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Assessment of psychological and physiological responses to auditory and visual stimuli during recovery from acute stress induction

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ABSTRACT

Workplace stress is one of the main sources of stress for adults, although physiological and cognitive factors may impact each person's stress response. Numerous studies have shown heart rate, heart rate variability, neural activity, and cognitive performance are affected by stress. Additionally, visual and auditory stimuli in one's environment have been shown to affect individuals' reaction to stressful events. To our knowledge, few studies have examined how each of these physiological and cognitive measures relate to one's perception of stress, the ability to recover from stress, and what environmental factors may help with stress recovery. Here, 80 healthy adults performed a laboratory-controlled stress induction task where they experienced and recovered from an acute psychological stressor (Trier Social Stress Test, TSST, using verbal math skills and a public presentation that was videotaped). Throughout the assessment, heart rate, heart rate variability, and neural activity were measured using wearable devices to assess changes before, during, and after the stressor. Additionally, participants were assessed their perceived stress levels at specific times throughout the assessment. After the psychological stressor, participants were randomly assigned to one of four recovery conditions within a multisensory relaxation room: Control (C), Auditory Only (A),

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Visual Only (V), or Combined Auditory and Visual (AV). During the stressor, anxiety, heart rate, and beta EEG power increased and high-frequency power and heart rate variability decreased, confirming participants reactivity to the stressor ($P < 0.01$ for all vs. baseline). Only the V and AV conditions led to notable reductions in anxiety (15 and 17%, respectively) vs. the C condition, but these did not reach statistical significance. There was no difference between V and AV, suggesting a stronger impact of V. We observed no differences between conditions during recovery for HR and HRV. Overall, these findings suggest the visual features of the relaxation room impacted self-reported anxiety, however physiological and neurological effects did not demonstrate a statistically meaningful response.

KEYWORDS

stress, biophilia, heart rate variability

INTRODUCTION

Workplace stress is one of the primary stressors amongst adult workers. When manageable, stress can actually boost performance on certain tasks [1]; however, excessive stress has been shown to be detrimental to both physical and mental health, and can cause burnout [2]. Burnout is costly for both the individual worker and the organization. In the U.S. healthcare system alone, burnout costs related to personnel turnover and other factors exceed $4.6 billion each year for physicians alone [3], with similar findings across different employment environments. Employers have used several approaches to mitigate burnout and workplace stress; however, no strategy has been proven to be most effective, mainly due to a lack of data comparing stress reduction interventions.

When exposed to certain stressors, the nervous system undergoes changes that can result in short-term benefits, i.e. the fight or flight response, but these changes can be detrimental under chronic exposure to these stressors. The hypothalamic-pituitary-adrenal (HPA) axis is the pathway in the autonomic nervous system (ANS) that contributes to the stress response. The HPA axis is involved in the cardiac stress response cortisol levels increase, affecting the sympathetic nervous system (SNS) [4, 5]. Activating the SNS yields arousal and acceleration of particular body functions including increasing heart rate (HR), bronchodilation, pupillary dilation, to name a few [6]. Conversely, the parasympathetic nervous system (PNS) inhibits the SNS and HPA axis, can help the body to relax, and is important in both recovery and prevention of burnout due to SNS overactivity. From a cardiac perspective, there is a balance between how the HPA activates the SNS to increase HR, and the PNS which inhibits the HPA and decreases HR. However, the ANS responds to a multitude of factors beyond stress, both physiological and environmental, which can make it challenging to attribute changes in ANS to specific stressors. The addition of measured heart rate variability (HRV) to HR provides one approach to disentangling the effects of SNS and PNS activity in response to these internal or external stimuli [6, 7].

