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RESEARCH ARTICLE

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The TSST triggers self-reported stress and biological stress and frustrates basic psychological needs: general and specific buffering effects of physical activity and social support

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ABSTRACT

Situations characterized by uncontrollability and critical social evaluation frustrate basic psychological needs, as outlined in Self-Determination Theory (SDT). Uncontrollability and social evaluation are central elements of the Trier Social Stress Test (TSST), leading to the hypothesis that the TSST, in addition to increasing self-reported stress and cortisol responses, also frustrates the needs for autonomy, competence, and social relatedness. Participants ($N = 195$) reported elevated stress and reduced need satisfaction, and increased cortisol responses during the TSST. The roles of assessed physical activity and experimentally-induced social support were also examined. Indeed, in time-sensitive and specific manner, the TSST frustrated basic psychological needs. Social support however mitigated frustration of social relatedness. Physical activity buffered against self-reported stress, the frustration of competence and the cortisol response. Further research is recommended to explore more differentiated interventions that can counteract the negative effects of psychosocial stressors.

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Stress; basic psychological needs; Self-Determination Theory; physical activity; social support

The Trier Social Stress Test (TSST; Kirschbaum et al., 1993) is a well-established method for inducing stress under experimental conditions reliably eliciting physiological stress responses (e.g. increase in cortisol, Dickerson & Kemeny, 2004; Kudielka et al., 2007; Allen et al., 2017) and psychological stress responses (Klaperski et al., 2013; Rimmele et al., 2007). The TSST induces stress by requiring participants to give a brief speech as part of a job interview scenario and then perform arithmetic tasks in front of a panel. As identified in a meta-analyses by Dickerson and Kemeny (2004), *social-evaluative threat* and *uncontrollability* are key features of the TSST that lead to strong stress responses. Social-evaluative threat is created by having participants deliver the speech and perform the math tasks in front of a panel of alleged experts in behavioral analysis. The panel members behave in a standardized cold manner and do not provide any feedback, encouragement, or other forms of friendly gestures such as smiling or nodding. Uncontrollability is created by keeping participants in the dark about what to do, insufficient preparation time for the speech, the surprising arithmetic task after the speech, and the experience of being unable to elicit any reaction from the panel members.

With the aim to integrate a perspective into stress research, which has received limited study so far, namely a needs perspective, we argue that stress per se can be interpreted as the fundamental frustration of basic (physiological or psychological) needs. According to Self-Determination Theory (SDT; Deci & Ryan, 1985), basic psychological needs are innate and universal psychological nutrients that are essential for an individuals' well-being, adjustment, and personal growth (Ryan, 1995; Ryan & Deci, 2000; Vansteenkiste et al., 2020). The basic needs for autonomy (need for choices and the voluntary determination of one's actions), competence (need to experience a sense of mastery and acting effectively), and social relatedness (need to feel a sense of belonging to other people or groups) are psychological needs, the satisfaction of which leads to several positive psychological consequences (Ryan et al., 2022; Tang et al., 2020; Vasquez et al., 2016), while their frustration significantly impairs well-being and motivation (Chen et al., 2015). Consequently, in the TSST social evaluation and uncontrollability are prototypical features of situations that frustrate these basic psychological needs (Ryan & Deci, 2017). More specifically, the perceived lack of control during the TSST is diametrically opposed to the characteristics of autonomy-supportive environments as proposed by SDT researchers (Reeve, 2015; Reeve & Cheon, 2021): The strict guidelines of the TSST setting leave no room for choices, explanations are not provided, emotions are not acknowledged (poker face of the panel), and informational language is partly lacking (instead, participants are surprised

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with an arithmetic task), while pressuring language and time constraints prevail. The social evaluation by the panel creates a threat to the self (Dickerson & Kemeny, 2004), and the "unfriendly neutrality" of the panel members corresponds to social exclusion rather than social-relatedness. The lack of verbal or mimetic feedback on performance makes experiencing competence difficult. In summary, we recognized the TSST as a prototype of a situation that reduces basic psychological need satisfaction (Ryan & Deci, 2017; Vansteenkiste et al., 2020).

Being an essential component of individuals' health and personal growth (Ryan, 1995), it is not surprising that impaired basic need satisfaction is associated with perceived stress and stress-related disorders (Campbell et al., 2018; Gerber et al., 2018; Li et al., 2013). Assessing the satisfaction of basic needs for autonomy, competence, and social relatedness, alongside previously measured more general psychological (e.g. state anxiety, perceived stress; Klaperski et al., 2013; Rimmele et al., 2007), and physiological stress indicators (e.g. cortisol response; Gu et al., 2022) enhances TSST research by offering potential avenues for more targeted interventions.

One such intervention, that we interpreted as targeted to one specific psychological need, is social support. Social support has already been shown to act as a stress buffer in other TSST-studies (Ditzen et al., 2007; Heinrichs et al., 2003), and is positively associated with the basic need for social relatedness (Shin & Park, 2022). We expected a specific buffer effect of the kind that experimentally-induced social support buffers the negative effects of the TSST settings on the basic need for social-relatedness satisfaction, but leaves the basic needs for autonomy and competence unaffected. In contrast, more general stress-buffers, that are based on unspecific (partly biological) mechanisms (e.g. physical activity, relaxation methods, breathing techniques) were expected to have general effects on a broader spectrum of stress indicators (e.g. perceived stress, anxiety, basic need satisfaction, cortisol response). Such a general stress-buffer is physical activity (Gerber & Pühse, 2009) that is assumed to strengthen the capacity to cope with stress (Forcier et al., 2006; Jonsdottir et al., 2010; Lindwall et al., 2014) and that has already been found to be related to reduced physiological and psychological stress responses in TSST settings (Mücke et al., 2018).

