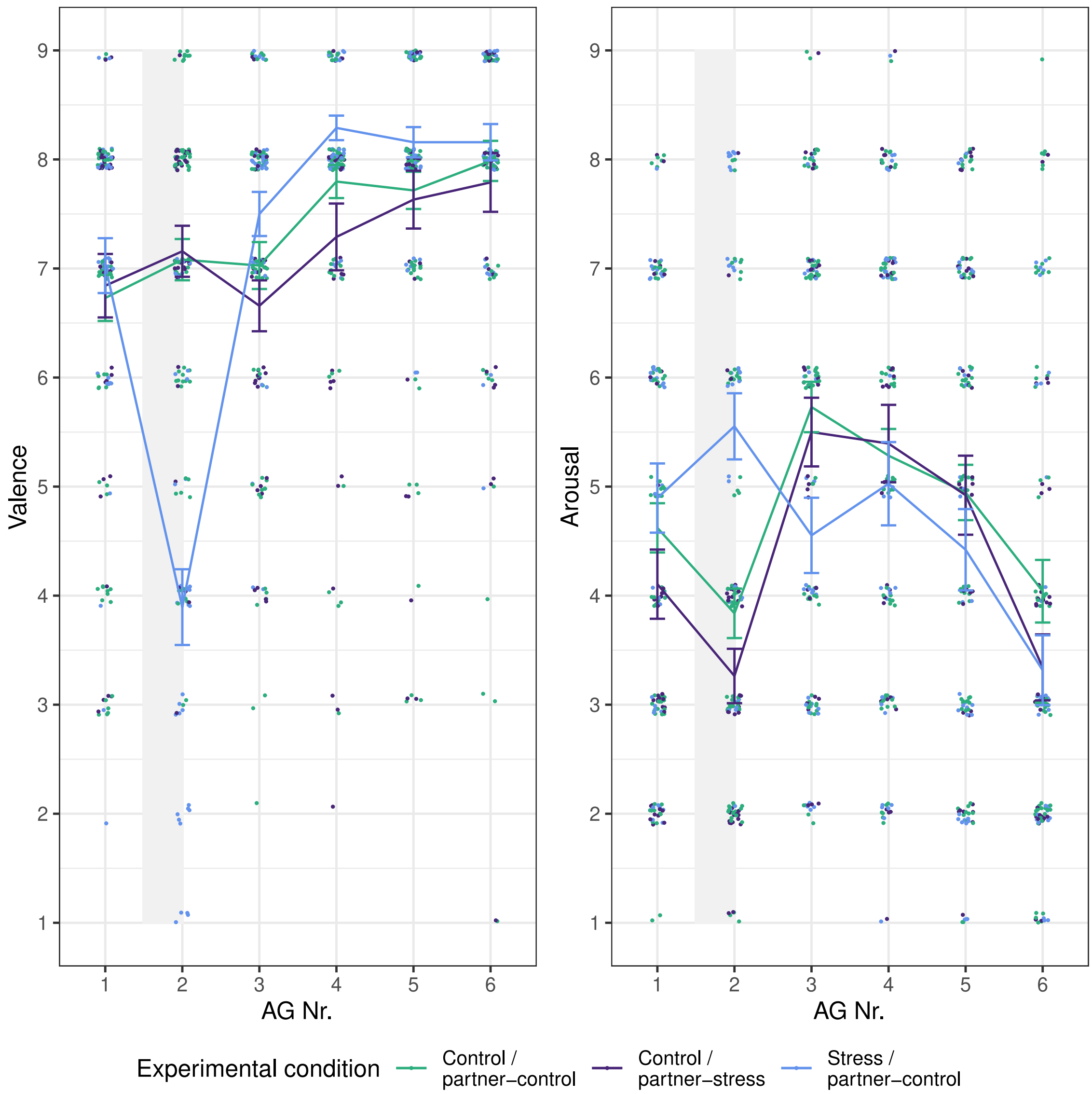


Fig. 4. Affect Grid valence and arousal trajectories (mean and standard error) by experimental condition over time. Possible values ranged from 1–9 for both measures. The gray rectangle indicates the intervention (SECPT or control-SECPT).

for measurement point 2 (directly following the intervention; $b = -3.47$, $p < .001$). Other measurement point and experimental condition interactions were not significant (all $p > .05$).

The multilevel model with emotional arousal as the dependent variable showed that arousal values were significantly higher in the *Stress/partner-control* condition for measurement point 2 (directly after the intervention; $b = 1.44$, $p < .001$), and significantly lower for time measurement 3 (after the synchronization task; $b = -1.45$, $p = .001$), compared to the *Control/partner-control* condition. Other interaction effects were non-significant (all $p > .05$).

