THESIS

EVALUATION OF PHYSIOLOGICAL AND PSYCHOLOGICAL STRESS RESPONSES ON ACTIVITY-PERMISSIVE WORKSTATIONS: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

EVALUATION OF PHYSIOLOGICAL AND PSYCHOLOGICAL STRESS RESPONSES ON ACTIVITY-PERMISSIVE WORKSTATIONS: A RANDOMIZED CONTROLLED TRIAL

Background: Activity-permissive workstations (APWs), such as treadmill and standing desks, offer a potential strategy to reduce sedentary behavior and improve well-being. However, it remains unclear whether light-intensity activity during cognitively demanding or stressful tasks alters physiological or psychological stress responses.

Methods: In this preregistered 2 (TSST vs. non-TSST) × 3 (sitting, standing, walking) laboratory-based experimental study, 157 adults ($M_{age} = 29.8 \pm 11.1$ years) completed the Trier Social Stress Test (TSST) or a control task while seated, standing, or walking on a treadmill desk for approximately 85 minutes. Psychological (perceived stress, affect), physiological (heart rate, heart rate variability, blood pressure, cortisol), and behavioral (speech, math) responses were assessed across baseline, reactivity, and recovery phases. Linear mixed-effects models with spline-coded time captured reactivity (T2–T3; cortisol T3–T4) and recovery (T3–T5; cortisol T4–T5) slopes, adjusting for baseline, age, gender, BMI, session time, sleep, caffeine, and medication use.

Results: The TSST elicited robust psychological and physiological stress responses across all conditions (*p*s < .001). Contrary to our hypotheses, workstation type did not significantly affect reactivity or recovery for stress, affect, blood pressure, heart rate, or cortisol. Walking participants reported higher overall positive affect ($p = .013$), and post-session ratings indicated that walking was more enjoyable than sitting ($p = .02$) and more comfortable than standing (*p*

= .002). HRV was lower and flatter in active conditions, consistent with posture-related vagal withdrawal rather than stress modulation. Task performance did not differ across workstations.

Conclusions: Light-intensity movement during an acute stressor did not attenuate stress responses but also did not amplify them, while preserving task performance and improving comfort and enjoyment. These findings suggest that low-intensity movement can be incorporated into cognitively demanding contexts without amplifying stress and may enhance long-term feasibility and adherence to active workstation use.

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INTRODUCTION

Rapid technological advancements leading to increased computer work and sedentary leisure activities (e.g., watching TV, playing games) have heightened concerns regarding the extensive time office workers spend in sedentary behaviors throughout the day (Li et al., 2022; Park et al., 2020; Thorp et al., 2012). Sedentary behaviors, defined as sitting or reclining posture with an energy expenditure of ≤1.5 metabolic equivalents, are particularly prevalent during the majority of working hours of office workers, often in bouts longer than 30 minutes (Parry & Straker, 2013; Prince et al., 2014; Thorp et al., 2012). Sedentary behavior increases the risk of cardiovascular diseases, type 2 diabetes and obesity, especially when the static sitting periods are prolonged and uninterrupted (Neuhaus et al., 2014; Wilmot et al., 2012). Notably, this effect persists even when daily physical activity levels are accounted for (Hamilton et al., 2008; Leiva et al., 2017). Furthermore, research has linked sedentary behaviors to increased symptoms of depression, anxiety, and stress (Rebar et al., 2014). These adverse impacts significantly deteriorate individuals' overall quality of life, affecting both physical and mental health.

Interventions aimed at combating sedentary lifestyles generally take three forms: reducing sitting directly, increasing physical activity, combining both approaches. Specifically, strategies directly targeting reductions in sedentary behaviors have been more effective compared to interventions focused solely on increasing physical activity or interventions targeting both approaches (Prince et al., 2014). Sedentary behavior is conceptually different from physical inactivity, which refers to not engaging in sufficient amount of physical activity (i.e., not meeting guidelines). Active individuals can still spend long periods of time being sedentary, so it is reasonable to see that interventions solely focusing on physical activity had the most modest effect among the three types of interventions. However, the independent health benefits associated with both reducing sedentary time and enhancing physical activity underscore a need for interventions that address both behaviors simultaneously (Panahi & Tremblay, 2018). Such holistic approaches are essential for promoting overall health and well-being, given the complexity of lifestyle behaviors and the interplay between sedentary time and physical activity in influencing health outcomes.

Buman et al. (2014) analyzed data from the 2005–2006 US National Health and Nutrition Examination Survey (NHANES) and found that reallocating 30 minutes per day of sedentary time to physical activity correlates with improvements in cardiovascular disease risk biomarkers. Specifically, replacing sedentary time with light-intensity physical activity (LPA) resulted in significant health benefits: a 1.9% reduction in triglycerides, a 2.4% decrease in insulin levels, and a 2.2% improvement in the homeostasis model assessment of β-cell function. Although reallocating time to moderate-to-vigorous intensity physical activity (MVPA) yields greater per-minute improvements in biomarkers (improvements ranging from 2% to 25% for a 30-minute reallocation to MVPA), substituting sedentary time with LPA for longer periods (e.g., 90 minutes) also leads to significant, clinically meaningful improvements in cardiovascular risk (6-12% improvement in biomarkers). More importantly, LPA can be more readily integrated into daily work routines as a replacement for sedentary time using activity-permissive workstations (APWs), for instance, making it a viable option especially for individuals unable to engage in MVPA.

APWs offer a variety of options, including standing desks, treadmill desks, cycling desks, pedaling exercisers underneath desks, and yoga ball seats, allowing for self-initiated movement with self-controlled intensity during desktop work. Previous interventions combining reducing sedentary behaviors and increasing physical activity were shown to be less effective in sedentary time reduction than interventions targeting reducing sedentary behaviors alone, likely due to the combined strategy typically involving additional and separate efforts for both changes (Adams et al., 2013; Barwais et al., 2013; Prince et al., 2014). However, APWs enable simultaneous engagement in LPA and work tasks, integrating both behaviors seamlessly without the need for separate effort. A systematic review and meta-analysis of the effects of APWs revealed a pooled effect size of a 77-minute reduction in sedentary time across 20 field-based trials and 18 laboratory studies. This analysis also found a notable reduction in waist circumference in 5 out of 6 studies measuring this outcome. The meta-analysis reported inconsistent or insignificant improvements in other physical health-related outcomes, likely due to the short duration of most studies and the heterogeneity of APW types; 17 studies focused on height-adjustable desks, 10 on standing desks, 12 on treadmill desks, 5 on various other types of APWs, such as pedal exercisers, cycle ergometers, and stepping devices, and 1 on both treadmill and cycle ergometers (Neuhaus et al., 2014). As 60% of the APW studies focused primarily on reducing sedentary time (i.e., encouraging standing) rather than on reallocating sedentary time to LPA, and 60% of the studies were short-term, lasting less than a month, minimal changes in physical health outcomes were anticipated. Despite these findings, walking at a modest pace of 1 mph on a treadmill desk can increase caloric expenditure by 100-150 calories per hour compared to sitting. Consequently, employees walking for just one hour daily during the workweek could burn an additional 500-750 calories each week (Thompson et al., 2008). Overall, the existing evidence suggests that APWs, particularly those that encourage LPA like treadmill desks, hold promise for reducing sedentary time and potentially improving physical health over the long term.

Beyond their potential benefits for physical health, APWs have also been shown to positively impact mental health. The aforementioned systematic review and meta-analysis found improvements in psychological well-being, including stress, mood, and anxiety, in 80% of the studies reviewed (Neuhaus et al., 2014). At the time of this review, psychological outcomes were not the primary focus in the majority of APW studies. Sliter & Yuan (2015) highlighted this gap and called for more research to systematically evaluate the psychological outcomes of APWs. In this between-subjects experiment (*N* = 180) by Sliter & Yuan (2015), the researchers found that participants using treadmill desks experienced higher arousal, lower boredom, and lower stress compared to either sitting or standing participants. In another within-subject experiment (*N* = 96), using a standing desk for 30 minutes increased alertness (Finch et al., 2017). In a university setting, a within-subject study found that undergraduate students (N = 88) reported better mood after they used standing desks in class compared to traditional sitting desks (Green et al., 2020). Similarly, a pilot study in France explored the acceptability of various active classroom workstations, such as standing desks, exercise balls, cycling desks, and pedal- or stepper-boards. This study found that both students and lecturers reported lower fatigue, distraction, and boredom; they also preferred cycling desks and exercise balls over the other options (Grosprêtre et al., 2021). Consequently, the current body of evidence suggests a promising potential for APWs to enhance psychological well-being.

Among the psychological benefits of APWs, the potential for stress reduction is particular noteworthy, given that in an increasing number of jobs, employees being immobile at their workstations, and work-related stress are negatively affecting mental health and even quality of life (Law et al., 2020; Testa & Simonson, 1996). Edelson & Danoffz (1989) measured stress using the 20-item Stress Arousal Checklist in a within-subject experiment (*N* = 5) and found that participants reported significantly lower stress after using a treadmill desk compared to sitting. Sliter & Yuan (2015) used the same scale and found similar results in a larger sample ($N = 180$), as mentioned in the previous paragraph. A large multicomponent intervention in England ($N = 756$) provided one-third of workers with a height-adjustable workstation and found small but significant improvements for stress measured by the Perceived Stress Scale in this intervention group after 12 months (Edwardson et al., 2023). There have been only two studies assessing stress-related physiological outcomes in relation to APWs. In a within-subject experiment ($N = 20$), participants had larger decrease in cortisol from morning to afternoon on days using treadmill desks and sit-stand desks, compared to sit-only days (Gilson et al., 2017). This indicates the potential effects of APWs on regulating stress within a day. Another recent study has assessed individuals' heart rate variability (HRV) during the use of a cycling desk while performing cognitively demanding tasks, also using a within-subject design ($N = 11$). They found both lower sympathetic and parasympathetic reactivities in the active condition compared to the sitting condition, indicating that using a cycling desk is potentially a coping mechanism for stress (Pilcher et al., 2022).

Despite the promising evidence for APWs' potential to alleviate stress, current studies have not fully captured the multifaceted nature of stress responses, which include both physiological and psychological dimensions. Much of the existing research has taken place in naturalistic settings that, while having high external validity and real-world applications, did not impose any controlled stressors. Given our current limited knowledge of the underlying mechanisms of how APWs help mitigate stress, this raises concerns about the replicability of methodologies. Based on the current knowledge about the relationship between physical activity and stress, I will detail four potential mechanisms that could explain the observed stress-reducing effects of APW use demonstrated in the literature.

Potential mechanism 1: Changes in mood

First, LPA induced by APW use improves mood, and consequently reduces stress. Physical activity not only reduces the risk of many physical illnesses, including cardiovascular disease, stroke, diabetes, hypertension, and cancer, but also improves mood and reduces stress (Chan et al., 2019; Fox, 1999; Kanning & Schlicht, 2010). Lifestyle physical activity interventions are effective in improving many common mental health problems (Farris & Abrantes, 2020). Most studies in this area used a longitudinal or cross-sectional approach, indicating that regular physical activity is associated with better mental health, but a systematic review indicated that a 10- to 30-minute exercise bout is actually sufficient to improve mood (Chan et al., 2019). However, this review also indicated that there was not a conclusive finding in regard to whether exercise intensity moderated the benefits of improving mood due to the heterogeneity of study designs.