In summary, we first anticipated that the TSST would increase stress responses and diminish basic need satisfaction. We hypothesized that self-reported stress and basic need satisfaction would fluctuate across the phases of the TSST, with distress rising after the social stressor announcement and during stress exposure, followed by a return to baseline levels during the recovery phase. We expect salivary cortisol concentration to increase during stress exposure, a peak concentration in the recovery phase and a decline until the end of the TSST procedure (Gu et al., 2022). Second, we hypothesized that social support would buffer against the negative effects of TSST-induced stress on basic need for social relatedness, without affecting other stress indicators (competence, self-determination, self-reported stress, cortisol response). Physical activity was expected to function as a general stress buffer, influencing both self-reported stress, basic needs satisfaction, and cortisol response.

Methods

Participants and procedure

Participants (107 women, 88 men, 0 diverse, mean age = 23.25 years, *SD* = 4.50) were recruited using online platforms and social media from the University of the first author. The study involved a screening web-survey (LimeSurvey GmbH) and a lab session (TSST-G), detailed in Figure 1. The web-survey included study information, consent, eligibility assessment (≥18 years, proficient in German, mentally and physically healthy, nonsmokers, not on medications or drugs, no psychology students beyond the 4th semester, and not having participated in prior TSST studies), demographics, and the physical activity measure. Furthermore, the web-survey collected information on the use of hormonal birth control ($n = 103$ women: not using birth control pills, $n = 4$: no information provided) and the phase of the menstrual cycle (menstrual phase: $n = 22$ women, follicular phase: $n = 26$, around ovulation phase: $n = 6$, luteal phase: $n = 41$, $n = 12$ did not report their cycling phase). Participants were instructed to abstain from caffeine, alcohol, and exercise 24 hours before, from eating or brushing teeth 2 hours before, consuming soft drinks 1 hour before, or using lipstick and chewing gum during the session. Lab sessions, all starting at 5:00 p.m. (similar time frame to von Dawans et al., 2011, for a summary of TSST delivery times see Allen et al., 2017) included the TSST as a group test (von Dawans et al., 2011). We chose the TSST-G, which is a more economical stress test procedure compared to the individual TSST setting, while remaining comparable in its effectiveness in inducing stress responses (Childs et al., 2006; von Dawans et al., 2011). Due to COVID-19 restrictions, researchers and participants wore masks.

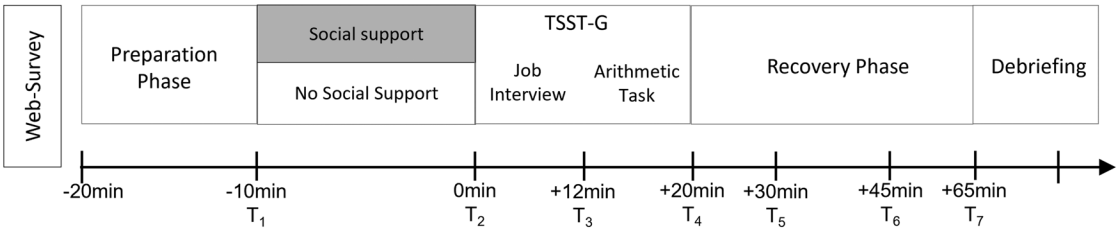

Figure 1. Study procedure and points of data collection.
Note. Figure 1 shows the data collection process and the measurement time points (T1–T7) at which psychological stress, basic need satisfaction, and cortisol levels were measured. The gray box highlights the participant group that received social support.

Participants were randomly assigned to a social support or no social support condition. The data collection for the research question underlying this paper was embedded within a larger study with a different research focus (Schüler et al., 2025; Cortisol data has already been published here), so more data (e.g. HR, further questionnaires) were collected than those reported here (see detailed study protocol on OSF, https://osf.io/xpwf3/). Figure 1 depicts the study flow.

During the *preparation phase,* participants completed a web survey (assessed variables not relevant for the present research question), and provided demographic data. A saliva sample and baseline questionnaires (self-reported stress, basic need satisfaction) were collected 10 min before stress induction (T1; −10 min). According to the standard TSST-protocol (von Dawans et al., 2011), participants received instructions for a three-minute job interview, followed by a questionnaire. They were then led to separate rooms for stress induction, with participants in the social support condition accompanied by a confederate. The confederate provided social support (see https://osf.io/xpwf3/ for standardized support protocol) before participants provided a saliva sample and completed a questionnaire (T2; 0 min). During the *stress induction phase*, participants faced a panel for a three-minute job interview, provided a further saliva sample and completed a questionnaire afterward (T3; +12 min). Participants engaged in an arithmetic task and again provided another saliva sample and completed a questionnaire (T4; +20 min). Additional saliva samples and self-report data were collected during the recovery phase (T5–T7; +30 min, +45 min, +65 min). In sum, self-reported stress, basic need satisfaction, and saliva samples were collected at 7 time points (T1–T7). Participants received €20 compensation post-debriefing.