The perception of the intervention was assessed after the intervention, consisting of participants' assessment of their feelings of stress (data available for $N = 147$ participants), uncomfortableness ($N = 142$), pain ($N = 149$), and difficulty in completing the intervention ($N = 147$). The sum score of those items ($N = 140$) was significantly higher in the stress condition ($mean = 214.32$, $SD = 106.18$) than in the control condition ($mean = 29.22$, $SD = 40.36$; $t(39.80) = 10.34$, $p < .001$). Similarly, the item indicating feelings of stress was also significantly higher in the stress condition ($mean = 42.89$, $SD = 31.14$) than in the control condition ($mean = 6.61$, $SD = 12.41$; $t(41.16) = 6.98$, $p < .001$).

3.3. Physiological synchrony

After the exclusion of bad-quality data, HR data for synchrony analysis were available for $N = 70$ dyads. Each dyad completed three different tasks together, resulting in data for $n = 210$ tasks across dyads.

3.3.1. High-frequency cross-wavelet power

We compared trajectories between experimental conditions for high-frequency cross-wavelet power (HF CWP; see Fig. 5). The full model is detailed in the Supplementary Materials Section C. Omitting non-significant variables from this model resulted in the simplified version reported here. In a model including random intercepts, random slopes across and within the different phases of the experiment, the experimental phase, the time within each phase, and the experimental condition, as well as the control variables that were significant in the full model, we found a significant main effect of the experimental