Additionally, neural activity from the central nervous system (CNS) has been strongly correlated with responses to stress [8]. Specific brain regions are engaged when processing and adapting to stress and regulating both physiological and behavioral responses to stress [9]. Neuroimaging studies using functional magnetic resonance imaging have identified key

brain networks involved in processing the stress response, including the default mode network, salience network, and central executive network [10–12]. These brain networks are important for cognitive function, behavior, and regulating the HPA stress response [8]. Spectral analysis of electroencephalography (EEG) is a powerful tool to understand how temporal changes relate to stressors [12]. Common frequency bands such as alpha, beta, and theta have been linked to the consolidation of memories during sleep, cognitive interference, working memory function, and sensory and motor processing, among numerous other functions [12–17]. Therefore, the measurement of how spectral activity, similar to HR and HRV, is modulated is important in characterizing physiological changes in response to a stressor.

Although quantitative measures, such as HR, HRV, and EEG, are important in determining the stress response to the body, self-report is the most often used form of identifying when individuals are stressed, typically using perceived stress or anxiety-related questionnaires. Another way of detecting stress is through the measurement of changes in cognitive performance tasks, especially related to executive function. Executive function is a crucial subset of cognitive function, which refers to the higher-level cognitive processes that enable us to plan and execute goal-directed actions [18, 19]. Prior studies have shown both positive and negative effects of stress on individual cognitive processes, but in a meta-analysis conducted by Shields and colleagues [20], working memory and cognitive flexibility were impaired by stress. Given this previous work and the multifactorial nature of factors relating to stress response, combining self-report, cognitive function, and quantified cardiovascular and EEG data allows for a more complete picture of the person's response to a stressor.

One approach to reducing burnout being promoted at some institutions is the use of respite (or relaxation) rooms to provide temporary moments of relaxation for those who work in stressful situations during work hours. While there is data to suggest that the use of a relaxation room results in acute improvements in perceived stress and well-being, there have been few research studies demonstrating multiple perceived and physiological impacts of workplace relaxation rooms. Further the environment of relaxation rooms vary from simply a quiet room, to a darkened room, to one with relaxing sounds and altered lighting and biophilic elements. However, the individual contributions of these inputs, and their impact on the physiological response to stress, has not been studied in detail. As described in a previous manuscript by our group [21], visual and auditory elements from nature has been shown to reduce stress in humans [22–26]. Physiological benefits also occur after experiencing naturalistic visual and auditory stimuli [27, 28], as has cognitive performance [20, 29]. Taken together, we hypothesize that physiological measures and cognitive performance after a stressful event will return to pre-stress levels faster when experiencing both auditory and visual stimuli of the MindBreaks room compared to only auditory or visual stimuli or neither.

The objective of this study protocol was to determine whether different visual and/or auditory features of a relaxation room affect the recovery of physiological signals, perceived stress, and cognitive function after an experimentally controlled acutely stressful event (TSST). Because the efficacy of such relaxation rooms has historically been determined based on self-report of stress by the individual [30] the understanding how features of a relaxation room affect physiological responses and cognitive function, in addition to perceived stress levels, could lead to a more individualized approach to reducing workplace stress and burnout.

METHODS

Participants

Eighty working professionals (29 males and 51 females) aged 19 – 62 years (mean = 29.75 yrs) were recruited from a major healthcare organization. We excluded participants who (1) reported mood, anxiety, or major health disorders; (2) were currently using steroid-based medications; (3) had a history of drug/alcohol use disorders; (4) were recovering from nicotine dependency and could not use a nicotine patch for two h prior to and throughout the study; (5) consumed excessive amounts of caffeine (more than 400 mg per day as defined by the FDA, 2018); (6) had severe sleep disturbance (e.g., sleep apnea) based on self-report; (7) were pregnant; (8) had a history of cognitive impairment; (9) had not completed a full COVID-19 vaccine regimen; and/or (10) had cosmetics or head products that might interfere with the electroencephalography (EEG) recordings. The Mayo Clinic Internal Review Board reviewed and approved the study (21-005885). All participants were recruited from a large medical center and provided written informed consent prior to study and received remuneration for their participation upon completion.