The study complies with the ethical principles set forth in the 2013 Declaration of Helsinki by the World Medical Association. Approval for the study was obtained from the Institutional Review Board of the first author's university.

Measures

We calculated a self-reported stress score from three items ("How strong do you think your fear is at the moment?", "How tense do you feel right now?", "How stressed do you feel?"), which were rated by participants using a 5-point rating scale (1: not at all – 5: very much). Due to satisfactory internal reliability (T1–T7 between .627 and .883), these were aggregated to a mean value for each of the seven measurement points. Basic need satisfaction was assessed by asking, "How do you feel right now?" with one item each for the basic need for autonomy ("self-determined"), competence ("competent"), and social relatedness ("socially-related"). Participants rated the items using a 7-point Likert scale (1: not at all – 7: very much). Physical activity was assessed using the leisure time physical activity and the sports activity scale of the German Physical Activity, Exercise, and Sport Questionnaire (Bewegungs- und Sportaktivitäts-Fragebogen, BSA; Fuchs et al., 2015). Physical activity in leisure time was assessed by summing up the multiplied frequency and duration (in minutes) of 7 physical activities (e.g. cycling, gardening) and then dividing by four to calculate the minutes per week. Sports activity was measured by asking participants to list their sports activities (up to a maximum of 3). Frequency (in the last 4 weeks) and duration (in minutes) were multiplied, the products were summed across the different sports, and the result divided by 4 to obtain a metric for sports activity in minutes per week. We calculated an overall Physical Activity score by summing leisure-time physical activity and sports (Fuchs et al., 2015, p. 63), as the hypotheses did not differentiate between different forms of physical activity.

Cortisol was measured in saliva collected through a straw into Salicaps (IBL International) at seven time points, ranging from the announcement of the social stressor to the recovery phase (see Figure 1; procedure based on Hellhammer & Schubert, 2012). The saliva samples were frozen, stored at −20 °C, and analyzed at the Stress Biomarkers Laboratory of the Institute of Medical Psychology, Heidelberg University Hospital. Cortisol levels (ng/mL) were determined using the Cortisol Free in Saliva ELISA assay from Demeditec.

Analyses and results

We utilized RStudio (2023.06.1 + 524,R Core Team, 2023) for conducting descriptive statistics (R package "psych"; Revelle, 2017), used the "mice" package in R (van Buuren & Groothuis-Oudshoorn, 2011) for multiple imputation of missing data and the "tidyverse" package (Wickham et al., 2019) for data manipulation. To examine the effects of the stress induction (TSST) on psychological stress, basic psychological need satisfaction (self-determination, competence, social relatedness), and cortisol, these variables were treated as dependent variables in separate linear mixed-effects models (LMMs). Time, physical activity, and social support (and their interactions with time) were considered fixed effects (independent variables), while a random intercept for participants was included to account for within-subject variability. Models were fitted using the "lme4" package (Bates et al., 2015). Two separate models were tested: one assessing the interaction between social support and time (seven time points as illustrated in Figure 1), and another assessing the interaction between physical activity and time. In both models, a random intercept for participants was included to account for within-subject effects. Statistical significance of fixed effects was determined using the "lmerTest "package (Kuznetsova et al., 2017). To explore significant time effects, pairwise comparisons were conducted using estimated marginal means with Bonferroni adjustment for multiple comparisons ("emmeans "package; Lenth et al., 2025). Significant main and interaction effects were visualized using the "ggplot2" package (Wickham, 2016). In cases of significant Physical Activity × Time point interactions in LMMs, for the figures mean values for each time point were plotted separately for individuals with high versus low physical activity using a median split. Because sex differences were reported in detail in a publication with a different research focus based on the same dataset (Schüler et al., 2025), we refrain from providing an in-depth presentation of sex differences here. In supplemental analyses reported in the results section, we used linear mixed-effects models (LMMs) to examine whether men

and women differed in the trajectories of the dependent variables (basic needs, self-reported stress, and cortisol).

Descriptive statistics

A total of 136 individuals reported engaging in leisure time physical activity ($M = 378.92$ minutes per week, $SD = 371.97$), and 97 participants were involved in at least one additional sport ($M = 276.37$ minutes per week, $SD = 243.49$), resulting in a mean overall physical activity score of $M = 576.04$ minutes per week ($SD = 48.62$). In the self-report measures during the laboratory phase, stress had three missing values at T1, T3, and T7, self-determination had four missing values at T1 and two at T3 and T7, and competence and social-relatedness had 2 missing values (T1, T7). These missing values resulted from data-collection mistakes and were imputed using multiple imputation. Self-reported stress scores at the 7-time points range from $M = 1.36$ (SD = .49) at T7 to $M = 2.67$ (SD = .95) at T2. During the TSST, the average experience of felt self-determination ranges from $M = 4.36$ ($SD = 1.61$, T3) to $M = 5.11$ ($SD = 1.36$, T1), competence from $M = 4.26$ ($SD = 1.59$, T3) to $M = 4.71$ ($SD = 1.23$, T1), and social-relatedness from $M = 3.98$ ($SD = 1.65$, T6) to $M = 4.68$($SD = 1.43$, T1). Cortisol scores ranged from $M = 4.50$ ($SD = 3.19$) at T2 and $M = 8.84$ ($SD = 6.39$). Missing data (T1: 2 missings; T2: 3 missings; T3: 2 missings; T4: 4 missings; T5: 7 missings; T6: 3 missings; T7: 2 missings), due to data collection errors and contaminated saliva samples, were replaced using multiple imputation. Means and standard deviations for the imputed data—reported for the overall sample and stratified by physical activity level (high vs. low), social support (provided or not), and sex (men vs. women)—are provided in a table available on the Open Science Framework (OSF).