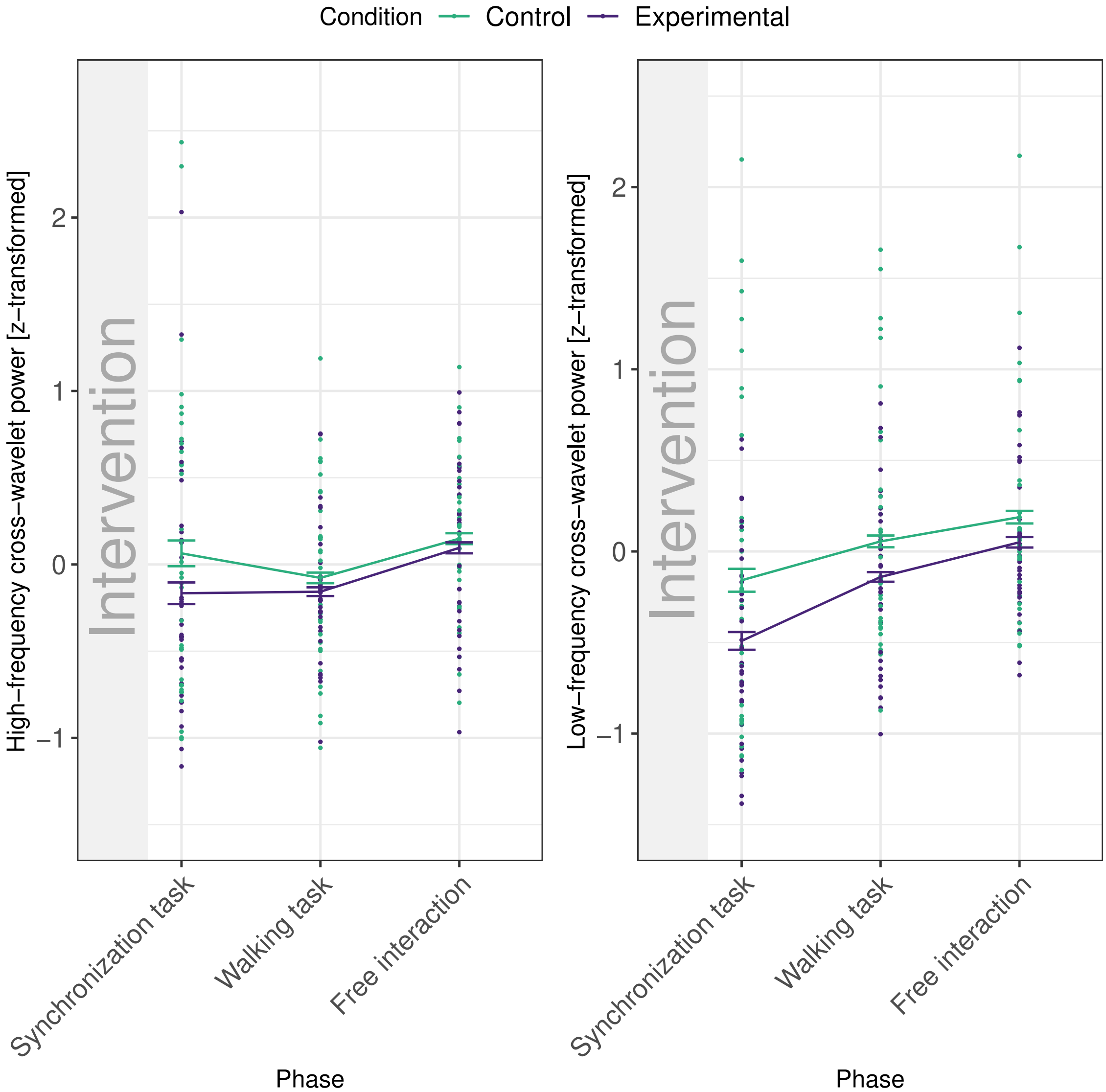


Fig. 5. Synchrony trajectories, as measured by high-frequency cross-wavelet power (HF CWP, left) and low-frequency cross-wavelet power (LF CWP, right), averaged for each phase of the experiment. The shaded area represents the intervention task (SECPT or control-SECPT).

condition (compared to the reference level control condition), where HF CWP was decreased in dyads with one stressed partner (*experimental condition*). Further, HF synchrony was associated with individuals' HF HRV values, their age, minimum BMI, medication intake, and physical health. Effect sizes for the simplified model are depicted in Fig. 6 (left). The overall model could explain R^2 = 22.6% of variance (confidence interval 20.3–25.9%). All model coefficients are shown in Table 2. A notation of the model is available in the Supplementary Materials Section C. An additional exploratory analysis included the effect of the sex of the stressed participant, resulting in the levels *Control group*, *Experimental group/female stressed*, and *Experimental group/male stressed*. For HF CWP, dyads in the experimental condition showed lower synchrony than dyads in the nonstressful control condition, when female participants ($b = -0.25$, $p < .001$) as well as when male participants underwent the SECPT ($b = -0.13$, $p = .048$), compared to dyads with no stress induction. All coefficients for this model are shown in the Supplementary Material, section D. We additionally explored whether HF synchrony changed over time during the different experimental phases, and how this interacted with the experimental condition. Results indicate no significant three-way interaction between time, experimental condition, and experimental phase (all $p > .05$; see Supplementary Materials section D). Excluding participants in the *severe medication* category did not change the significance of predictors.

3.3.2. Low-frequency cross-wavelet power

We also conducted a multilevel model analysis to compare LF CWP in the experimental compared to the control condition. Our full model included random intercepts, random slopes for each dyad across and within the different experimental phases, fixed effects for the time within each phase, the phase, the experimental condition, and an interaction between experimental condition and phase, as well as the control variables (see Supplementary Materials Section C). In a model including only significant variables, we found decreased LF CWP for dyads in the experimental compared to the control condition (see Fig. 6, right side, for effect sizes). LF CWP was further related to the dyad members' HF HRV values, and individuals' age, BMI, medication status, and physical health. The variance explained by the model was 26.2%(confidence interval 23.8–29.4%). All model coefficients are shown in Table 3. The model structure is detailed in Supplementary Materials Section C. An exploratory analysis including the sex of the stressed participant revealed lower LF CWP for dyads in the experimental condition, for both dyads with a female stressed partner ($b = -0.26$; $p < .001$) and dyads with a male stressed partner ($b = -0.13$; $p = .048$), compared to control dyads. An exploratory analysis including a three-way interaction between time, experimental condition, and phase showed a small but significant effect for a time *x* walking task *x* condition

Table 2
Results of the simplified multilevel model for high-frequency cross-wavelet power (HF CWP). Bold-faced variables were significantly different from 0. R^2 denotes the partial proportion of variance explained by each variable.

HF CWP					
Predictor	Estimate	CI	DF	*p*-value	R^2(%)
(Intercept)	−0.17	[−0.27, −0.06]	4623	.002*	
Phase: walking	0.52	[0.41,0.63]	4623	< .001*	4.95
Phase: free interaction	0.53	[0.44,0.63]	4623	< .001*	4.95
Time within phases	−0.0006[a]	[0.00,0.00]	4623	< .001*	1.84
Condition: experimental	−0.20	[−0.29, −0.11]	56	< .001*	1.9
Min. HF HRV	0.30	[0.22,0.39]	4623	< .001*	3.29
Max. HF HRV	0.26	[0.18,0.35]	4623	< .001*	2.33
Min. baseline HF HRV	0.31	[0.21,0.41]	56	< .001*	4.26
Min. HF HRV AUCg	−0.13	[−0.16, −0.09]	56	< .001*	5.23
Max. HF HRV AUCg	−0.08	[−0.11, −0.05]	56	< .001*	2.91
Min. age	0.10	[0.06,0.14]	56	< .001*	2.83
Max. age	−0.09	[−0.13, −0.06]	56	< .001*	3.39
Min. BMI	0.04	[0.02,0.07]	56	< .001*	1.66
Medication – none+contraceptives	−0.05	[−0.15,0.06]	56	.351	0.84
Medication – none+severe	−0.09	[−0.38,0.2]	56	.556	0.84
Medication – none+other	−0.29	[−0.52, −0.07]	56	.011*	0.84
Medication – contraceptives+severe	−0.12	[−0.66,0.43]	56	.675	0.84
Min. physical health	0.06	[0.01,0.11]	56	.031*	0.53
Max. physical health	−0.07	[−0.13, −0.01]	56	.024*	0.58