Study design and interventions. For each participant, the study session began at 1,300 h to control for the known circadian effects on the physiological responses and cognitive function [31, 32]. Participants were asked to refrain from caffeine and/or to use a nicotine patch (if needed) two h before the start of the study which are known to affect physiological measures of interest [6, 7]. Upon arrival, participants put on a collection of wearable devices and then began the experiment during which they performed working memory assessments and completed questionnaires and had baseline measures (Fig. 1). Following baseline measures, the subjects underwent a stress-induction (Trier Social Stress Test, TSST, using verbal math skills and a public presentation that was videotaped TSST) and then were observed for two 20 min periods of recovery. During recovery, the subjects were assigned to one of four environmental conditions, as described below.

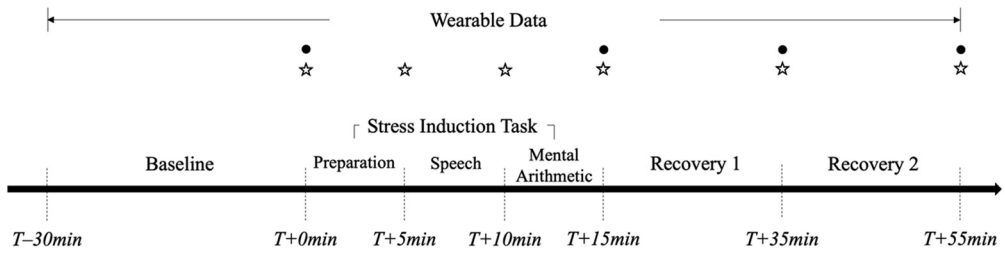

Fig. 1. A timeline of the different epochs of the experiment. Participants were asked to perform the cognitive assessment tasks (●) and fill out self-reports of stress and anxiety (☆) before and after the stress induction task

Trier Social Stress Test (TSST)

Each participant performed a modified version of the classical Trier Social Stress Test (TSST) to induce an acutely stressful event [59]. The current study used 30 min for the baseline epoch, 15 min for the stress induction task epoch, and two 20-min recovery epochs. The stress induction task consists of five min of speech preparation for a job interview about their ideal job, five min of speech delivery in front of strangers, and five min of mental arithmetic in front of two judges wearing a lab coat and a video camera. Because this study was performed, in part, when Covid restrictions were in place, all judges wore masks for each subject to maintain consistency across participants. As indicated in Fig. 1, participants performed cognitive tasks and answered questions related to stress and anxiety between specific epochs of the experiment. Most participants took six to eight min to complete the cognitive tasks and less than one min to fill out the questionnaires. The study coordinator logged the start and end of each experimental epoch on an iPad (Apple Inc., California, USA) so we were able to align and analyze the data collected (e.g., start and stop time of baseline epoch).

Recovery procedure

Following the stress induction task, participants spent the recovery epochs in a relaxation room with either: no intervention (control), biophilic visual intervention (visual), auditory intervention (auditory) or a combined visual and auditory intervention (visual and auditory) designed to reduce stress and promote recovery [24, 33–35]. For the visual and auditory stimuli for recovery, artificial green wall, plants, a skylight, light fixtures, and speakers were placed around the room to create an immersive restorative environment. The room design was optimized to mimic a biophilic environment, including sound choices, which included rain, streams, etc. However, during the control epoch neutral-colored curtains covered the walls of the room so that participants were not exposed to any stimuli. Recovery was assessed at 20 and 40 min, post-stress.

Outcome measures

Questionnaires. The Short-form of the State-Trait Anxiety Inventory (STAI-6) [36] and a single question from the perceived stress scale (PSS) were used to assess participants' state anxiety and perceived stress level throughout the experiment session. The STAI-6 consists of six questions from the state measure of the original State-Trait Anxiety Inventory [37]. Each question is rated on a 4-point scale (not at all, somewhat, moderately so, very much so) and the range of possible scores is from 6 to 24. The PSS asks individuals about their current feelings of stress and uses a single numeric rating scale from 1 (not at all stressed) to 7 (extremely stressed).