Linear Mixed-Effects Models examining self-reported stress

The LMM analyzing the effect of Social Support, Time, and their interaction on self-reported stress, while accounting for individual differences estimated that the fixed effect Social Support was not significant, estimate = −0.085, CI [−0.29, 0.12], $p < .001$), $p = .420$, indicating that social support did not have a direct effect on psychological stress. The interaction between Social Support and Time was not significant for any time point (all $p > .23$), suggesting that the trajectory of psychological stress over time did not differ based on Social Support conditions. Regarding the fixed effect Time, estimated marginal means (EMMs) revealed significant variations in psychological stress levels across time points. Pairwise contrasts revealed that psychological stress at T2 (immediately before stress exposure) was significantly higher than at all other time points ($p < .001$). Stress at T3 (during stress exposure, beginning of arithmetic task) was also significantly higher than at later time points. Self-reported stress continued to decrease significantly between subsequent time points, with T5, T6, and T7 showing significantly lower levels than earlier measurements ($p < .001$). The only non-significant differences were between T5 and T6 ($p = .062$) and between T6 and T7 ($p = 1.00$), suggesting that stress levels have resumed to baseline in the later stages (exact estimates, p-values, and confidence intervals for the post-hoc test for all time points are listed in OSF). In sum, psychological stress initially increased, peaking at T2, followed by a gradual decline and stabilization at the later time points. The trajectory of psychological stress across the time points is illustrated in Figure 2(A) (black line).

The LMM examining the fixed effects of Physical Activity, Time, and their interaction on self-reported stress, showed that the main effect of Physical Activity was not significant (estimate = −.00015, $p = .204$, CI [−0.01, 7.93]). However, a significant interaction effect was observed at Time Point 3 which is the beginning of the arithmetic task (estimate = −0.00041, $p = .035$, CI [−0.001, −1.88]), indicating that individuals with lower physical activity levels showed a greater increase in stress compared to those with higher activity levels. Thus, while physical activity does not have an overall effect on psychological stress, its buffering influence becomes more pronounced during the acute stress exposure. Figure 2(A) shows the trajectories of psychological stress across time, separated for people with low (red line) and high (blue line) physical activity levels.

Linear Mixed-Effects Models examining self-determination

The LMM examining the effect of Social Support, Time, and their interaction on felt self-determination revealed neither a significant main effect of Social Support (estimate = .034, $p = .876$, CI[−0.39, 463]), nor for the interaction between Social Support and time points (all $p > .1$). Analyses of the main effect of Time showed a significant decline in feeling self-determined from baseline (T1) to all subsequent time points (T2–T7, all $p < .0001$). The largest difference was observed between T1 and T3 (estimate = .74, $p < .0001$, CI [0.47, 1.01]). However, no significant differences were found between adjacent time points from T2 onward (all $p > .1$), except for a decline between T3 and T7 (estimate = −.29, $p = .0228$, CI [−0.56, −0.02]). Overall, self-determination significantly decreased after T1 and remained relatively stable at later time points, with only minor fluctuations. Figure 3 summarizes the unmoderated felt self-determination trajectory across the seven time points. The LMM examining the effect of Physical Activity, Time, and their interaction on felt self-determination revealed neither main effect of Physical Activity (estimate = −.0002, $p = .224$, CI [−1.76e-04, 7.58e-04]) nor a significant interaction between Physical Activity and Time (all <.05).

Linear Mixed-Effects Models examining competence

The LMM testing the effect of Social Support, Time, and their interaction on the experience of competence did not reveal a significant interaction effect (all p-values >.16). The main effect of Social Support was also not significant (estimate = −9.154e-03, $p = .965$, CI [−0.42, 0.40]). The estimated marginal means analysis for competence across the time points revealed a significant decline in competence from T1 to T3 ($p < .001$) and T1 to T4 ($p < 0.001$), indicating a decrease