LPA associated with APW use may modulate neurotransmitters and hormones that influence mood and stress responses. Physical activity has been shown to increase several neurotransmitters in the brain, including norepinephrine, endorphins, dopamine, and serotonin. Specifically, physical activity increases the circulating β-endorphin, the natural painkiller in our body, which also helps attenuate acute stress responses (Pilozzi et al., 2021). Although β-endorphin concentration depends upon exercise intensity and duration, a recent study found that a single session of 3-km low-intensity walking (3km/h, 1.86mph) effectively increased β-endorphin levels (Lu et al., 2019; Schwarz & Kindermann, 1992). This intensity and duration of walking are particularly suited for some APWs (e.g., a treadmill desk), potentially explaining alleviated stress responses during their use. A review by Greenwood (2019) indicates that exercise increases dopamine, which not only increases positive mood, but also helps overcome aversive feelings like stress. However, this review article did not mention whether the intensity of exercise moderates the effects of overcoming stress. Additionally, while physical activity is associated with increased serotonin and norepinephrine release, both of which play important roles in regulating mood and potentially buffering the negative effects induced by stress (Baixauli, 2017; Meeusen & De Meirleir, 1995; Ressler & Nemeroff, 1999), most studies linking exercise and these neurotransmitter levels focused on regular physical activity of at least moderate intensity or unspecified intensity (Greenwood, 2019; Marques et al., 2021; Young, 2007; Zouhal et al., 2013). The immediate short-term effects of LPA on these neurotransmitters remain underexplored.

While studies specifically examining the impact of LPA on mood are lacking, numerous investigations have demonstrated that walking, often conducted outdoors, enhances mood, although it is challenging to distinguish the restorative effects of the natural environment from those of LPA (Hartig et al., 1991; Robertson et al., 2012). Research involving APWs, such as treadmill and cycling desks, has consistently reported significant mood enhancements, particularly in arousal and alertness, suggesting the intrinsic affective benefits of LPA independent of environmental factors (Edelson & Danoffz, 1989; Grosprêtre et al., 2021; Sliter & Yuan, 2015). Thus, it is likely that APWs reduce stress by improving mood after engaging in LPA for some time.

Potential mechanism 2: Distraction

Second, APWs facilitate a form of distraction that allows for adaptive coping under stress. Distraction, a common coping mechanism, functions by redirecting attention away from stressors, thereby reducing their immediate impact. Shifting attention to wellness behaviors, such as taking a walk or seeking social support, typically represents an adaptive coping strategy. On the other hand, distraction becomes a maladaptive strategy when the person aims at simply avoiding the difficult thoughts and feelings through passive behaviors, such as watching TV (Woodward et al., 2020). In a study using the Trier Social Stress Test in a laboratory setting (N = 61), participants who used distraction coping had faster cortisol level recovery after the acute stress (Janson & Rohleder, 2017). Exercise is a common coping method under stress by inducing relaxation, reducing tension in the body and mind, and also providing an effective distraction (Cairney et al., 2014). Within the context of APWs, it is possible that participants using active workstations might be distracted more by the body movement or using the workstation itself under acute stress, thus having mitigated stress responses compared to being sedentary.

However, it is possible that this type of distraction increases stress level in the multitasking framework. Wetherell & Carter (2014) developed a laboratory multitasking stress paradigm, asking participants to attend and response to multiple stimuli, induced both psychological and physiological stress reactivity, and perceived workload. Current literature primarily focused on the mental switch between different tasks, and found worse work-related outcomes when individuals were multitasking (Appelbaum et al., 2008; Crews & Russ, 2020). In the literature of APWs, work performance (e.g., speech quality, task completion and error rate) and cognitive performance (e.g., reading comprehension, attention, processing speed) were not compromised at all when individuals were using active workstations like treadmill desks (Cox et al., 2011; John et al., 2009; Sliter & Yuan, 2015; Thompson & Levine, 2011). It is likely that the type of physical activity associated with an APW is not perceived as a mental distraction that would interfere with task performance, but it is unknow how much attention is allocated to the APW and whether it affects stress reactivity under acute stress.

Potential mechanism 3: Attribution of arousal

Third, physical arousal induced by APWs can influence emotional responses through misattribution. In the 1970s, Dutton & Aron (1974) did the famous Capilano Suspension Bridge study, demonstrating that men who crossed a dangerous, anxiety-provoking suspension bridge were more likely to misattribute their heightened physiological arousal as sexual attraction to female confederates, compared to men who crossed a normal, stable bridge. This is an example of the misattribution theory of arousal, rooted in the two-factor theory of emotion, suggesting that the source of physiological arousal can significantly influence emotional experience, as arousal caused by one stimulus can be easily attributed to another, changing the interpretation or the emotional impact (Schachter & Singer, 1962; Zillmann, 1976). Brooks (2014)'s research on reappraisal of anxiety as excitement before anticipated stressful tasks applied the two-factor theory of emotion. This study found that individuals who reappraised their anxious arousal as excitement experienced less anxiety, higher excitement, higher self-efficacy, lower heart rate (HR), and performed better in various tasks including singing, public speaking, and math test.

Given physical activity is known to provoke physiological changes similar to those induced by stress (e.g., increased HR, heavier breathing, adrenaline release), it is reasonable to hypothesize that if individuals on the APWs experience acute stress and are able to attribute the physiological arousal more to the body movement rather than to the stress, they might experience lowered stress. On the other hand, if they attribute their physiological arousal more to the stressor, they might experience amplified psychological stress even under a mild stressor. Although in past APWs studies measuring psychological stress consistently reported reduced stress, they did not induce any stressor during the study period (Edelson & Danoffz, 1989; Edwardson et al., 2023; Sliter & Yuan, 2015). Further research is needed to determine whether the perceived source of physiological arousal impacts the psychological stress experience under acute stress while using APWs.

Potential mechanism 4: Outlet for stress

Fourth, APWs may provide an outlet for energy induced by stress-related physiological responses. When individuals are under stress, the hypothalamic-pituitary-adrenal (HPA) axis is activated, and then we experience increased HR, increased blood pressure (BP), heavier breathing, and the release of glucose and fat into the bloodstream. From an evolutionary perspective, all these steps get us ready to enter the fight-or-flight state (Padgett & Glaser, 2003). However, if the energy caused by the fight-or-flight response cannot be utilized, for example, due to being sedentary at work, it may contribute to bodily wear and tear (i.e., allostatic load), escalating risks for physical and mental illness (McEwen, 1998). Using APWs facilitates physical activity that may provide an outlet or dissipate this stress-induced energy, then potentially reducing stress (Edelson & Danoffz, 1989; Sapolsky, 2004). Yet, this hypothetical theory lacks direct empirical testing in humans. Although previous studies have shown that following a single session of acute exercise, particularly moderate-intensity aerobic bouts, stress-induced HR and BP reactivity are lowered (Chen et al., 2022; Mariano et al., 2022), it is unclear whether the HPA axis activation under acute stress could be lowered *during* physical activity, especially LPA in the context of APWs.

Current Study

Given several gaps mentioned above, I aim to further our understanding of whether and how the use of APWs can help individuals reduce stress, and determine how APWs influence both physiological stress reactivity and psychologically perceived stress. Therefore, this current study employs the Trier Social Stress Test (TSST; Kirschbaum et al., 1993) a validated paradigm for eliciting stress responses in a controlled laboratory setting, to measure both subjective and objective indicators of stress while participants are using different types of APWs. Additionally, to better suit the TSST protocol to the context of APWs, we adapted the remote virtual version of the TSST (delivered through Zoom), which has been widely used during the COVID-19 pandemic and shown effectiveness in inducing stress (Helminen et al., 2019). Participants are randomly assigned to a traditional sitting desk, a standing desk, or a treadmill desk (walking), allowing us to investigate the effect of LPA on stress; then participants are further randomly assigned to a TSST condition (going through the TSST paradigm) and a non-TSST condition (watching a nature documentary on the assigned workstation), as little is known about individuals' stress-related physiological changes while using APWs without acute stress. Upon completion of the APW use, participants answer questions related to distraction (what elements they pay attention to while using the APW) and attribution (what factors lead to their physiological arousal during the TSST), aiming to understand the potential underlying mechanisms if APWs influence stress responses.

Hypotheses

Given the 2 (TSST vs non-TSST) ×3 (sit, stand, walk) study design, we predicted that there will be both main effects of each independent variable (stress condition and workstation type) and an interaction between the two independent variables. In a previous study, we found that individuals using treadmill desk reported significantly better mood than individuals using seated desk; additionally, the participants experienced higher enjoyment than individuals using both standing desk and a seated desk, while there was no statistically significant difference between sitting and standing participants (Yu & Graham, 2024). Thus, in this study, we hypothesized that among participants exposed to the stressor, those assigned to the walking workstation would exhibit lower physiological and psychological stress reactivity and faster recovery compared to those in the sitting or standing conditions.

Implications of findings

The findings from this study will contribute to both theory (e,g., to the theoretical framework of stress responding) and practice (e.g., by offering practical insights into the application of APWs). Despite extensive research on physical activity's impact on stress, most studies focused on MVPA, and the effects of light physical activities like walking, particularly under simultaneous stressors, remain less explored. Moreover, the influence of walking on stress reactivity when both stressors and physical activity occur simultaneously remains poorly understood. This study will provide valuable insights for researchers to understand the effects of LPA on stress responses in the context of concurrent stressors and physical activity, encompassing both physiological and psychological aspects, as well as potential underlying mechanisms. Furthermore, examining treadmill desks' impact on stress, alongside moderating factors such as age, gender, and regular physical activity habits, will enable tailored recommendations to mitigate sedentary behavior, enhancing well-being and quality of life.

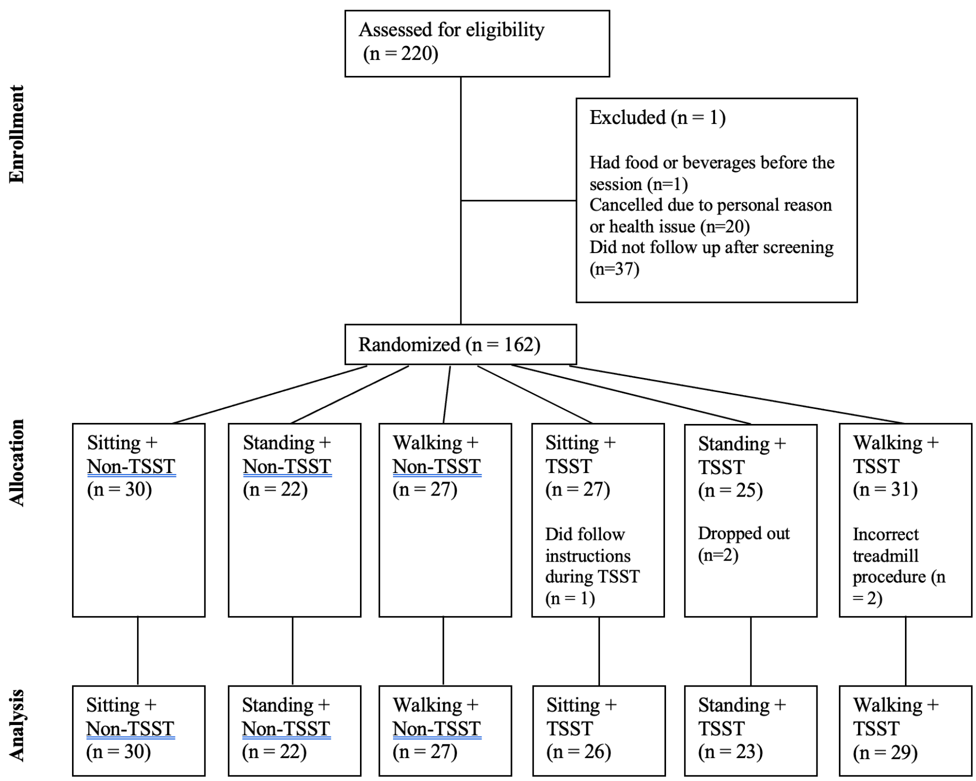
METHODS

Participants

A total of 157 adults participated in the study, with data collection occurring between February and December 2024 (Figure 1). Participants were primarily residents of Northern

Colorado and were recruited through email advertisements distributed via Colorado State University listservs. Eligibility criteria included being at least 18 years old, fluent in English, and able to engage in LPA for approximately 80 minutes. Individuals who were pregnant or unable to safely perform such activity were excluded. Participants received a $20 Amazon gift card as compensation. This study was approved by Colorado State University Institutional Review Board.