Cardiac assessment (heart rate and heart rate variability). A Polar^{TM} H10 (Polar Electro Oy, Kempele, Finland) chest strap, with integration with a Polar watch and Polar application was used to measure HR and HRV. This device is an electrocardiogram-based (ECG) chest strap sensor and is used to collect R-R intervals (RRI). Umair and colleagues [38] assessed the accuracy of RRI capturing from Polar H10, and it was comparable to a reference-grade EKG device and reliable to obtain HRV components. Based on the recommendations of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology guidelines [39], we calculated the following time-domain components: standard deviation of all

normal RRIs (SDNN) and the square root of mean squared difference between normal heartbeats (RMSSD), and frequency-domain components: low frequency (0.04 – 0.15 Hz, LF) and high frequency (0.15 – 0.40 Hz, HF) bands. High frequency (HF) HRV power is thought to reflect changes in the PNS and decrease when someone is under stress or anxiety [40] whereas low frequency (LF) HRV power, is more complex and thought to reflect both sympathetic nervous system (SNS) and PNS activity [6, 40] with stress induction. We included the percentage of adjacent normal RRIs that differ from each other by more than 50ms (pNN50) as recent studies found that it is also affected by mental stress [41]. All of the HRV components were retrieved through Kubios HRV Premium software (version 3.3.1) [42].

As an exploratory analysis, we analyzed the time-course of the high frequency HRV signals. The *RHRV* package (version 4.2.6) in R was used to assess these temporal changes of HF HRV power throughout the experimental session for each participant. The same frequency band of 0.15–0.40 Hz with a window size of 40 s with 1 s overlapping windows was used to calculate HF power for each participant. Based on the start time of every epoch logged by the study coordinator, we aligned the data with the onset of the stress manipulation epoch. Median, 25th, and 75th percentile values of each data point across the participants were calculated.

Neural recordings, electroencephalography. Neural activity was recorded by the Dreem 3 EEG headband (Dreem, Paris, France). This headband has four electrodes located at O1, O2, F7, F8, and one electrode located at Fp2 as a reference signal based on the 10-20 system. This system has a sampling rate of 250 Hz and is able to classify sleep stages accurately comparable to polysomnography [43].

Neural analyses were performed in Python using the MNE toolbox [44]. Neural recordings were pulled from the Dreem Portal and analyzed for each participant. The data were recorded from the Dreem headband in a differential montage: F8-O1, F8-F7, and F8-O2. In order to estimate each electrode separately, F8 was calculated from the common average of these three differential recordings. We acknowledge that, due to the low channel count, common averaging may have introduced additional noise, however this was still considered the simplest approach to estimating the activity from each frontal and occipital electrode. From the raw Dreem data, each channel was bandpass filtered from 1 to 100Hz (Finite Impulse Response (FIR) Hamming filter) using the MNE 'filter' function. The AutoReject MNE Plugin was used to automatically reject bad epochs from the recordings [45]. Each channel was sorted into fixed 3-s windows and the AutoReject toolbox was used to identify thresholds for detecting bad epochs and replacing them with not-a-numbers (NaNs). Although this is a lower channel count than typically used for the AutoReject toolbox, automatically identifying a threshold provided an approach to remove user bias in selecting a threshold to decide between "good" and "bad" electrodes. Power spectral densities (PSDs) were calculated in the beta frequency band (13–32Hz) for each epoch using Welch's algorithm (function 'welch') from the scipy python toolbox [46]. The PSDs from each epoch were combined again into a continuous time series for the entire experiment (with NaN epochs replacing the bad epochs identified earlier) and time was aligned to the start of the presentation phase of the stress induction task. The PSDs were then labeled based on the different epochs of the experiment as defined in Fig. 1.

Working memory assessments. Previous studies have shown that working memory performance is affected by acute stress [47, 20]. Here, participants performed two working memory tasks: the

Operation Span (OSPAN) task and the Symmetry Span (SSPAN) task [48, 49] at specific times during the study (Fig. 1). Participants were asked to remember sets of letters while solving math problems (OSPAN) or sets of red squares on 4 × 4 grids while making judgements on whether images were vertically symmetrical or not (SSPAN). Participants performed the working memory assessments on a 12.9″ iPad Pro (Apple Inc., California, United States) positioned at the same location on a desk to provide consistent placement across participants. For both tasks, Unit Score, the proportion of letters or squares recalled in correct order presented on the screen, was used in analysis and compared across the experiment to detect any effect before and after stress on task performance.