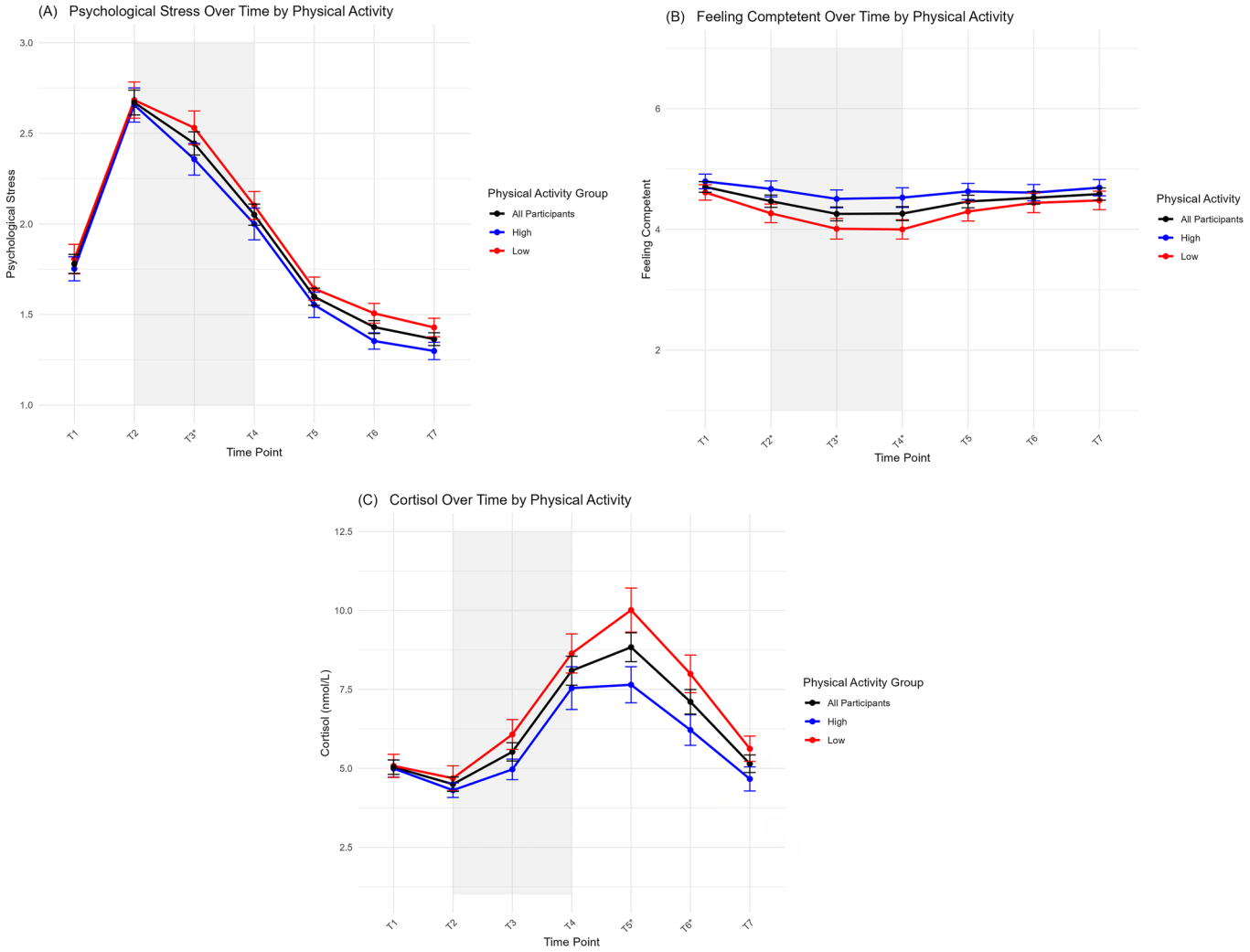

Figure 2. Illustration of significant effects of Physical Activity on trajectories of psychological stress (A), experience of competence (B), and level of cortisol (C).
Note. Figure 2 displays the trajectories of psychological stress (A), experience of competence (B), and level of cortisol (C) across the seven time points of measurement for the overall sample (black line), and separated for participants with low levels of physical activity (PA) (red line, scores below the median of PA) and high levels of PA (blue line, scores above the median of PA). The grey area represents the stress exposure period (presentation and arithmetic task). The error bars indicate standard errors. The "*" marks the time points at which the interaction between time and PA is statistically significant.

in competence over time. However, no significant differences were observed between T1 and later time points (T5–T7). Additionally, significant differences were observed between T3 and later time points, with competence increasing from T3 to T6 (p = .028) and from T3 to T7 (p = .0015), as well as from T4 to T6 (p = .033) and from T4 to T7 (p = .0029). The trajectory of competence across time is displayed in Figure 2(B) (black line).

The LMM evaluating the interaction effect of Physical Activity, Time, and their interaction on the experience of competence showed no significant main effect of Physical Activity (estimate= 9.18e-05, p = .685, CI [−3.52, 0.01]). However, the interaction effect Physical Activity x Time was statistically significant at T2 (estimate = 3.58e-04, p = .046, CI [−5.94, −0.17]), T3 (estimate = 6.67e-04, p < .001, CI [−9.28e-01, −0.50]), and T4 (estimate = 6.59e-04, p < .001, CI [−9.20e-01, −0.49]). Trajectories of the experience of competence for participants with low and high physical activity are shown in Figure 2B.

Linear Mixed-Effects Models examining social-relatedness

The LLM including the effects of Social Support, Time, and their interaction did not reveal a significant main effect of Social Support (estimate = .267, p = .228, CI [−0.17, 0.70]). A significant Social Support×Time effect immediately before stress exposure at T2 (estimate = .465, p = .002, CI [0.17, 0.76]) indicates that participants in the social support group felt more socially-related (Figure 4).