Note: * indicates $p < .05$.
CI = confidence interval; DF = degrees of freedom. $N = 70$ dyads.
HF HRV = high-frequency heart rate variability; AUCg = area under the curve with respect to the ground; BMI = body mass index.
[a] Significant estimates with absolute values < 0.01 are shown with a higher number of digits to indicate the direction of the effect.

Table 3
Results of the simplified multilevel model for low-frequency cross-wavelet power (LF CWP). Bold-faced variables were significantly different from 0. R^2 denotes the partial proportion of variance explained by each variable.

LF CWP					
Predictor	Estimate	CI	DF	*p*-value	R^2(%)
(Intercept)	−0.25	[−0.35, −0.15]	4625	< .001*	
Phase: walking	0.44	[0.33,0.54]	4625	< .001*	6.36
Phase: free interaction	0.54	[0.45,0.63]	4625	< .001*	6.36
Condition: experimental	−0.20	[−0.3, −0.11]	53	< .001*	2.04
Min. HF HRV	0.16	[0.09,0.23]	4625	< .001*	1.23
Min. baseline HF HRV	0.22	[0.12,0.32]	53	< .001*	2.11
Min. HF HRV AUCg	−0.07	[−0.1, −0.03]	53	< .001*	1.66
Max. HF HRV AUCg	−0.12	[−0.15, −0.1]	53	< .001*	10.4
Min. age	0.09	[0.05,0.13]	53	< .001*	2.25
Max. age	−0.12	[−0.15, −0.08]	53	< .001*	4.55
Min. BMI	0.07	[0.04,0.1]	53	< .001*	2.74
Max. BMI	−0.04	[−0.06, −0.01]	53	.008*	0.81
Smoking – one partner	0.12	[0,0.24]	53	.056	0.47
Smoking – both partners	−0.08	[−0.31,0.16]	53	.515	0.47
Medication – none+contraceptives	−0.14	[−0.25, −0.04]	53	.009*	5.22
Medication – none+severe	−0.51	[−0.82, −0.2]	53	.002*	5.22
Medication – none+other	−0.46	[−0.68, −0.23]	53	< .001*	5.22
Medication – contraceptives+severe	1.10	[0.55,1.64]	53	< .001*	5.22
Min. physical health	0.08	[0.02,0.13]	53	.006*	0.93
Max. physical health	−0.11	[−0.18, −0.05]	53	.001*	1.35

Note: * indicates $p < .05$.
CI = confidence interval; DF = degrees of freedom. $N = 70$ dyads.
HF HRV = high-frequency heart rate variability; AUCg = area under the curve with respect to the ground; BMI = body mass index.

interaction ($\beta < 0.01$, $p = .019$), indicating a more pronounced decline in LF synchrony during the walking task for the control compared to the experimental condition (see Supplementary Materials section D). Excluding participants in the *severe medication* category did not change the significance of predictors.

4. Discussion

In this study, we investigated whether stress of one partner would subsequently affect physiological synchrony (PS) during an interaction of romantic partners. We found decreased high-frequency (parasympathetic) and low-frequency (mixed sympathetic and parasympathetic) cardiac synchrony after stressor exposure across a nonverbal synchronization task, a walking task including a standardized conversation topic, and an unstructured interaction. Our findings thus support our preregistered hypothesis that the situation-specific variable stress would impact cardiac PS in young-adult romantic couples.