Figure 1. CONSORT diagram showing the flow of participants through each stage of a randomized trial.



Measures and Materials

Activity-Permissive Workstations

A height-adjustable desk was used across all conditions (sitting, standing, and walking) with participants able to adjust the desk to a comfortable height. In the sitting condition, participants used a regular plastic chair without wheels. For standing, they adjusted the desk to the height for standing on the floor. The walking condition incorporated a LifeSpan Workplace treadmill (Model DT-3) under the desk, with speeds ranging from 0.4 to 4.0 mph. Treadmill speed was continuously visible on the control panel. Participants were advised to choose a pace comfortable for about 80 minute, but they could adjust their speed at any point during the session. Speed changes were recorded by the research team, and an average walking speed for each participant was calculated across the full workstation period.

Physiological Stress Responses

We monitored HR and HRV continuously using a Polar Beat HR monitor, with data recorded on the Elite HRV app. We record HR data separately for each phase (T1-T5; see Figure 1 for details) and use the average HR, HRV RMSSD (calculated as the square root of the mean of the squared differences between consecutive time intervals between heartbeats), and HRV high frequency (HF) power (reflecting the activity of the parasympathetic nervous system) for each phase in the analysis. BP, including systolic BP (SBP) and diastolic BP (DBP), is measured every five minutes in each phase (13 measures in total) and averaged through each phase to eliminate noises, using an Omron Hem 907XL monitor. Because HR, HRV, and BP are all sensitive to posture and movement, values in the standing and walking conditions should be interpreted in the context of these physiological influences rather than as isolated indicators of stress reactivity. Saliva samples for cortisol levels are collected using Salivettes® (Sarstedt, Germany) at the end of each phase (T1-T5) and stored at -20°C until analysis. Participants placed the cotton roll in the cheek pouch for two minutes without chewing, allowing passive saliva absorption before returning the swab to the tube without using their hands.

Psychological stress responses and mood

Mood was measured using the 20-item Positive and Negative Affect Schedule (PANAS; Watson et al., 1988). PANAS is widely used in the TSST paradigm due to its sensitivity to change and quick assessment (Narvaez Linares et al., 2020). Participants were asked to rate the degree to which they feel ten positive emotions (e.g., excited, proud) and ten negative emotions (e.g., ashamed, irritable) at each time point on a 5-point scale (1 = not at all, 5 = extremely). Perceived stress level was measured using the Visual Analogue Scale (VAS) for stress, which was a single question asking participants to rate their perceived stress on a 1-to-100 scale. This allows for a rapid quantitative assessment to capture the psychological stress at different time points throughout the study (Lesage et al., 2012).

Sociodemographic and health information

Sociodemographic information includes participants' age, gender, race/ethnicity, education level, job, marital status, and household income. Health information includes participants' body mass index (BMI) and health behaviors affecting physiological functioning (e.g., caffeine, medication use over the past 24 hours, and hours slept the night before the session), aligning with previous research using the TSST as the stress paradigm (Rodriguez et al., 2023).

Task load

The NASA Task Load Index (NASA-TLX), developed by Hart & Staveland (1988), was administered after the use of workstations to assess perceived workload during task completion on the assigned workstation. NASA-TLX includes six subdomains of task load: mental, physical, temporal, effort, performance, and frustration level. Participants rate each of these domains on a 7-point scale (1 = low task load/good performance, 7 = high task load/poor performance).

Distraction and attention

Participants in the TSST condition rated their level of attention toward each element, including "the workstation you were using," "the evaluators' facial expressions," "the task itself," "your emotions," "your physiology (e.g., HR, breathing, sweating)," "the environment you were in," during the TSST on a 5-point scale (1 = did not pay attention to this at all, 5 = paid full attention to this).

Attribution of arousal

Participants in the TSST condition were first asked to answer whether they felt changes in their breathing and HR during the TSST task, and which direction was the change. If they answered yes, then they would respond to a four-item scale asking what factor they think influenced their breathing and HR. The items were "excitement," "nervousness," "the workstation", "other (please specify)." Participants rated each of these items on a 5-point scale (1 = no influence at all, 5 = very strong influence).

Speech performance

During the TSST, participants delivered a 5-minute impromptu speech that was audio recorded and later transcribed verbatim. Four indices of speech performance were extracted: (1) total word count, representing verbal output; (2) productive word ratio, defined as the proportion of meaningful, content-related words (excluding fillers, repetitions, false starts, and abandoned utterances) relative to total word count; (3) nonfluency ratio, calculated as the percentage of filler words (e.g., "um," "uh") in the total word count; and (4) speech content quality, rated independently by two trained coders using a standardized 10-item rubric assessing confidence, persuasiveness, clarity, and overall delivery. Each item was scored on a 7-point Likert scale (1 = strongly disagree to 7 = strongly agree), with one negatively keyed item ("the speaker was anxious") reverse-scored. The 10 items were averaged to yield an overall speech quality score.

Math performance

During the TSST, participants completed a serial subtraction task. Arithmetic accuracy was operationalized as the best sequence score, defined as the highest number of consecutive correct subtractions achieved within a single sequence.

Procedure

Participants were first randomly assigned to one of the three workstation conditions: sitting, standing, or walking. Subsequently, they were randomly assigned to either the TSST condition or non-TSST control condition. Upon arrival, participants signed a consent form, and wore a HR monitor.

Pre-workstation baseline

All participants sat quietly and read nature magazines for 10 minutes. Once the participants sat down quietly, the research assistant (RA) began tracking their HR and HRV. BP was measured at the 5-minute and 10-minute marks. At the end of this 10-minute period, the RA collected a saliva sample, and participants completed the VAS for stress and the PANAS on a laptop, marking the first time point (T1). Following this assessment, participants were directed to their assigned workstations, which included options of a traditional sitting desk, a standing desk, or a treadmill desk.

Adjusting to the workstation

To help participants adjust themselves to the assigned workstation, they were asked to complete the sociodemographic and health information survey on the workstation as their first task. The survey took approximately 9 minutes to complete, although completion time varied based on the participant's pace.

Pre-TSST baseline

Participants watched a nature documentary at the assigned workstation for 10 minutes. Similarly, the RA started tracking HR at the beginning of this phase. BP was measured at both 5-minute and 10-minute marks. Upon completion of this 10-minute phase, the RA asked participants to stop the video, provide saliva samples, and complete the VAS for stress and the PANAS for the second time (T2).

TSST phase

In the TSST condition, the RA instructed participants to prepare for a speech task for five minutes, followed by a math task. They were told that a panel of trained experts will evaluate their speech and non-verbal behaviors, and they were reminded that the conversation will be recorded. The RA started tracking HR as soon as participants started the preparation period. After five minutes, the RA collected the preparation materials (paper and pen) and directed participants to join a Zoom meeting with the evaluators. The evaluators, consisting of one male and one female researcher, began the recording and prompted the participant to start their speech upon entry into the meeting. The speech task lasted for five minutes. During the speech, if the participant stopped talking, evaluators reminded them to continue the speech. At the three-minute mark, evaluators interrupted the speech and asked the participant to discuss another strength to elevate stress levels further. To maintain consistency, evaluators did not pose any other questions during the speech. Following the speech, evaluators asked participants to start a mental arithmetic task by counting down in increments of 13 from 1022, with instructions to restart upon any error and to increase the pace if participants proceed smoothly. BP was measured after the preparation, speech, and math tasks, respectively. After the arithmetic task, participants exited the Zoom meeting. The RA in the room stopped the HR reading and asks participants to provide saliva samples and complete the VAS for stress and the PANAS (T3). Meanwhile, participants in the non-TSST condition continued watching the nature documentary in this phase, with all the measures taken at the same time points.

Recovery phase

Participants continued watching the nature documentary at the assigned workstation for two consecutive 15-minute periods (30 minutes in total). Similar to earlier phases, the RA started tracking HR at the beginning and collected other stress responses (saliva samples, VAS for stress, and PANAS) at the end of each 15-minute period (marked as time points T4 and T5). BP was measured at five-minute intervals throughout this phase.

Following the recovery phase, participants removed the HR monitor and returned to the seat in the pre-workstation phase, and then completed the post-workstation survey assessing subjective task load. Upon completion, they were debriefed and provided with compensation.

Statistical Analysis

Analyses were conducted in R (version 4.4.1) and preregistered on OSF (https://doi.org/10.17605/OSF.IO/JZ9R2). Descriptive statistics summarized participant characteristics. To confirm successful randomization, one-way analyses of variance (ANOVAs) and chi-square tests compared demographic and baseline variables across workstation × stress conditions.

Primary analyses tested effects of workstation condition (sitting, standing, walking), stress condition (TSST vs. non-TSST), and their interaction on psychological, physiological, and behavioral stress responses. Linear mixed-effects models with spline coding for time using the lme4 modeled within-person change across the stress task (Bates et al., 2015). For all outcomes except cortisol, a knot at T3 distinguished the reactivity phase (T2–T3) from the recovery phase (T3–T5). For cortisol, which peaks later, the knot was placed at T4, defining reactivity (T3–T4) and recovery (T4–T5). Time points were nested within participants, with random intercepts for individuals. Random slopes for time segments were included when model convergence permitted; otherwise, fixed slopes were used. All models adjusted for the baseline value of the outcome (T1) and prespecified covariates, including age, gender, BMI, time of day of the session, and acute behavioral factors (recent caffeine use, hours of sleep the previous night, and current medication use). Fixed effects included Workstation, TSST Condition, Time Segment (s_1 = reactivity, s_2 = recovery), and all two- and three-way interactions. Estimated marginal means (EMMs) and pairwise contrasts among workstation conditions were computed using the emmeans package with Kenward-Roger degrees of freedom and Tukey-adjusted p-values (Kuznetsova et al., 2017; Lenth, 2016).

Two-way ANOVAs examined post-session subjective outcomes, including comfort, enjoyment, concentration difficulty, workload, and perceived safety, testing the main and interactive effects of Workstation (sitting, standing, walking) and TSST Condition (stress vs. control). Estimated marginal means (EMMs) and pairwise contrasts were computed using the emmeans package to decompose main effects since all interactions were insignificant, with Tukey-adjusted p-values for multiple comparisons. Effect sizes were expressed as partial η^2 for each effect.