Estimated marginal means using the overall sample described the fixed factor Time. A gradual decline in social relatedness from T1 to later time points were observed. Bonferroni-adjusted pairwise comparisons further showed that the difference between T2 and later time points (T3-T7) was also significant (p<0.01). No significant differences were observed between T3, T4, T5, T6, and T7 (p>0.10), suggesting that the decline plateaued after T3. In the second LMM, social-relatedness was neither predicted by Physical Activity

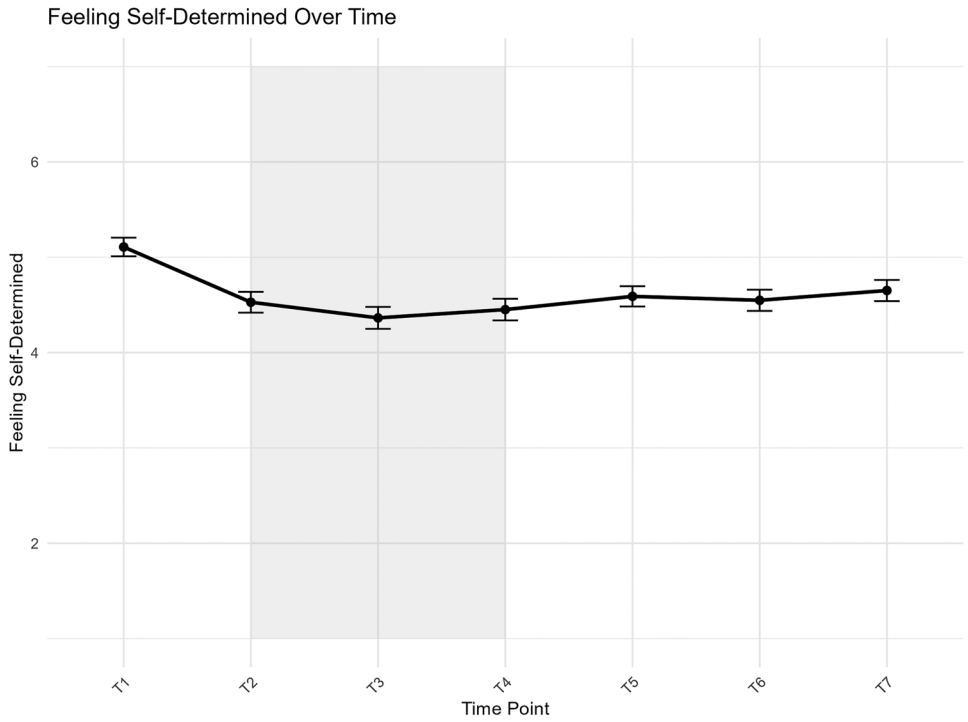

Figure 3. Illustration of the trajectory of felt self-determination across the 7 points of measurement.
Note. Because neither social support nor physical activity influenced the trajectory of self-determination across the seven measurement points, only the solid black line representing the overall sample is displayed. The grey area represents the stress exposure period (presentation and arithmetic task). The error bars indicate standard errors.

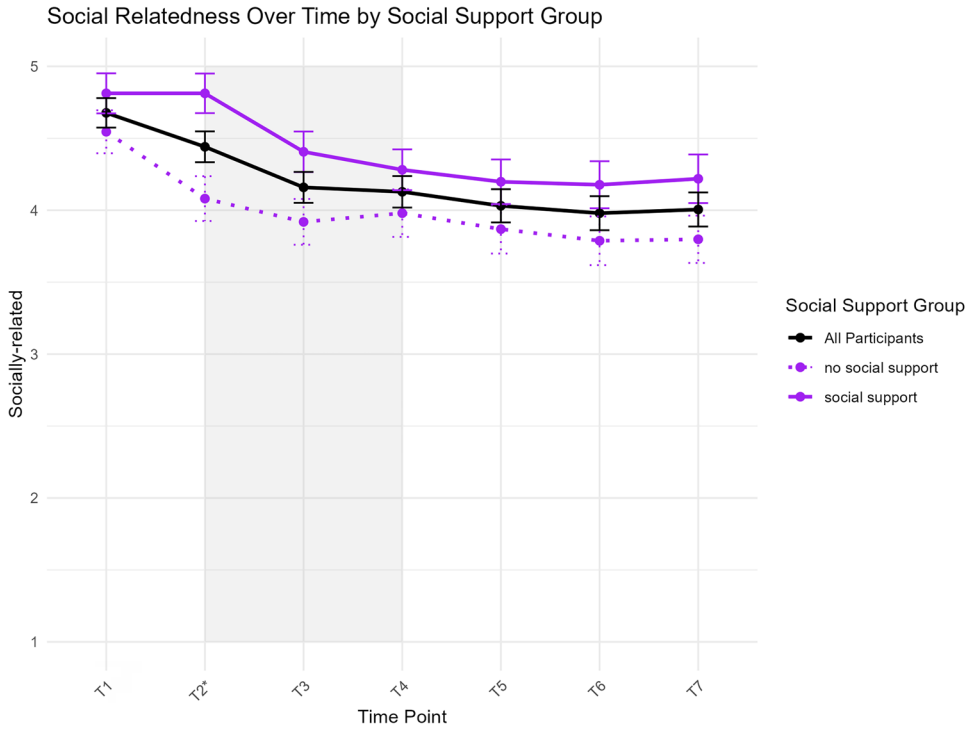

Figure 4. Illustration of effect of social support on the trajectory of social-relatedness.
Note. Figure 4 shows the trajectory of participants' feelings of social-relatedness across the seven measurement points for the overall sample (black line), and separated for participants in the social support group (solid purple line), and in the control group without social support (dotted purple line). The grey area represents the stress exposure period (presentation and arithmetic task). The error bars indicate standard errors. The "*" at T2 indicates a significant Social Support x Time interaction.