While multiple different stress induction protocols are available, we induced acute stress in participants using the SECPT (Schwabe et al., 2008). We found higher salivary cortisol and HR in stressed participants compared to those performing the control task, indicating a successful induction of a physiological stress response. While an increase in cortisol is in line with previous studies employing the SECPT (Becker et al., 2019; Schwabe & Schächinger, 2018), findings on autonomic markers were mixed (Schwabe & Schächinger, 2018). In the present

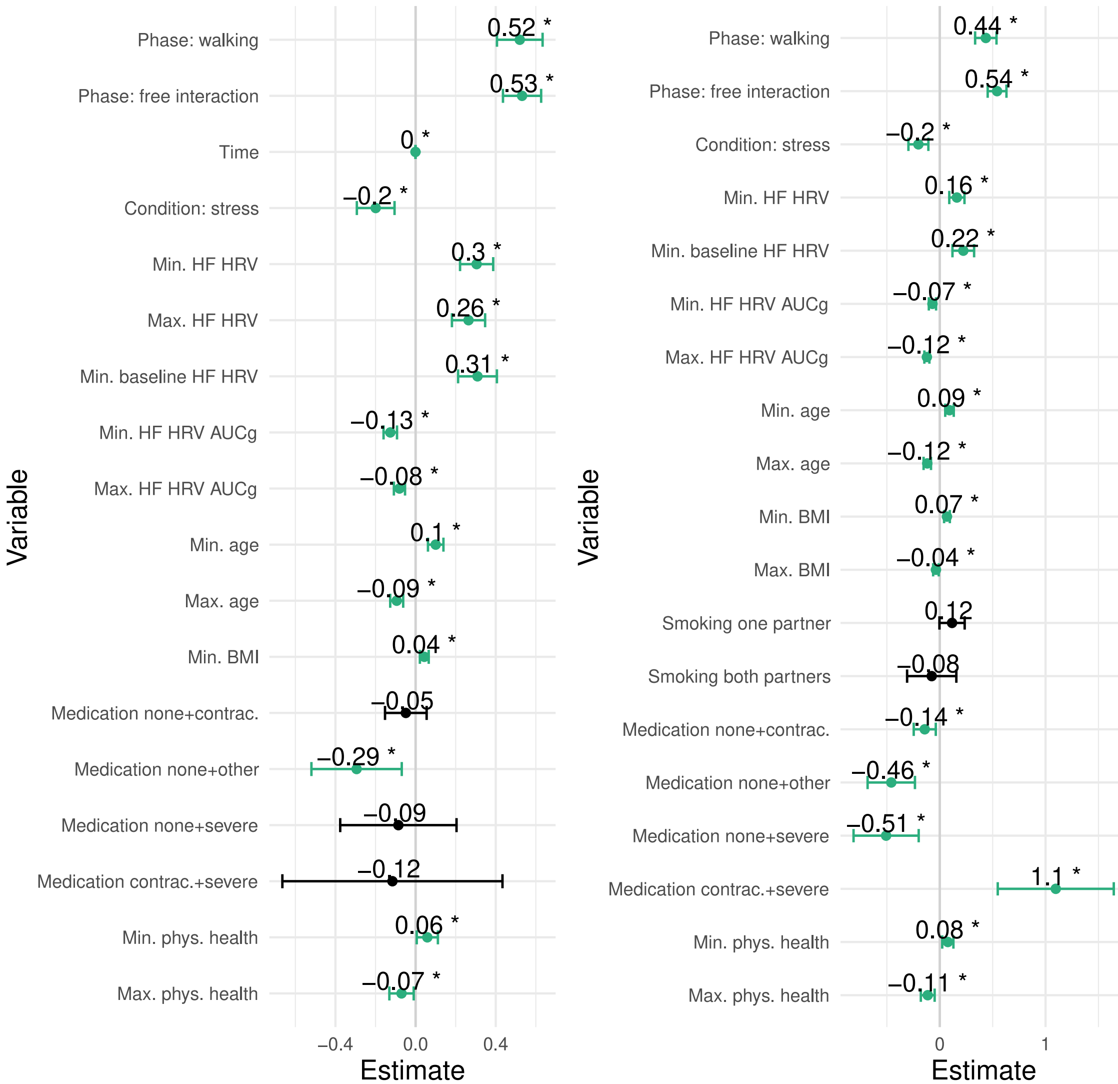


Fig. 6. Estimates for the multilevel models in which high-frequency cross-wavelet power (left), and low-frequency wavelet power (right) were predicted. * denotes significant effects ($\alpha < .05$).

study, HF HRV levels did not differ between experimental conditions, indicating parasympathetic activation did not decrease in response to the stressor. This may be explained by the effect of cold water on increased vagal activity (Jungmann et al., 2018; Richer et al., 2022), which may counteract PNS withdrawal from stress. Previously, McGinley and Friedman (2015) found an effect of the SECPT on time-domain HRV measures, but not on the frequency-domain measure HF HRV. Psychologically, participants experienced significantly higher emotional arousal and more negative emotional valence after the stress induction than after the non-stressful control paradigm, also reflected in higher scores on a questionnaire assessing their perception of intervention stress and difficulty. Altogether, the SECPT successfully elicited physiological as well as psychological stress responses. Interestingly, stressed participants showed an “overcompensatory” effect during recovery, with significantly lower HR and emotional arousal than non-stressed participants during the subsequent synchronization task. A “rebound” effect for ANS variables was previously shown directly following a stressor (Mezzacappa et al., 2001). As we did not assess dyads with two stressed partners, we can only speculate whether the decreased physiological and affective arousal compared to their non-stressed partners may stem from the stress-buffering effects of (albeit nonverbal) social support (Berretz et al., 2022).