Additionally, we investigated psychological mechanisms of stress regulation through two exploratory analyses. We used mediation analyses to test whether post-task ratings of attention allocation (degree of focus on the task vs. the workstation) mediated effects of workstation condition on perceived stress and cortisol (calculated using Area Under the Curve in regard to increase, AUCi). Moderation analyses examined whether attributions of arousal (e.g., attributing physiological changes to nervousness, excitement, or workstation activity) influenced the relationship between workstation condition and perceived stress and cortisol (calculated using AUCi). Finally, TSST performance data (speech fluency, word count, speech content quality rating, and math accuracy) were analyzed post hoc as an additional exploratory analysis using one-way ANOVAs to provide a more comprehensive assessment of behavioral performance under stress. All statistical tests were two-tailed with $\alpha = .05$.

RESULTS

Participant Characteristics

Data collection occurred from February 2024 to December 2024, and 157 participants completed the study. Participant characteristics are summarized in Table 1. The mean age was 29.81 years ($SD = 11.06$), and the mean body mass index (BMI) was 24.71 kg/m² ($SD = 5.10$). Participants reported an average of 7.13 hours of sleep ($SD = 1.20$) the night before the session. The sample included 63.5% women ($n = 99$), 28.2% men ($n = 44$), and 8.3% non-binary or preferred not to say ($n = 13$). Racial and ethnic composition was primarily White (66.0%), followed by Asian (9.6%), Hispanic or Latinx (9.6%), Multiracial (8.3%), and smaller proportions identifying as Black or African American (4.5%) or Other (0.6%). Most participants were English-speaking (89.7%) and had at least a bachelor's degree (68.7% with bachelor's or higher). The majority were single (68.6%), and nearly half were employed full-time (47.8%).

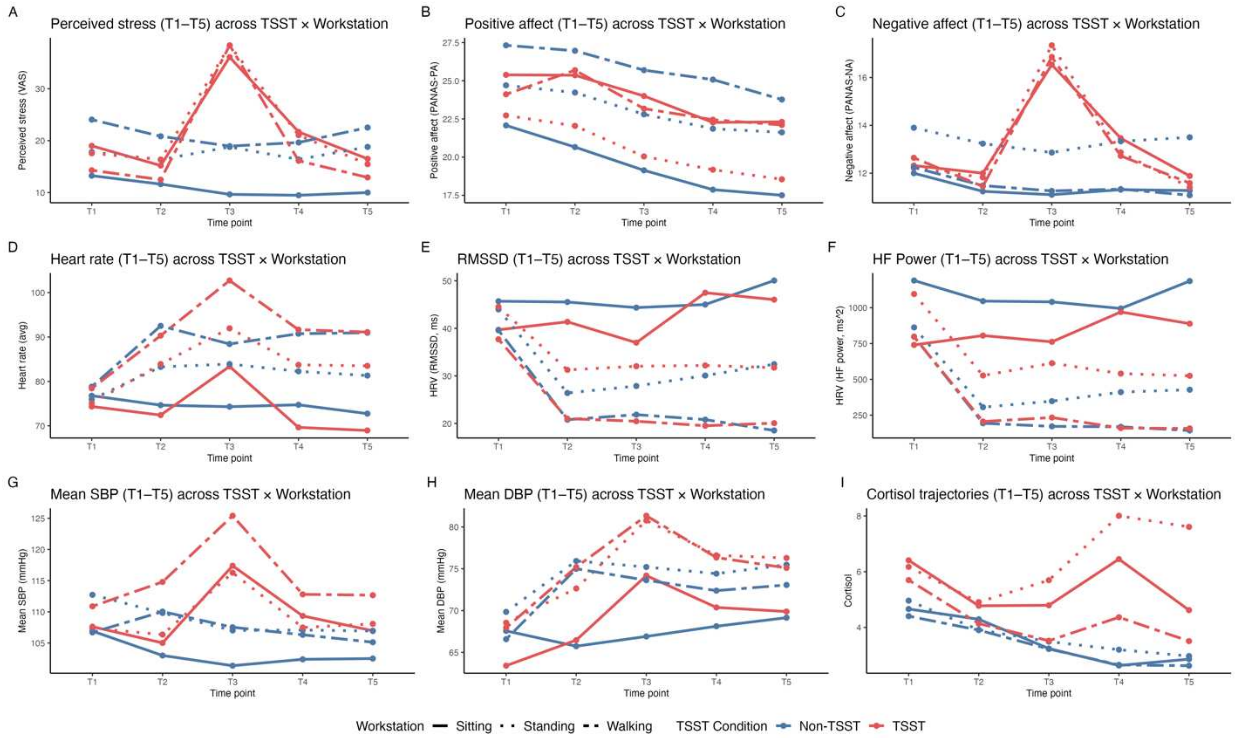
Self-reported physical activity indicated that 53.2% of participants had exercised on the day of testing, and 34.0% reported taking prescription medication, while 26.3% reported using nonprescription medication. About 15% of participants reported a diagnosed mental health condition, most commonly anxiety and depression, with smaller numbers reporting attention-deficit/hyperactivity disorder or other conditions.

Participants were randomly assigned to one of six conditions combining workstation type (sitting, standing, or walking) and stress manipulation (TSST vs. non-TSST). One-way analyses of variance (ANOVAs) and chi-square tests were conducted across these conditions for all demographic and health variables and no significant between-group differences were observed, indicating successful randomization and balanced baseline characteristics. Among participants assigned to the walking condition, treadmill walking lasted an average of 85 minutes (SD = 5.0), at a mean speed of 1.26 mph (SD = 0.59), covering an average distance of 1.78 miles (SD = 0.83).

Manipulation Check: Stress Induction Validity

The TSST elicited significant increases in both psychological and physiological stress markers (Figure 2). As shown in Table 2 and Table 3, reactivity slopes among the TSST conditions (s_1 × TSST) were significantly larger than non-TSST conditions for perceived stress ($\beta = 18.85$, $p < .001$), negative affect ($\beta = 4.58$, $p < .001$), HR ($\beta = 9.02$, $p < .001$), SBP ($\beta = 13.29$, $p < .001$), DBP ($\beta = 7.90$, $p < .001$), and cortisol ($\beta = 2.64$, $p = .001$). Recovery slopes (s_2 × TSST) were negative and significantly larger regarding the absolute value for these same outcomes (all ps< .01), indicating expected post-stress decreases. Trajectory plots (Figure 1) illustrate these patterns, showing sharp increases from baseline to peak (T2–T3) followed by steady declines through recovery (T4–T5). These results confirm that the stress induction procedure successfully produced robust and transient elevations in subjective, autonomic, and endocrine stress responses.

Figure 2. Primary Outcomes: Stress Response Trajectories by Workstation × TSST



Primary Outcomes

Psychological Stress and Mood

Across all participants, the TSST produced significant changes in psychological responses. Perceived stress and negative affect increased sharply during reactivity (s_1 × TSST, *p*s < .001) and declined during recovery (s_2 × TSST, *p*s < .001). Positive affect decreased after stress exposure ($\beta = -2.14$, $p = .026$).

Workstation type did not significantly affect perceived stress or negative affect (*p*s > .05, Table 2; Figure 2). No workstation × TSST interactions reached significance, indicating that under stress, workstation type did not influence the psychological stress reactivity and recovery process. However, a significant main effect of workstation was found for positive affect, with walking participants reporting higher overall positive affect than those sitting ($\beta = 2.33$, *p*

= .013). Estimated marginal slopes suggested numerically smaller reactivity in walking (Table 4); however, pairwise Tukey-adjusted contrasts were not significant (Table 5).

Physiological Stress Responses

Across all participants, the TSST elicited significant physiological stress responses. HR, SBP, and DBP increased sharply during reactivity ($s_1 \times$ TSST, *p*s $< .001$) and decreased during recovery ($s_2 \times$ TSST, *p*s $< .001$), confirming successful physiological activation and recovery following the stress induction.

Workstation type did not significantly affect cortisol levels (Table 3; Figure 2). However, participants in the standing and walking conditions showed higher mean HR, lower HRV, higher BP across time ($p < .001$) relative to sitting, consistent with LPA during these workstation conditions. Recovery slopes for HR were steeper in the standing condition compared with sitting ($\Delta s_2 = -3.25$, $p = .025$), suggesting faster autonomic recovery after stress exposure.

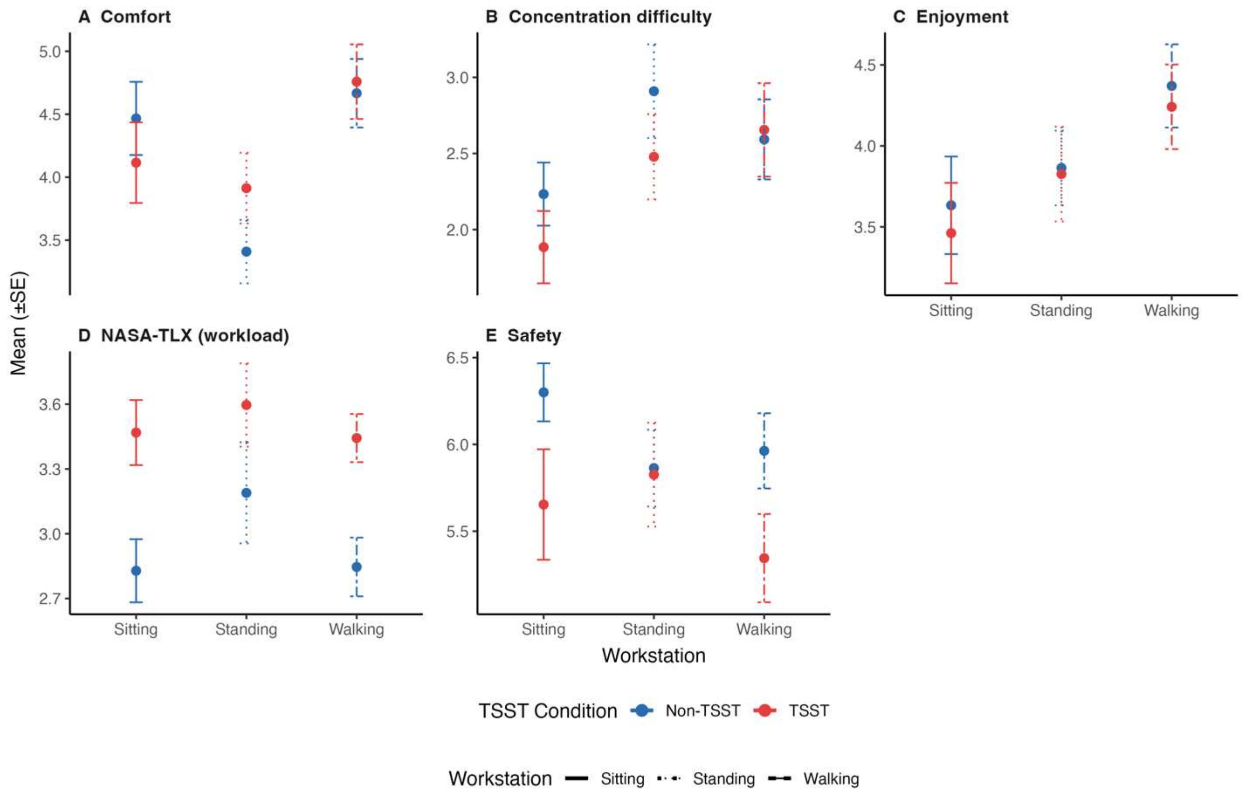
Participants in the standing and walking conditions showed lower HRV values immediately after initiating the workstation task (T2), indicating reduced parasympathetic activity before the stressor. HRV remained relatively stable across the stressor and recovery periods in these conditions. Pairwise slope comparisons (Table 5) indicated that the sitting condition had significantly greater HRV recovery slopes than both standing ($\Delta s_2 = 5.41$, $p < .001$) and walking ($\Delta s_2 = 5.18$, $p < .001$), with no difference between standing and walking ($p = .98$). Similar patterns were observed for HRV-HF power, where sitting participants showed steeper recovery ($\Delta s_2 = 142.26$ and 136.98, *p*s $< .01$). These results suggest that HRV recovery of parasympathetic activity was strongest in the sitting condition, whereas standing and walking showed lower overall HRV and flatter recovery slopes, likely reflecting physiological adjustment to light activity.