(estimate = 2.838e-04, p =.243, CI [−1.91e-04, 0.001]), nor by the interaction of Physical Activity and any of the time points (all p >.05).

Linear Mixed-Effects Models examining cortisol response

An LMM was conducted to assess the effects of Social Support and Time on cortisol levels. Neither the main effect of Social

Support (estimate = −0.324, p = .641, CI [−1.68, 1.03]), nor the interaction between Social Support and Time was significant ($p > 0.1$ for all interaction terms). The estimated marginal means analysis showed a clear pattern of fluctuation: A sharp increase in cortisol was observed from time point 3 to time point 4, followed by a peak at time point 5. Cortisol levels then declined at time 6 and returned near baseline at time 7 (Figure 2(C), black line). Pairwise comparisons showed several significant differences between time points (e.g. T1 vs. T4, T5, T6; T2 vs. T4, T5, T6; T3 vs. T4, T5, T6; T5 vs. T1, T2, T3, T7; T5 vs. T6; T5 vs. T7, all $p < .0001$). The trajectory of cortisol response for the overall sample is displayed in Figure 2(D) (black line).

The LLM conducted to examine the effects of Physical Activity and Time on cortisol levels, including their interaction, showed no significant main effect of Physical Activity (estimate = −0.00050, p = .504, CI [−0.002, 0.001]). However, a significant Physical Activity × Time interaction was found, specifically at T5 (estimate = −0.0027, $p < .001$, CI [−0.004, −0.001]) and T6 (estimate = −0.0019, p = .004, CI [−0.003, 0.0006]). At these time points, higher physical activity levels were associated with lower cortisol levels, suggesting a potential stress-buffering effect of physical activity on peak cortisol responses during acute stress exposure. No significant interactions were found at T2, T3, T4, or T7 (all $p > .1$). Trajectories of cortisol levels for high physical activity (blue line) and low physical activity (red line) are illustrated in Figure 2C.

Supplemental analyses: sex differences in the dependent variables

Additional LMMs tested whether men and women differed in the dependent variables (basic needs, self-reported stress, and cortisol) across the seven points of measurement. Regarding self-reported stress, no main effect of participants' sex was found (estimate: −0.0399, p = .708, CI[−0.2486, 0.16873]). However, a significant Sex x Time interaction occurred at T3 (estimate: −0.2385, p = .034, CI[−0.459, −0.0182]). At the beginning of the arithmetic task (T3), men (M = 2.29, SD = 0.848) felt less stressed than women (M = 2.57, SD = 0.918), t (190.35) = 2.1973, p = .029. The LMM predicting felt self-determination again revealed no main effect of participants sex (estimate: −0.1341, p = .5421, CI[−0.5649, 0.2967]), but significant Sex × Time effects at T5 (estimate: 0.364, p = .0394, CI [0.0180, 0.7101]), at T6 (estimate: 0.377, p = 033, CI [0.0306, 0.7228]), and at T7 (estimate: 0.376, p = .033, CI [0.0301, 0.7222]). They indicate that men felt more self-determined than women (T5: men: M = 4.72, SD = 1.48; women: M = 4.49, SD = 1.49; T6: men: M = 4.68, SD = 1.53; women: M = 4.44, SD = 1.58; T7: men: M = 4.78, SD = 1.57; women: M = 4.54, SD = 1.53). When predicting felt competence, again, no main effect of sex occurred (estimate: 0.2521, p = .229, CI [-0.15767, 0.6619]. However, the interaction of Sex x Time at T4 was significant (estimate: 0.3274, p = .048, CI [0.0026, 0.6522]) indicating that men (M = 4.58, SD = 1.58) felt more competent than women (M = 4, SD = 1.60). Feeling socially related was neither predicted by sex (estimate: −0.1567, p = .485, CI[−0.5965, 0.2830]) nor any of the Sex × Time interactions (all $p > .20$). The LMM predicting cortisol showed no main effect of sex (estimate: 0.3517, p = .607, CI[×0.987, 1.6905]). Significant Sex × Time interaction effects occurred at T3 (estimate: 1.4224, p = .015, CI[0.2729, 2.5720], T4 (estimate: 1.4387, p = .01431, CI[0.2892, 2.5883]), T5 (estimate: 2.6946, p = 4.82e-06, CI[1.5450, 3.8441]), and T6 (estimate: 2.0520, p = .0005, CI[0.9024, 3.2015]). At these points of time men had higher cortisol levels than women (T3: men: M = 6.50, SD = 4.88, women: M = 4.72, SD = 2.98; T4: men: M = 9.08, SD = 6.45, women: M = 7.29, SD = 6.28; T5: men: M = 10.5, SD = 7.16, women: M = 7.46, SD = 5.33; T6: men: M = 8.43, SD = 6.20, women: M = 6.02, SD = 4.44).