In the aftermath of the stressor, we explored potential differences between non-stressed participants with a stressed compared to a non-stressed partner. After having reunited with the partner (i.e., during the synchronization task), HF HRV was significantly decreased from baseline for control participants with a stressed partner compared to control participants with a nonstressed partner. This hints at stress contagion effects, where nonstressed participants may experience an empathic response to a stressed partner’s state (Engert et al., 2019). In contrast to previous studies, partners were not observed whilst experiencing the stressor but encountered each other afterwards. Therefore, nonverbal pathways of stress contagion should be explored further. Alternatively, the decrease in HF HRV for participants with a stressed partner may stem from a regression to the mean. Those participants showed relatively high baseline HF HRV (see Fig. 3), which could have normalized over the course of the experiment.

The decrease in PS following stress could have different underlying mechanisms. In a study by Waters et al. (2014), stress in mothers led to increased SNS PS with their infants in a subsequent interaction, interpreted as stress contagion. In our study, stress was associated with decreased PS; however, the setting differed, and we did not measure purely sympathetic PS. The divergent findings highlight the specific role of the relationship (mother-infant dyads compared to romantic relationships) in the influences on PS. Decreased cardiac PS following stress in romantic relationships could indicate a "disrupted" interpersonal connection at the physiological level with a romantic partner. On the one hand, this disruption could be interpreted as an inability to synchronize with one's partner adequately. We could assume that stress may shift attention or importance away from the other person (e.g., thinking about the past stressful experience more than about the partner). However, past research showed mixed results regarding the effect of stress on attention to social stimuli and prosocial behavior (Forbes et al., 2024; Von Dawans et al., 2021). Alternatively, instead of an inability to pay attention to the partner, decreased PS may be adaptive to prevent stress contagion in the non-stressed partner (Gates et al., 2015), and leaving a synchronized state may allow for increased self-regulation (Thorson & West, 2018). With participants who had undergone the stressor showing positive emotional valence and low emotional arousal following the synchronization task, their self-regulation efforts may have been successful, but at the expense of strong PS with their partner. As discussed in the introduction, PS is not necessarily beneficial regarding relationship outcomes (Coutinho et al., 2021; Gates et al., 2015), and may increase the risk for emotional contagion (Prochazkova & Kret, 2017). The extent of PS, or the "falling in and out of" PS (Zilcha-Mano, 2024), may thus depend on its adaptivity in a given situation. A decrease in PS following a one-sided stressor in young adult romantic couples may thus play a role in the emerging emotion-regulation patterns that characterize romantic relationships at this developmental stage. Interestingly, both measures of synchrony were increased with a higher minimum age in the dyad, but decreased with a higher maximum age. This could indicate changes in physiological interaction patterns as couples go through young adulthood.

Examining the results more closely, we had operationalized PS as cross-wavelet power (CPW). CWP in higher frequencies (HF CWP) and low-frequency CWP (LF CWP) were both decreased in stressed compared to non-stressed couples during their interaction. HF CWP is associated more with parasympathetic processes, whereas LF CWP is influenced by both parasympathetic and sympathetic activation, similar to traditional frequency-based analyses of HRV (Bernston et al., 1993). In light of past studies finding differential outcomes of PNS- versus SNS-related PS (Coutinho et al., 2021; Danyluck & Page-Gould, 2018), we differentiated between these frequency bands. The PNS may have a unique relation to social processes: According to the Polyvagal Theory (Porges, 2021), parts of the vagus nerve, the main component of the PNS (Brosschot et al., 2016), have evolved to facilitate social interactions. While aspects of the Polyvagal Theory are discussed critically (Grossman, 2023), other theories similarly propose PNS activation as a marker of social processing (Thayer & Lane, 2000). Along that line, a connection between the PNS and social processes has been shown experimentally (Goodyke et al., 2022; Shahrestani et al., 2015; Smith et al., 2020; Zadok et al., 2024). As low-frequency PS emerges from both SNS and PNS influences (Reyes Del Paso et al., 2013), it offers a less clear interpretation on the system level than PS in purely SNS- or PNS-influenced variables. However, both HF and LF CWP were influenced by the one-sided stress state. Including absolute HF HRV values, as well as their changes over time, into the model as control variables showed that synchrony depended on the absolute activation of the PNS, which should be taken into account when measuring interpersonal ANS processes. Despite controlling for absolute individual activation, stress effects on PS were present, indicating that the effect goes beyond the individual ANS activation. Beyond controlling for absolute PNS activation, we statistically controlled for potential covariates. Demographic and health-related variables were significantly associated with HF and LF synchrony, specifically, age, BMI, smoking cigarettes, medication, and physical health. These results indicate that variables related to individuals' heart rate (see Laborde et al., 2017) may also influence heart rate synchrony. However, clear guidelines on relevant covariates in heart rate synchrony are yet to be established. For some covariates in our sample, especially medication categories, small sample sizes or a small variance limit the interpretability of their effects.