Cortisol concentrations followed the expected delayed pattern, increasing after stress exposure (s_1 × TSST, p = .001) and declining during recovery (s_2 × TSST, p = .012). Neither workstation main effects nor workstation × TSST interactions were significant (ps > .10).

Secondary Outcomes: Subjective Experience of Workstations

Two-way ANOVA results with estimated marginal means are presented in Table 6, and Figure 3 visualizes the corresponding group means differences (± SE). Significant main effects of workstation were found for comfort (F = 6.24, p = .002, η^2 = .075), enjoyment (F = 3.88, p = .023, η^2 = .049), and concentration difficulty (F = 3.29, p = .040, η^2 = .041). Tukey-adjusted comparisons indicated that walking was rated as significantly more enjoyable than sitting (p = .02) and more comfortable than standing (p = .002), while concentration difficulty was marginally higher for sitting than standing (p = .06). The TSST condition significantly increased perceived workload (F = 18.22, p < .001, η^2 = .107) and reduced perceived safety (F = 5.17, p = .024, η^2 = .033). No significant workstation × TSST interactions were observed for any outcome.

Figure 3. Secondary Outcomes by Workstation × TSST (Means ± SE)



Exploratory Analyses

Moderation by Attribution of Arousal

Results from moderation models are presented in Table 7. Among participants in the TSST condition who perceived a change in breathing and HR (n = 73), attributions of physiological arousal to "nervousness" marginally predicted higher self-reported stress (p = .088) but did not moderate the relationship between workstation condition and stress reactivity. No significant effects were observed for attributions to excitement or to the workstation itself. Model R^2 values ranged from .02 to .20, indicating small to modest explained variance. Because these analyses relied on a smaller TSST subgroup (n = 73), estimates should be interpreted cautiously as power to detect moderation effects was limited.

Mediation by Attention Allocation

Indirect effects are summarized in Table 8. Participants in the standing and walking conditions reported significantly lower attention to the stressor compared with those sitting (a_1 = −0.51, p = .035; a_2 = −0.47, p = .034). Greater attention to the task was associated with higher stress reactivity (b = 13.42, p = .020). Indirect effects were nonsignificant (p = .15). The pattern was directionally consistent but not statistically reliable, indicating that reduced attention to the stressor may be modestly associated with lower stress reactivity.

TSST Performance

As an additional exploratory analysis not included in the original preregistration, we examined participants' task performance during the TSST, including speech fluency and content as well as math accuracy (Table 9). One-way ANOVAs showed no significant differences across workstation conditions in any speech or math outcomes (all *p*s > .05). These results suggest that workstation type did not influence participants' verbal or cognitive task performance during the stressor. Because these analyses were added post hoc, they should be interpreted as exploratory, intended only to provide a fuller picture of how active workstations relate to behavioral and physiological responses.

DISCUSSION

This study found that light-intensity movement during an acute psychosocial stressor did not alter psychological, physiological, or behavioral stress responses. Contrary to our hypotheses, we did not observe evidence that treadmill desk use attenuated stress reactivity or enhanced recovery relative to sitting or standing conditions. Across walking, standing, and sitting conditions, participants showed comparable trajectories in perceived stress, affect, HR, BP, and cortisol. Positive affect was modestly higher in the walking condition, and speech and math performance were equivalent across workstations. Physiological differences between workstations likely reflected posture-related baseline variation (e.g., higher HR and BP in active conditions) rather than differences in stress reactivity. Post-session ratings indicated that walking was experienced as more enjoyable and, relative to standing, more comfortable. Although HRV was included as a marker of parasympathetic regulation, interpretation is limited because HRV dropped sharply upon transitioning from sitting to standing or walking and remained relatively flat thereafter, which could be a pattern consistent with posture-related vagal withdrawal rather than stress-induced change (Fagraeus & Linnarsson, 1976; Fontolliet et al., 2018). These shifts likely reflect normal autonomic adjustments to maintaining upright posture or continuous movement, which can suppress short-term variability even in the presence of stress. Future research should measure respiratory rate and consider adding complementary indices such as pre-ejection period (PEP) to disentangle sympathetic and parasympathetic contributions to autonomic responses during APWs use (Schächinger et al., 2001). Importantly, these findings indicate that light-intensity movement does not amplify stress responses, supporting its integration into cognitively demanding contexts without disrupting adaptive stress responding.

The findings partially support the proposed mechanisms. First, LPA has been shown to improve mood, enhance attention, and activate neurochemical systems (e.g., norepinephrine, endogenous opioids) that support stress regulation (Chan et al., 2019; Greenwood, 2019; Meeusen & De Meirleir, 1995; Pilozzi et al., 2021; Reed & Ones, 2006; Salmon, 2001). Our data align with modest affective benefits during light walking, reflected in higher overall positive affect relative to sitting, but they do not indicate additional buffering of acute reactivity or recovery. Two boundary conditions likely matter here. The activity and the stressor occurred simultaneously rather than sequentially, which can offset affective gains, and the movement intensity was low, which may be sufficient for comfort and enjoyment but insufficient to shift endocrine responses. However, enjoying walking without added stress cost is meaningful for adoption/adherence (Phillips & Chapman, 2012).

Second, distraction can promote adaptive coping and has been linked to faster cortisol recovery in some contexts (Cairney et al., 2014; Janson & Rohleder, 2017). APWs may draw a portion of attention to the bodily task, as suggested by our exploratory finding that standing and walking reduced reported attention to the stressor while leaving speech and math performance unchanged. These data suggest a plausible attentional-allocation pathway in which light movement may disengage attention from the stressor without harming performance, although indirect effects were nonsignificant.

Third, two-factor models suggest that labeling physiological arousal can alter emotional experience (Schachter & Singer, 1962; Zillmann, 1976), and reappraising anxiety as excitement can improve performance and self-efficacy in evaluative tasks (Brooks, 2014). In our exploratory moderation analyses, attributions of arousal did not meaningfully change stress responses across workstations. Within a simultaneous movement-plus-stressor context, attributing sensations to the workstation may not be sufficient to shift appraisals, or the manipulation strength may have been too modest to change interpretation.

Fourth, classic models suggest that mobilized energy during stress requires an outlet, and that physical activity may help dissipate arousal and protect against allostatic load (McEwen, 1998; Sapolsky, 2004). Prior research shows that acute exercise bouts performed before stress exposure can reduce cardiovascular reactivity (Chen et al., 2022; Mariano et al., 2022). In contrast, our findings did not support this mechanism when movement occurred during the stressor. Low-intensity, concurrent activity neither amplified nor attenuated acute responses, implying that any protective outlet effects may depend on higher intensity or post-stressor timing. Moreover, participants remained on their assigned workstation continuously from baseline to recovery for approximately 85 minutes in total, a duration longer than the average American adult walks in an entire day (Ussery et al., 2018). Such prolonged, low-intensity movement may not provide the brief, metabolically active ‘outlet’ that classic models describe. Future studies should compare short, acute movement bouts before or immediately after stress exposure with longer continuous APW use to identify the timing and intensity at which movement might function as an effective outlet.

With these mechanisms in mind, the present findings extend prior laboratory work demonstrating that active workstations can improve comfort and mood without compromising task performance (Cox et al., 2011; Grosprêtre et al., 2021; Sliter & Yuan, 2015; Yu & Graham, 2024). However, most previous research examined active workstation use during non-stressful cognitive or occupational tasks and assessed stress or affect only retrospectively, often after task completion. In contrast, the present study tested simultaneous movement during an acute, validated social-evaluative stressor while continuously tracking psychological, autonomic, and endocrine responses. This design allows a more rigorous test of whether light-intensity movement alters the dynamics of stress reactivity and recovery, rather than post-task perceptions of stress. The results challenge the assumption that movement during demanding work necessarily buffers or amplifies stress, suggesting instead that LPA remains largely neutral for stress physiology while improving user experience. Importantly, retrospective appraisals of stress and comfort may capture a different but equally meaningful dimension of the experience. Whereas momentary stress reflects immediate psychophysiological regulation, retrospective evaluations may represent overall satisfaction and behavioral reinforcement that influence continued workstation use (Phillips & Chapman, 2012). Future research should examine both perspectives within the same study to clarify how real-time stress and remembered experience jointly shape perceptions of feasibility and long-term adherence.

These findings also refine resource-based models positing that physical activity replenishes affective and cognitive resources (Calderwood et al., 2020); here, resource replenishment appeared more evident in enhanced comfort and enjoyment than in short-term physiological responses when activity occurred concurrently with the stressor.

Public Health Implications

Workers can walk slowly or stand during cognitively demanding or evaluative tasks without risking greater stress load or poorer performance. Walking improved comfort and enjoyment, which are well-established predictors of continued use in behavior-change research (Phillips & Chapman, 2012). Highlighting these positive experiential qualities provides a realistic pathway for long-term adherence, which is essential for population-level impact. Organizations planning activity-permissive work should set expectations appropriately. They should not promise immediate stress-reduction benefits from concurrent light movement, yet they can emphasize comfort, acceptability, and long-term health gains of reduced sedentary time and increased LPA. Pairing active work with brief seated recovery or paced breathing after acute stressors may capitalize on parasympathetic rebound while preserving movement during work.

Strengths and Limitations

Strengths include a preregistered experimental design, a robust stress induction, and multimethod assessment spanning subjective, autonomic, and endocrine domains. Inclusion of performance metrics and user-experience outcomes strengthens translational relevance. Limitations include single-session exposure, which constrains inference about adaptation and adherence; a sample skewed toward younger, educated adults; and heart-rate variability that was highly sensitive to posture and movement, reducing its utility for workstation comparisons in this paradigm. Speech and math performance analyses were exploratory and added post hoc; they warrant confirmation in preregistered replications. Although the overall sample was adequate for primary tests, exploratory moderation/mediation involved smaller subsets, limiting power for indirect effects.

Future Directions

Several lines of work follow directly from these data. First, timing and intensity experiments should manipulate movement relative to the stressor and vary intensity to test whether pre-, concurrent-, or post-stressor walking, or slightly higher speeds produce measurable buffering in autonomic and endocrine systems. Second, attentional-mechanism tests using eye tracking, pupillometry, or EEG can quantify attentional allocation during active versus seated conditions and link these indices to appraisals and performance. Third, longitudinal studies can evaluate whether weeks of active workstation use shift baseline autonomic flexibility, improve perceived control, or alter daily stress recovery in the field. Fourth, implementation research should examine whether comfort and enjoyment predict real-world workstation use, and whether combining active work with structured recovery practices improves day-end fatigue and mood. Finally, future studies should assess both in-the-moment and retrospective evaluations of stress and comfort to capture complementary aspects of experience. Momentary responses inform mechanisms of stress regulation, while retrospective appraisals may drive behavioral reinforcement and sustained engagement. Comparing these perspectives within the same individuals would clarify how users integrate immediate experiences into lasting attitudes toward active workstations.