Discussion

Previous research using the TSST paradigm (Kirschbaum et al., 1993) has primarily focused on general self-reported stress indicators (e.g. perceived stress, anxiety; see Klaperski et al., 2013; Rimmele et al., 2007). The present study additionally assessed responses specifically aligned with the TSST stressor components. Interpreting stress from a needs-perspective, we argued that the rigid, predetermined nature of the TSST setting makes the experience of autonomy (in our study termed *self-determination*, because it corresponds directly to the German item used to assess autonomy) impossible, while uncontrollability hinders the experience of competence, and the social interactions during the TSST signal social rejection. Thus, the TSST setting was expected to frustrate basic psychological needs (Deci & Ryan, 1985). Our analyses confirmed this, although the trajectories of self-reported stress and frustration of needs over time differed slightly. Self-reported stress increased sharply after the announcement of the stressor, began to decrease during the stress exposure, and returned to baseline levels by the end of the study. This pattern indicates a strong anticipatory self-reported stress response, which is not nearly as pronounced during the actual stress exposure. This highlights the importance—similar to endocrine stress parameters—of measuring anticipatory and exposure phases separately and considering them in analyses either as control variables or as distinct aspects of the research question (Engert et al., 2013; Helminen & Scheer, 2023). In contrast to self-reported stress, on a descriptive level the satisfaction of all three basic needs decreased after the stress announcement and remained low throughout the stress exposure. Competence satisfaction and self-determination returned to baseline levels by T7, indicating full recovery, while social relatedness remained significantly impaired until the end of the study (T7). This underlines how important it is to create a socially supportive and friendly atmosphere, when participants are debriefed at the end of the TSST. The trajectory of cortisol levels across the time points during the TSST procedure was as expected and consistent with previous findings (Gu et al., 2022), confirming the effectiveness of our stress induction. LMMs tested the assumed general and specific stress buffer effects of social support and physical activity. In accordance with our hypotheses, the provision of *social support* counteracted the frustration of social-relatedness caused by the TSST-setting, but leaves feelings of competence, self-determination, perceived

stress and cortisol level unaffected. Future studies could examine whether impairments in the experience of autonomy and competence can also be attenuated through interventions that are specifically aligned to the TSST stressor components. Examples include *providing choices* about the order of tasks (i.e. order of job interview and arithmetic task; Wulf et al., 2014), or *providing positive feedback* (e.g. nodding of the panel members) to increase felt competence.

The Physical Activity x Time interactions showed that physical activity predicted changes in self-reported stress, the experience of competence, and the cortisol level. This confirms earlier correlational studies showing positive relationships between physical activity and well-being (Wiese et al., 2018) and demonstrating the buffering role of physical activity against impairments to well-being during stressful life phases (e.g. Takiguchi et al., 2023) and its buffering effect on cortisol release in the experimental TSST setting (Rimmele et al., 2007). Interestingly, for the central basic need for autonomy (self-determination) the mitigating effect of physical activity does not apply. Furthermore, whereas feeling socially-related was influenced by social support as mentioned above, it was unrelated to physical activity.

The supplemental analyses examining potential sex differences in basic psychological need satisfaction, self-reported stress, and cortisol responses during the various phases of the Trier Social Stress Test (TSST) yielded noteworthy findings. While men and women did not differ in their subjective stress experience immediately following the announcement of the upcoming speech task (T2), sex differences emerged when participants were unexpectedly instructed to solve the arithmetic task. Men perceived significantly lower levels of stress compared to women (T3). Moreover, following this stress exposure (T4), men indicated higher feelings of competence than women. Future research could explore the underlying mechanisms of these differences by investigating the specific referents of participants' stress and competence experiences. For instance, it remains to be determined whether women's heightened stress and lower competence perceptions stem from a greater fear of failure in arithmetic-based tasks (Geary et al., 2019; Rossi et al., 2022) or whether alternative processes are at play that lead women to experience greater basic need for competence frustration during certain TSST phases. Additionally, in the post-stress phases (T5, T6, T7), women reported feeling less self-determined than men. Because sex differences are not consistent with the universality assumption of Self-Determination Theory (SDT), which posits that all individuals should respond similarly to the frustration of basic psychological needs (Ryan, 1995; Ryan & Deci, 2000; Vansteenkiste et al., 2020), future studies may address this open question and further investigate the potential moderating role of sex in basic need-based responses to social-evaluative stress. In accordance with previous TSST studies (Kudielka & Kirschbaum, 2005), men had higher cortisol levels than women (T3, T4, T5, T6) (for a critical discussion, see Liu et al., 2017).

A limitation of the present study was that, due to the COVID-19 pandemic, both participants and the experimenter wore face masks, deviating from the standard TSST-G protocol (von Dawans et al., 2011). These face coverings may have limited the ability to read or accurately interpret emotional cues from the panel members or experimenter (Carbon & Serrano, 2021; Parada-Fernández et al., 2022). However, our data support that our stress induction was still effective, which is in line with research from Helminen and Scheer (2023), who found that COVID-19 adaptations, such as social distancing and face masks, still elicited physiological stress responses comparable to standard TSST protocols. Whether this also applies to the experience of need satisfaction has however, to the authors' knowledge, not yet been investigated. Interpreting the stress response from a basic needs-perspective can integrate different lines of research and thereby contribute to a better understanding of the TSST's effects on psychological parameters. Focusing on the influence of social support and physical activity, can help identify individual constellations of needs and stress buffers, and based on this, develop interventions that specifically target need fulfillment during times of stress.

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