We tested the effect of stress on PS using three tasks that differed in their physiological demand and standardization. During the first task, participants refrained from talking. That we could still detect differences in PS between experimental conditions during this more standardized and nonverbal task hints at the existence of underlying nonverbal processes during social interactions. The Neurocognitive Model of Emotional Contagion (Prochazkova & Kret, 2017) suggests that PS arises because a "receiver" automatically and unconsciously processes behavioral cues sent by a "sender", which leads to inter-brain synchrony, resulting in the synchronization of peripheral processes. According to the model, if physiological changes from PS become conscious, emotional contagion arises – a prerequisite for empathy. In this way, a nonstressed partner may have felt a rising stress contagion in themselves and then decoupled themselves from the partner's physiology to avoid the spillover of negative emotions. In the meantime, stressed participants may have not synchronized with their partner to focus on self-regulatory efforts. This may also explain the different result compared to the study finding increased PS in infants after their mothers' stress (Waters et al., 2014), as infants generally benefit and learn from PS with their caregivers (see Feldman, 2017), whereas adults may have learned to escape PS when not beneficial to the situation (Zilcha-Mano, 2024). This highlights the developmental changes reflected in more autonomous young adult romantic relationships as compared to the stronger dependency characterizing caregiver-child interactions.

Exploratory analyses of sex effects indicate a physiological decoupling regardless of the sex of the stressed partner. Descriptively, this effect was larger when a female participant was stressed as compared with a male participant. Previous findings suggest sex and gender-specific differences in emotion regulation (e.g., Dedovic et al., 2009). Furthermore, there is a long line of stress research on the possible role of sex hormones and gender socialization in shaping stress responsivity (Domes et al., 2024). For example, the pharmacological manipulation of the autonomic and endocrine stress systems in men and women results in sex-specific stress responses and behavioral stress outcomes (Ali et al., 2020). Lastly, stress buffering effects of partners are sex-specific (Berretz et al., 2022). Due to the unbalanced and small group sizes in our study, the sex-specific effects need to be considered with caution. However, a more in-depth investigation of possible sex-specific effects on synchrony in stressful situations may be warranted in the future.

While our study offered novel insights into the impact of stress on subsequent social interactions, we acknowledge some limitations that may impact the interpretation of our findings. Firstly, the effect we found might not be specific to stress, and future research is necessary to examine the specificity of decreased PS due to stress versus a general mismatch in physiological or psychological states. Some methodological limitations include the measurement of PS and HF HRV. The use of CWP was a clear strength of our analysis, as it enabled the closer analysis of frequency-related information compared to other analysis methods (Denk et al., 2024). That said, a difficulty resulting from this analysis approach is that there is still no agreed-upon recommendation regarding the calculation and aggregation of wavelet-based outcomes. Additionally, the use of alternative methods for PS analysis would have highlighted different aspects of PS (e.g., leader–follower dynamics). This limits the generalizability of our conclusions to time-frequency analyses of PS. Generally, there is not one best-suited method for PS analysis (daSilva & Wood, 2024; Palumbo et al., 2017). Our decision to use CWP was made based on a review of different methods for analyzing ANS PS, where we showed through the use of simulated data the ability of CWP analysis to detect different PS properties (Denk et al., 2024). Through the addition of an exploratory cross-correlational analysis, we could replicate the results using a different method; however, other methods, such as cross-recurrence quantification analysis (Coco et al., 2021) would have been possible as well. Regarding the interpretation of our results, while we saw some differences between different frequency bands, their meaning is less clear. While HF synchrony may be associated with parasympathetic processes, the interpretation is not as clear-cut for synchronization in LF frequency bands, which mixes sympathetic and parasympathetic activity. In contrast to the psychological correlates of HRV frequency bands (Laborde et al., 2017; Ritz, 2024), the connection between HF and LF CWP and psychological variables has not yet been established, whereby this study is one of the first to investigate this relationship. Our findings on LF synchrony provide the first evidence that this is a potentially useful marker to study interpersonal interactions, which should be explored in future studies. An additional limitation is the measurement of HRV, which should be assessed accounting for respiration characteristics (Ritz, 2024). In this experiment, we have not assessed respiration due to feasibility reasons, which may limit the interpretation of the HRV results. Moreover, breathing could not only impact HRV itself, but potentially also cardiac synchronization. Thus, breathing should be measured and controlled for in future studies.