Conclusion

Individuals doing light walking or standing on an APW during an acute stressor showed similar patterns of stress reactivity and recovery as those sitting, while also maintained task performance and improving user experience, especially among participants using the treadmill desk. These findings clarify that low-level movement can be integrated into cognitively demanding work without altering how people respond to or recover from stress, and they highlight practical strategies that pair activity-promoting design with realistic expectations for stress regulation.

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Table 1.

Descriptive statistics of participant demographics and health conditions across experimental conditions

	Overall (*N*=157)	Sitting + non-TSST (*n*=30)	Standing + non-TSST (*n*=22)	Walking + non-TSST (*n*=27)	Sitting + TSST (*n*=26)	Standing + TSST (*n*=23)	Walking + TSST (*n*=29)
Participant characteristics	*M* (SD) / *n* (%)	*M* (SD) / *n* (%)	*M* (SD) / *n* (%)	*M* (SD) / *n* (%)	*M* (SD) / *n* (%)	*M* (SD) / *n* (%)	*M* (SD) / *n* (%)
Age (years)	29.81 (11.06)	29.37 (10.33)	27.36 (8.66)	31.15 (13.67)	30.88 (9.75)	30.30 (12.86)	29.59 (10.96)
BMI	24.71 (5.10)	24.47 (4.82)	25.56 (4.71)	25.07 (6.14)	23.81 (4.11)	24.93 (4.82)	24.63 (5.89)
Sleep hours last night	7.13 (1.20)	7.10 (1.32)	7.14 (1.13)	6.92 (1.26)	7.08 (0.74)	7.13 (1.25)	7.38 (1.37)
Gender (*n*=156)							
Male	44 (28.2)	5 (16.7)	8 (36.4)	9 (34.6)	11 (42.3)	4 (17.4)	7 (24.1)
Female	99 (63.5)	20 (66.7)	12 (54.5)	14 (53.8)	14 (53.8)	18 (78.3)	21 (72.4)
Non-binary	12 (7.7)	5 (16.7)	2 (9.1)	3 (11.5)	1 (3.8)	0 (0.0)	1 (3.4)
Prefer not to say	1 (0.6)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (4.3)	0 (0.0)
Sexuality (*n*=156)							
Heterosexual/straight	109 (69.9)	17 (56.7)	14 (63.6)	16 (61.5)	20 (76.9)	16 (69.6)	26 (89.7)
Homosexual/gay	12 (7.7)	3 (10.0)	0 (0.0)	3 (11.5)	3 (11.5)	2 (8.7)	1 (3.4)
Bisexual	20 (12.8)	4 (13.3)	6 (27.3)	4 (15.4)	2 (7.7)	2 (8.7)	2 (6.9)
Asexual	7 (4.5)	3 (10.0)	2 (9.1)	1 (3.8)	0 (0.0)	1 (4.3)	0 (0.0)
Other	3 (1.9)	2 (6.7)	0 (0.0)	0 (0.0)	0 (0.0)	1 (4.3)	0 (0.0)
Prefer not to say	5 (3.2)	1 (3.3)	0 (0.0)	2 (7.7)	1 (3.8)	1 (4.3)	0 (0.0)
Racial Ethnicity (*n*=156)							
White/Caucasian	103 (66.0)	18 (60.0)	16 (72.7)	14 (53.8)	19 (73.1)	17 (73.9)	19 (65.5)
Black/African American	7 (4.5)	0 (0.0)	0 (0.0)	3 (11.5)	2 (7.7)	0 (0.0)	2 (6.9)
Hispanic/Latinx	15 (9.6)	7 (23.3)	1 (4.5)	1 (3.8)	2 (7.7)	3 (13.0)	1 (3.4)

Asian	15 (9.6)	2 (6.7)	3 (13.6)	3 (11.5)	2 (7.7)	2 (8.7)	3 (10.3)
Multiracial	13 (8.3)	2 (6.7)	2 (9.1)	4 (15.4)	1 (3.8)	1 (4.3)	3 (10.3)
Other	1 (0.6)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.4)
Prefer not to say	2 (1.3)	1 (3.3)	0 (0.0)	1 (3.8)	0 (0.0)	0 (0.0)	0 (0.0)
Education Level (*n*=156)							
High school diploma/GED	13 (8.3)	2 (6.7)	4 (18.2)	2 (7.7)	0 (0.0)	2 (8.7)	3 (10.3)
Some college/Associate's degree	35 (22.4)	9 (30.0)	2 (9.1)	9 (34.6)	4 (15.4)	5 (21.7)	6 (20.7)
Bachelor's degree	42 (26.9)	8 (26.7)	6 (27.3)	2 (7.7)	11 (42.3)	7 (30.4)	8 (27.6)
Master's degree	50 (32.1)	7 (23.3)	8 (36.4)	11 (42.3)	8 (30.8)	6 (26.1)	10 (34.5)
Doctoral degree	15 (9.6)	4 (13.3)	2 (9.1)	2 (7.7)	3 (11.5)	2 (8.7)	2 (6.9)
Professional degree (e.g., MD, JD)	1 (0.6)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (4.3)	0 (0.0)
Marital Status (*n*=156)							
Single	107 (68.6)	21 (70.0)	16 (72.7)	20 (76.9)	16 (61.5)	17 (73.9)	17 (58.6)
Married/Partnered	46 (29.5)	8 (26.7)	6 (27.3)	5 (19.2)	10 (38.5)	6 (26.1)	11 (37.9)
Divorced	3 (1.9)	1 (3.3)	0 (0.0)	1 (3.8)	0 (0.0)	0 (0.0)	1 (3.4)
Income level (*n*=156)							
Under $25,000	32 (20.5)	7 (23.3)	6 (27.3)	7 (26.9)	4 (15.4)	2 (8.7)	6 (20.7)
$25,000 - $49,999	26 (16.7)	5 (16.7)	3 (13.6)	4 (15.4)	4 (15.4)	4 (17.4)	6 (20.7)
$50,000 - $74,999	36 (23.1)	4 (13.3)	7 (31.8)	5 (19.2)	6 (23.1)	8 (34.8)	6 (20.7)
$75,000 - $99,999	8 (5.1)	1 (3.3)	0 (0.0)	3 (11.5)	1 (3.8)	0 (0.0)	3 (10.3)
$100,000 - $149,999	30 (19.2)	7 (23.3)	4 (18.2)	4 (15.4)	6 (23.1)	5 (21.7)	4 (13.8)

$150,000 and above	17 (10.9)	3 (10.0)	1 (4.5)	2 (7.7)	4 (15.4)	3 (13.0)	4 (13.8)
Prefer not to say	7 (4.5)	3 (10.0)	1 (4.5)	1 (3.8)	1 (3.8)	1 (4.3)	0 (0.0)
Employment Status (select all that apply; *n*=156)							
Employed full-time	75 (47.8)	14 (46.7)	10 (45.4)	11 (40.7)	15 (57.7)	13 (56.5)	12 (41.4)
Employed part-time	37 (23.6)	5 (16.7)	6 (27.3)	7 (25.9)	5 (9.2)	4 (17.4)	10 (34.5)
Unemployed	7 (4.5)	2 (6.7)	1 (4.5)	2 (7.4)	1 (3.8)	0 (0.0)	1 (3.4)
Student	58 (36.9)	12 (40.0)	10 (45.5)	12 (44.4)	9 (34.6)	6 (26.1)	9 (31.0)
Retired	1 (0.6)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (4.3)	0 (0.0)
Self-employed	4 (2.5)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	2 (8.7)	2 (6.9)
Other	4 (2.5)	1 (3.3)	2 (9.1)	0 (0.0)	1 (3.8)	0 (0.0)	0 (0.0)
Native Language (*n*=156)							
English	140 (89.7)	27 (90.0)	18 (81.8)	24 (92.3)	24 (92.3)	20 (87.0)	27 (93.1)
Other	16 (10.3)	3 (10.0)	4 (18.2)	2 (7.7)	2 (7.7)	3 (13.0)	2 (6.9)
Whether the participant has exercised today (*n*=156)							
No	73 (46.8)	11 (36.7)	11 (50.0)	13 (50.0)	12 (46.2)	13 (56.5)	13 (44.8)
Yes, for under 30 minutes	56 (35.9)	15 (50.0)	6 (27.3)	9 (34.6)	8 (30.8)	9 (39.1)	9 (31.0)
Yes, 30 minutes or more	27 (17.3)	4 (13.3)	5 (22.7)	4 (15.4)	6 (23.1)	1 (4.3)	7 (24.1)
Whether the participant took prescription medication today (*n*=156)							
No	103 (66.0)	14 (46.7)	15 (68.2)	19 (73.1)	16 (61.5)	18 (78.3)	21 (72.4)
Yes	53 (34.0)	16 (53.3)	7 (31.8)	7 (26.9)	10 (38.5)	5 (21.7)	8 (27.6)
Whether the participant took non-prescription medication today (*n*=156)							
No	115 (73.7)	20 (66.7)	15 (68.2)	17 (65.4)	22 (84.6)	20 (87.0)	21 (72.4)
Yes	41 (26.3)	10 (33.3)	7 (31.8)	9 (34.6)	4 (15.4)	3 (13.0)	8 (27.6)
Physical illness condition (*n*=23)							

Hypertension (High Blood Pressure)	2 (1.3)	0 (0.0)	1 (4.5)	0 (0.0)	0 (0.0)	1 (4.3)	0 (0.0)
Asthma	9 (5.7)	4 (13.3)	2 (9.1)	1 (3.7)	2 (7.7)	0 (0.0)	0 (0.0)
Allergies	4 (2.5)	3 (10.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.4)
Chronic Pain	3 (1.9)	1 (3.3)	0 (0.0)	2 (7.4)	0 (0.0)	0 (0.0)	0 (0.0)
Gastrointestinal Disorders (e.g., IBS, Crohn's disease)	2 (1.3)	1 (3.3)	0 (0.0)	0 (0.0)	1 (3.8)	0 (0.0)	0 (0.0)
Neurological Disorders (e.g., epilepsy, migraines)	3 (1.9)	1 (3.3)	0 (0.0)	0 (0.0)	1 (3.8)	0 (0.0)	1 (3.4)
Other	13 (8.3)	2 (6.7)	2 (9.1)	3 (11.1)	3 (11.5)	1 (4.3)	2 (6.9)
Mental illness condition (*n*=41)							
Anxiety Disorder	29 (18.5)	7 (23.3)	3 (13.6)	2 (7.4)	6 (23.1)	5 (21.7)	6 (20.7)
Depression	20 (12.7)	7 (23.3)	3 (13.6)	3 (11.1)	4 (15.4)	2 (8.7)	1 (3.4)
Bipolar Disorder	3 (1.9)	2 (6.7)	1 (4.5)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Post-Traumatic Stress Disorder (PTSD)	6 (3.8)	1 (3.3)	2 (9.1)	2 (7.4)	0 (0.0)	0 (0.0)	1 (3.4)
Obsessive-Compulsive Disorder (OCD)	3 (1.9)	0 (0.0)	1 (4.5)	0 (0.0)	1 (3.8)	0 (0.0)	1 (3.4)
Eating Disorder	2 (1.3)	0 (0.0)	0 (0.0)	0 (0.0)	1 (3.8)	0 (0.0)	1 (3.4)
Substance Use Disorder	1 (0.6)	0 (0.0)	0 (0.0)	1 (3.7)	0 (0.0)	0 (0.0)	0 (0.0)
Attention Deficit Hyperactivity	16 (10.2)	5 (16.7)	3 (13.6)	2 (7.4)	2 (7.7)	1 (4.3)	3 (10.3)

Disorder (ADHD)							
Other	4 (2.5)	1 (3.3)	0 (0.0)	1 (3.7)	0 (0.0)	0 (0.0)	2 (6.9)

Note. Values are mean (SD) or n (%). Percentages are column-wise. BMI = body mass index; TSST = Trier Social Stress Test.

Table 2.

Linear Mixed-Effects Models for Psychological Stress Responses

Predictor	Perceived Stress (n=112)		Positive Affect (n=148)		Negative Affect (n=148)	
	β	p	β	p	β	p
Fixed Effects						
Intercept	12.29	< .001 ***	25.71	< .001 ***	11.20	< .001 ***
s_1 (Reactivity)	–0.59	.84	–2.14	.026 *	–0.14	.84
s_2 (Recovery)	–0.25	.88	–0.59	.29	0.07	.84
Standing (ref. = Sitting)	2.39	.14	–0.30	.76	0.49	.24
Walking (ref. = Sitting)	1.12	.49	2.33	.013 *	–0.25	.51
Covariates						
Baseline (centered)	0.81	< .001 ***	0.89	< .001 ***	0.69	< .001 ***
Age (centered)	0.03	.57	–0.04	.25	0.01	.40
Caffeine (consumed in the past 8h, centered)	0.17	.73	0.32	.30	–0.06	.63
Sleep hours last night (centered)	0.21	.71	–0.32	.33	–0.03	.80
Time of day (Afternoon, ref. = Morning)	2.38	.11	–1.30	.13	0.68	.057
Gender (Female, ref. = Male)	–1.83	.23	–2.02	.030 *	–0.01	.97
Gender (Non-binary, ref. = Male)	–0.03	.99	–2.35	.18	–0.83	.21
Gender (Prefer not to say, ref. = Male)	–1.66	.81	–0.93	.84	0.10	.96
Prescription drug (Yes, ref. = No)	1.68	.25	–0.91	.30	0.71	.049 *
Non-prescription drug (Yes, ref. = No)	–2.13	.15	1.97	.028 *	–0.30	.39
Interactions						
s_1 × Standing	3.09	.48	0.88	.54	–0.11	.92
s_1 × Walking	–3.66	.43	1.07	.44	–0.04	.97
s_2 × Standing	0.06	.98	–0.08	.92	0.11	.85
s_2 × Walking	3.72	.17	–0.69	.40	–0.15	.77
s_1 × TSST	18.85	< .001 ***	0.66	.62	4.58	< .001 ***
s_2 × TSST	–9.56	< .001 ***	–0.23	.77	–2.41	< .001 ***
s_1 × Standing × TSST	–0.15	.98	–0.81	.69	0.65	.68
s_1 × Walking × TSST	6.74	.28	–2.13	.27	0.68	.65
s_2 × Standing × TSST	–2.48	.49	0.17	.89	–0.76	.33
s_2 × Walking × TSST	–5.50	.14	0.91	.42	–0.26	.73

Random Effects (SD)			
Intercept	2.42	3.94	1.18
S_1	11.49	3.84	3.30
S_2	6.79	2.40	1.58
Residual	6.60	2.28	1.51

Note. β = unstandardized coefficient. S_1 = reactivity; S_2 = recovery. Models include random intercepts and slopes for S_1 and S_2 by participant. *p* values are based on Satterthwaite's method. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 3.

Linear Mixed-Effects Models for Physiological Stress Responses

Predictor	Cortisol (n=130)		HR (n=142)		HRV RMSSD (n=141)		HRV HF Power (n=141)		DBP (n=139)		SBP (n=139)	
	β	p	β	p	β	p	β	p	β	p	β	p
Fixed Effects												
Intercept	3.83	<.001 ***	72.13	< .001 ***	42.94	< .001 ***	903.26	< .001 ***	68.99	< .001 ***	107.83	< .001 ***
s_1 (Reactivity)	–0.69	.171	–0.15	.936	–1.30	.417	–22.04	.794	0.38	.737	–1.66	.205
s_2 (Recovery)	0.22	.675	–0.28	.736	2.09	.008 **	50.52	.118	1.17	.025 *	0.58	.365
Standing vs Sitting	1.08	.243	9.31	< .001 ***	–14.45	< .001 ***	–488.30	< .001 ***	5.47	< .001 ***	2.15	.151
Walking vs Sitting	–0.11	.900	14.35	< .001 ***	–19.11	< .001 ***	–612.76	< .001 ***	7.95	< .001 ***	7.51	< .001 ***
Covariates												
Baseline (centered)	0.46 (T_2)	<.001 ***	0.79	< .001 ***	0.55	< .001 ***	0.42	< .001 ***	0.70	< .001 ***	0.78	< .001 ***
Age (centered)	–0.00	.908	–0.04	.542	0.18	.037 *	3.43	.342	0.01	.787	0.11	.031 *
Caffeine (consumed in the past 8h, centered)	–0.13	.629	0.10	.856	–0.56	.429	–18.91	.528	0.11	.761	0.05	.897
Sleep hours last night (centered)	0.13	.664	–0.79	.145	0.62	.388	29.83	.326	–0.43	.249	–0.72	.106 †
Time of day (Afternoon, ref. = Morning)	0.13	.871	1.62	.281	1.94	.327	73.95	.377	–1.77	.080 †	–2.08	.084 †
Gender (Female, ref. = Male)	–0.68	.391	4.13	.006 **	–3.12	.114	–59.73	.472	0.13	.898	–1.16	.384
Gender (Non-binary, ref. = Male)	–1.47	.327	4.62	.098 †	–2.04	.571	40.49	.791	0.28	.881	1.90	.413
Gender (Prefer not to say, ref. = Male)	–1.36	.741	11.23	.149	6.66	.515	–34.62	.937	3.53	.520	5.15	.429

Prescription drug (Yes, ref. = No)	1.02	.199	–2.57	.089 †	1.43	.483	–17.59	.833	–0.85	.409	–1.13	.346
Non-prescription drug (Yes, ref. = No)	–0.12	.879	–2.95	.057 †	–1.57	.451	–102.10	.247	–1.41	.169	–2.00	.102
Interactions												
s_1 × Standing	0.17	.831	0.88	.748	2.24	.340	49.19	.693	–0.88	.607	–1.40	.484
s_1 × Walking	0.14	.853	–2.88	.275	2.43	.283	15.89	.895	–1.99	.224	–2.15	.261
s_2 × Standing	–0.47	.578	–1.00	.403	0.19	.870	–11.55	.805	–1.07	.179	–0.61	.535
s_2 × Walking	–0.34	.654	1.35	.245	–3.03	.007 **	–55.68	.223	–1.29	.093 †	–1.24	.193
s_1 × TSST	2.64	.0005 ***	9.02	.0003 ***	–1.24	.579	15.26	.894	7.90	< .001 ***	13.29	< .001 ***
s_2 × TSST	–2.02	.012 *	–6.93	< .001 ***	3.05	.007 **	49.24	.291	–3.72	< .001 ***	–5.82	< .001 ***
s_1 × Standing × TSST	0.42	.708	–3.73	.294	1.92	.556	56.89	.735	0.00	.999	–1.10	.691
s_1 × Walking × TSST	–1.26	.231	4.68	.167	–0.89	.775	–8.35	.958	–0.43	.842	–0.78	.765
s_2 × Standing × TSST	1.77	.138	4.25	.014 *	–5.60	.0008 ***	–130.70	.055 †	1.00	.388	1.05	.468
s_2 × Walking × TSST	1.33	.231	–0.55	.737	–2.15	.170	–81.30	.208	0.12	.916	–0.25	.859
Random Effects (SD)												
Intercept	3.75		9.64		9.65		451.37		5.71		5.09	
s_1	—		8.14		5.76		375.01		5.05		3.18	
s_2	—		2.51		2.35		88.39		1.78		0.34	
Residual	1.89		4.57		4.29		187.81		3.10		4.96	

Note. β = unstandardized coefficient. S_1 = reactivity; S_2 = recovery. Models include random intercepts and random slopes for S_1 and S_2 by participant, except for the cortisol model, which included random intercepts only due to non-convergence when random slopes were added. Cortisol analyses were modeled with a later knot placement (T3-T4 for reactivity, and T4-T5 for recovery) to reflect delayed reactivity relative to other physiological measures.* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 4.

Estimated marginal slopes (s_1= Reactivity; s_2= Recovery) and 95% confidence intervals for stress outcomes by workstation and TSST condition.

Outcomes		Non-TSST Sitting (*n*=30)	Non-TSST Standing (*n*=22)	Non-TSST Walking (*n*=27)	TSST Sitting (*n*=26)	TSST Standing (*n*=23)	TSST Walking (*n*=29)
		Slope [95%CI]	Slope [95%CI]	Slope [95%CI]	Slope [95%CI]	Slope [95%CI]	Slope [95%CI]
VAS stress	s_1	−0.59 [−6.32, 5.14]	2.50 [−4.02, 9.03]	−4.25 [−11.37, 2.87]	18.26 [12.16, 24.36]	21.20 [14.95, 27.45]	21.34 [15.37, 27.30]
	s_2	−0.25 [−3.59, 3.09]	−0.19 [−4.00, 3.61]	3.47 [−0.72, 7.66]	−9.82 [−13.36, −6.27]	−12.24 [−15.94, −8.53]	−11.59 [−15.04, −8.15]
Positive affect	s_1	−2.14 [−4.02, −0.26]	−1.26 [−3.43, 0.91]	−1.07 [−3.07, 0.92];	−1.48 [−3.40, 0.44]	−1.41 [−3.47, 0.66]	−2.55 [−4.42, −0.68]
	s_2	−0.59 [−1.70, 0.51]	−0.68 [−1.98, 0.63]	−1.29 [−2.48, −0.09]	−0.83 [−1.95, 0.30]	−0.74 [−1.98, 0.50]	−0.61 [−1.71, 0.50]
Negative affect	s_1	−0.14 [−1.57, 1.29]	−0.26 [−1.98, 1.46]	−0.18 [−1.75, 1.39]	4.44 [2.89, 5.98]	4.97 [3.37, 6.57]	5.08 [3.63, 6.53]
	s_2	0.07 [−0.63, 0.78]	0.18 [−0.67, 1.02]	−0.08 [−0.86, 0.69]	−2.34 [−3.10, −1.59]	−3.00 [−3.79, −2.20]	−2.75 [−3.47, −2.04]
Cortisol	s_1	−0.69 [−1.68, 0.30]	−0.52 [−1.77, 0.74]	−0.55 [−1.61, 0.50]	1.95 [0.79, 3.10]	2.54 [1.42, 3.66]	0.83 [−0.19, 1.85]
	s_2	0.22 [−0.82, 1.26]	−0.25 [−1.54, 1.04]	−0.12 [−1.19, 0.95]	−1.80 [−2.98, −0.61]	−0.49 [−1.66, 0.68]	−0.81 [−1.85, 0.24]
Heart rate (bpm)	s_1	−0.15 [−3.82, 3.52]	0.73 [−3.25, 4.71]	−3.03 [−6.74, 0.68]	8.87 [5.07, 12.67]	6.02 [2.00, 10.03]	10.67 [7.11, 14.23]
	s_2	−0.28 [−1.89, 1.34]	−1.27 [−3.00, 0.45]	1.08 [−0.56, 2.71]	−7.21 [−8.90, −5.51]	−3.96 [−5.71, −2.21]	−6.40 [−7.95, −4.86]
HRV RMSSD (ms)	s_1	−1.30 [−4.47, 1.87]	0.94 [−2.44, 4.32]	1.13 [−2.03, 4.30]	−2.54 [−5.77, 0.70]	1.62 [−1.87, 5.11]	−0.99 [−4.00, 2.03]