Other limitations concern the experimental procedure. While shown to successfully elicit stress (Schwabe & Schächinger, 2018), the Cold Pressor Test paradigm can affect pulmonary parameters (Manhas et al., 2011), which may lead to differential respiration patterns during the stress induction, potentially influencing HRV results. Further research should thus consider alternative stressors, such as the Trier Social Stress Test (TSST; Kirschbaum et al., 1993). The SECPT was chosen for practical reasons; however, the specific effects of cold water on physiology may necessitate other stress induction methods in future research on stress and synchrony. For example, the Digital Stress Test works without the requirement of cold water or additional experimenters (Norden et al., 2022). Similarly, the increase in activity level during the experiment, especially during the walking task, led to increased physiological arousal, which influenced HR and may potentially influence synchrony. A further limitation of the study design is the lack of standardization for the unstructured interaction task. While this allowed for a maximum of ecological validity, different dyads may have varied in emotional content during this task, which could influence the interpretation of synchrony (Coutinho et al., 2021). Subjective ratings of this task indicated low to medium emotional arousal (mean = 3.68, $SD = 2.22$) and high emotional valence (mean = 7.98, $SD = 1.48$), indicating a relaxed atmosphere.

In addition to methodological questions, the generalizability of our findings to the larger population is limited. Couples who participated generally experienced high relationship satisfaction (see Supplementary Materials section B), whereas couples with a worse relationship quality might have avoided participating in a study specifically concerning their relationship. Yet, the relationship quality seems to impact the direction in which PS is influenced by situational factors (Coutinho et al., 2021). Further, future studies should take into account biological markers other than HR for the calculation of PS, as the effect of stress on PS may differ depending on the systems involved. Despite these limitations, our study achieved a successful manipulation of the situational variable stress state and introduced a set of standardized interactions in which its influence on PS could be determined.

Stress can be a disruptive experience. This is demonstrated by extensive research connecting chronic stress, as well as atypical responses to acute stress, to health risks and psychopathology (Epel et al., 2018). Allostatic load, the cumulative strain from repeated stressor exposure over life, is related to a range of health issues (Guidi et al., 2021). This illustrates the importance of investigating the social dynamics of stress, how stress is transmitted between interaction partners, and how stress impacts social functioning. Future stress-management interventions could take the interpersonal dynamics of stress into account. While the impact of stress on an individual's physiological responses is well-studied, our findings highlight that stress impacts social processes even after the acute stressor has passed. Even when participants' moods and individual ANS measures improved quickly after the stressor (see Fig. 4), the effect on the physiological connection between partners remained throughout the experiment.

To conclude, the present study shows how stress is not only an intrapersonal but an interpersonal phenomenon. Stress impacts social interactions, down to the physiological level at which people connect. Future research could additionally assess the effects of stress on social interactions between two stressed partners. Moreover, synchrony in other modalities, like movement, could provide a more complete picture of social interactions following (one-sided) stress (Zilcha-Mano, 2024). In PS research generally, an important question concerns its mechanism and function. Investigating PS in connection to stress might uncover possible underlying processes of PS, and give insights into why it may be useful in certain situations to synchronize with a partner – or not.

CRediT authorship contribution statement

Bernadette F. Denk: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Meier:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Sebastian Ocklenburg:** Writing – review & editing, Investigation, Conceptualization. **Julian Packheiser:** Writing – review & editing, Investigation, Conceptualization. **Stella Wienhold:** Writing – review & editing, Software, Methodology, Formal analysis. **Nina Volkmer:** Writing – review & editing, Methodology, Formal analysis. **Raphaela J. Gaertner:** Writing – review & editing, Investigation. **Elea S.C. Klink:** Writing – review & editing, Investigation. **Stephanie J. Ashcraft:** Writing – review & editing, Methodology, Investigation. **Annika B.E. Benz:** Writing – review & editing, Investigation. **Jens C. Pruessner:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

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

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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.

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Appendix A. Supplementary materials

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.biopsycho.2026.109205.Supplementary materials are available at https://osf.io/pndsc/files/osfstorage.

Data availability

The data are available at: https://osf.io/pndsc/.

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