	s_2	2.10 [0.53, 3.66]	2.28 [0.66, 3.90]	−0.94 [−2.48, 0.61]	5.15 [3.54, 6.75]	−0.27 [−1.95, 1.42]	−0.03 [−1.49, 1.42]
HRV HF power	s_1	−22.04 [−189, 145]	27.15 [−154, 209]	−6.15 [−175, 163]	−6.78 [−180, 166]	99.30 [−87.1, 286]	0.76 [−161, 162]
	s_2	50.52 [−13.2, 114.2]	38.96 [−28.5, 106.4]	−5.17 [−69.3, 59.0]	99.76 [33.0, 166.5]	−42.50 [−112.6, 27.6]	−37.23 [−97.7, 23.3]
SBP (mmHg)	s_1	−1.66 [−4.23, 0.92]	−3.06 [−6.07, −0.04]	−3.80 [−6.56, −1.05]	11.63 [8.83, 14.44]	9.14 [6.08, 12.19]	8.70 [5.96, 11.44]
	s_2	0.58 [−0.69, 1.86]	−0.03 [−1.52, 1.46]	−0.66 [−2.04, 0.73]	−5.23 [−6.69, −3.78]	−4.80 [−6.30, −3.30]	−6.72 [−8.16, −5.29]
DBP (mmHg)	s_1	0.38 [−1.84, 2.60]	−0.51 [−3.09, 2.07]	−1.61 [−3.96, 0.74]	8.28 [5.88, 10.67]	7.39 [4.78, 10.00]	5.86 [3.53, 8.18]
	s_2	1.17 [0.15, 2.19]	0.10 [−1.10, 1.29]	−0.12 [−1.23, 0.99]	−2.56 [−3.72, −1.39]	−2.63 [−3.83, −1.43]	−3.73 [−4.86, −2.59]

Note. s_1 = reactivity; s_2 = recovery. Values represent estimated marginal slopes (unstandardized) and 95% confidence intervals derived from linear mixed-effects models including workstation condition, TSST condition, and their interaction, adjusted for baseline, age, caffeine intake, sleep hours, time of day, gender, and medication use. Slopes represent rate of change during the reactivity (s_1; typically T2–T3) and recovery (s_2; T3–T5) phases. Cortisol analyses were modeled using a later knot placement (s_1=T3-T4, s_2=T4-T5) to reflect delayed physiological response and included random intercepts only due to non-convergence when random slopes were added.

Table 5.

Pairwise comparisons of estimated marginal slopes (s_1= Reactivity; s_2= Recovery) across workstation conditions within TSST.

	s_1 Reactivity						s_2 Recovery					
	Sit−Stand		Sit−Walk		Stand−Walk		Sit−Stand		Sit−Walk		Stand−Walk	
Outcome	*ΔSlope*	*p*	*ΔSlope*	*p*	*ΔSlope*	*p*	*ΔSlope*	*p*	*ΔSlope*	*p*	*ΔSlope*	*p*
VAS stress	−2.942	.783	−3.079	.756	−0.137	.999	2.423	.619	1.779	.756	−0.644	.966
Positive affect	−0.076	.998	1.069	.790	1.145	.696	−0.083	.995	−0.220	.959	−0.137	.985
Negative affect	−0.531	. 885	−0.646	.820	−0.115	.994	0.653	.467	0.409	.717	−0.244	.893
Cortisol	−0.593	. 748	1.119	.328	1.712	.069	−1.305	.273	−0.988	.437	0.317	.916
Heart rate	2.853	.565	−1.800	.774	−4.653	.203	−3.249	.025*	−0.805	.767	2.444	.100
HRV (RMSSD)	−4.159	.198	−1.548	.769	2.611	.503	5.412	<.001***	5.179	<.001***	−0.234	.977
HRV (HF power)	−106.08	.689	−7.54	.998	98.55	.710	142.26	.0119*	136.98	.0088**	−5.28	.993
SBP	2.498	.460	2.932	.305	0.434	.976	−0.436	.911	1.488	.325	1.923	.164
DBP	0.886	.874	2.420	.327	1.535	.661	0.072	.996	1.170	.333	1.098	.390

Note. ΔSlope = difference in estimated unstandardized slopes between workstation conditions. p values are Tukey-adjusted using the Kenward–Roger method. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 6

Two-way ANOVA and estimated marginal means (EMM) results for secondary outcomes.

Outcome Variable	Effect	*F*	*p*	η^2	EMM Contrast	Estimate [95% CI]	*p*
Perceived workload (*n*=155)	Workstation	1.54	.22	.018	Sitting - Standing	-0.24 [-0.63, 0.14]	.30
					Sitting - Walking	0.003 [-0.36, 0.37]	.37
					Standing - Walking	0.25 [-0.14, 0.63]	.63
	TSST	18.22	<.001***	.107	Non-TSST - TSST	-0.55 [-0.81, -0.29]	<.001***
	Workstation × TSST	0.28	.76	.003			
Concentration Difficulty (*n*=157)	Workstation	3.29	.04*	.041	Sitting - Standing	-0.63 [-1.28, 0.01]	.06
					Sitting - Walking	-0.56 [1.18, 0.05]	.08
					Standing - Walking	0.07 [-0.58, 0.72]	.96
	TSST	1.06	.30	.007	Non-TSST - TSST	0.24 [-0.20, 0.67]	.28
	Workstation × TSST	0.49	.61	.006			
Enjoyment (*n*=157)	Workstation	3.88	.02*	.049	Sitting - Standing	-0.30 [-0.98, 0.38]	.56
					Sitting - Walking	-0.76 [-1.40, -0.12]	.02*
					Standing - Walking	-0.46 [-1.14, 0.22]	.25
	TSST	0.27	.61	.002	Non-TSST - TSST	0.11 [-0.34, 0.57]	.63
	Workstation × TSST	0.03	.97	<.001			

Comfort (*n*=157)	Workstation	6.24	.002**	.075	Sitting - Standing	0.63 [-0.07, 1.33]	.09
					Sitting - Walking	-0.42 [-1.09, 0.24]	.29
					Standing - Walking	-1.05 [-1.76, -0.35]	.002**
	TSST	0.05	.83	<.001	Non-TSST - TSST	-0.08 [-0.55, 0.39]	.73
	Workstation × TSST	1.04	.36	.013			
Safety (*n*=157)	Workstation	1.11	.33	.014	Sitting - Standing	0.13 [-0.47, 0.73]	.86
					Sitting - Walking	0.32 [-0.25, 0.89]	.37
					Standing - Walking	0.19 [-0.41, 0.79]	.73
	TSST	5.17	.02*	.033	Non-TSST - TSST	0.43 [0.03, 0.84]	.03*
	Workstation × TSST	0.88	.42	.011			

Note. TSST = Trier Social Stress Test (stress vs. control condition). Workstation condition included sitting, standing, and walking. Each model examined the main effects of workstation type, TSST condition, and their interaction. For all main effects, Tukey-adjusted post hoc pairwise comparisons are shown with estimated marginal mean (EMM) contrasts, 95% confidence intervals, and adjusted p values. Effect size η^2 represents the proportion of total variance explained by each effect. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 7.

Exploratory moderation analyses examining attribution of arousal as moderators of the association between workstation condition and stress reactivity (perceived stress and cortisol, calculated using Area Under the Curve in regard to increase, AUCi) among participants who experienced the Trier Social Stress Test (TSST) and reported to perceive a change in breathing and heart rate (n=73).

	Self-reported stress (*n*=54)						Salivary cortisol (*n*=58)					
	Excitement		*Nervousness*		*Workstations*		*Excitement*		*Nervousness*		*Workstations*	
Predictor	*β*	*p*	*β*	*p*	*β*	*p*	*β*	*p*	*β*	*p*	*β*	*p*
(Intercept)	24.03	.004**	25.89	<.001***	23.70	.008	2.45	.068	2.33	.076	0.94	.597
Standing (vs. Sitting)	16.57	.174	2.34	.827	10.15	.420	0.82	.647	0.66	.712	1.96	.353
Walking (vs. Sitting)	5.71	.595	0.46	.964	6.31	.582	−1.63	.340	−1.50	.369	−0.10	.962
Moderator (centered)	2.35	.744	15.17	.088	−2.99	.745	−0.63	.547	0.56	.695	−1.86	.349
Standing × Moderator	17.32	.132	5.90	.676	−2.21	.853	−0.00	.998	0.57	.803	3.61	.109
Walking × Moderator	−8.77	.453	11.14	.446	6.53	.634	0.34	.843	0.07	.970	1.95	.394
Model Fit	$F(5, 48) = 1.25$, $p = .301$, $R^2 = .12$		$F(5, 49) = 2.48$, $p = .044$, $R^2 = .20$		$F(5, 49) = 0.22$, $p = .950$, $R^2 = .02$		$F(5, 52) = 0.66$, $p = .657$, $R^2 = .06$		$F(5, 53) = 0.63$, $p = .680$, $R^2 = .06$		$F(5, 53) = 1.29$, $p = .284$, $R^2 = .11$	

Note. Each linear regression model tested whether **attributions of arousal** (to what degree participants attribute physical arousal, such as increased heart rate, heavier breathing, to excitement, nervousness, or workstation influence; mean-centered) moderated the relationship between **workstation condition** (sitting, standing, walking) and **stress reactivity** measured by either **self-reported stress** or **salivary cortisol** during the Trier Social Stress Test (TSST). * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 8.

Indirect effects of workstation condition on perceived stress (calculated using Area Under the Curve in regard to increase, AUCi) through self-reported attention to the Trier Social Stress Test (*n*=57).

Path	Estimate	SE (Bootstrap)	95% CI [LL, UL]	*p*	Std. *β*
a paths (Workstation → Attention)					
Standing vs. Sitting (a_1)	−0.513	0.244	[−0.990, −0.036]	.035*	−0.31
Walking vs. Sitting (a_2)	−0.468	0.221	[−0.906, −0.037]	.034*	−0.31
b path (Attention → AUCi VAS)	13.419	5.789	[2.502, 25.346]	.020*	0.31
Direct effects (c′ paths)					
Standing vs. Sitting (c_1')	14.906	13.993	[−10.756, 44.102]	.287	0.21
Walking vs. Sitting (c_2')	10.989	8.856	[−6.968, 27.909]	.215	0.17
Indirect effects (a × b)					
Standing via Attention	−6.886	4.756	[−18.634, 0.066]	.148	−0.10
Walking via Attention	−6.276	4.311	[−16.533, 0.074]	.145	−0.09
Total effects (c′ + a × b)					
Standing vs. Sitting	8.020	12.756	[−16.083, 33.945]	.530	0.11
Walking vs. Sitting	4.713	8.903	[−14.043, 21.217]	.597	0.07

Note. Estimates are unstandardized unless otherwise indicated. Bootstrap standard errors and 95% confidence intervals are based on 5,000 draws. The mediator variable represents self-reported attention to the task during the Trier Social Stress Test (TSST). The dependent variable is stress reactivity, measured as the area under the curve with respect to increase (AUCi) for self-reported perceived stress. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 9

One-way ANOVA results for speech quality and math best score (n=77).

Outcome Variable	F	p
Speech word count	0.14	.87
Productive words/total words ratio	0.08	.93
Non-fluency words/total words ratio	0.26	.77
Speech content quality	0.01	.99
Math best score	1.49	.23