Data preparation and analyses. Responses from STAI-6 and PSS at the end of each epoch were analyzed as follows. Two different methods were used as STAI-6 is a sum of Likert scores whereas PSS is a single Likert score. Univariate linear mixed-effects analysis was used to examine state anxiety level throughout the experimental session using the *lme4* (Version 1.1–26) package in R (Version 3.6.3). To account for repeated measures, random intercepts for participants were included in the model. The *lmerTest* package (Version 3.1-3) [50] was used to obtain *P*-values using Satterthwaite's approximation [51], and confidence intervals for the fixed effect estimates were obtained using the *effects* package (Version 4.2-0) [52]. Pairwise comparisons between each epoch were performed using the estimated marginal means (*emmeans*) package (Version 1.6.0) [53]. A Friedman test was used to compare the perceived stress level across all experimental conditions and pairwise post-hoc Wilcoxon signed-rank tests using a Bonferroni correction were also performed.

Analysis of HR data collected from Polar Verity Sense was performed by Poisson generalized linear mixed models (GLMM) through the *lme4* package in R to assess the difference in HR values between each epoch compared to baseline. We excluded HR values below 40 and above 200. RRI data retrieved from Polar H10 was analyzed by Kubios HRV premium software (version 3.3.1) to acquire both time-domain (RMSSD, SDNN, pNN50) and frequency-domain (HF, LF) components of HRV. Five-minute windows were used to obtain each component for each experimental epoch, and the median value across windows was calculated and used in analysis of each HRV measure was performed using linear mixed effects models following the same procedure described above for STAI-6.

The analysis of working memory assessments also used the same approaches to analyze unit score. The first three blocks of working memory tasks were excluded in analysis as the intention of these initial blocks was to let participants become familiar with the tasks and to plateau their performance so that the changes observed after the baseline epoch are more related to their stress and recovery. For both tasks, we did not exclude data which did not meet an accuracy threshold (i.e., 85%) on the processing components (math accuracy for OSPAN, symmetry accuracy for SSPAN) as recent studies have found that performance measures of such tasks were similar with and without applying such thresholds [54].

The beta power calculated from the EEG recordings was analyzed similarly to the HR data. Because some participant recordings were noisier than others, participant recordings needed to include at least 60 s of data (not equal to NaN) in each epoch. For each participant and each electrode, the beta power was averaged for the duration of the baseline, stress, and both recovery periods. Beta power was normalized for each participant by dividing the power for each epoch by the baseline beta power to measure the relative increase (or decrease) in power during the

stress and recovery epochs compared to baseline. The normalized beta power for each participant was compared between baseline, stress, and both recovery epochs using linear mixed-effects models (using the *pymer4* python package) [55].

From this data, an analysis of variance (ANOVA) was performed to assess the recovery conditions for control, visual, auditory, and visual and audio. An alpha level of 0.05 was set for determination of statistical significance and, where appropriate, a Tukey post-hoc analysis was performed to compare groups when the overall ANOVA p was less than 0.05.

RESULTS

Eighty healthy participants performed the stress induction task. Table 1 contains the relevant demographic information for the participants according to their group designation.

Perceived anxiety and stress levels increased during the stress induction task. As shown in Fig. 2, participants had an approximately 50% increase in state anxiety level after the stress induction task compared to baseline (linear mixed effects model ($P < 0.001$) which returned to baseline levels by the first recovery epoch ($P > 0.05$) and remained there in the second recovery epoch ($P > 0.05$). Participants' perceived stress followed a similar trend to their state anxiety levels ($P < 0.001$), with their perceived stress during the stress epoch greater than baseline ($P = 0.001$, Bonferroni-adjusted) but returning to levels similar to baseline by the first recovery epoch ($P > 0.05$).

Similar to the participant's reported anxiety level and perceived stress findings HR increased approximately 15% during stress epoch and cognitive assessments ($P < 0.05$) (Fig. 3). This increase in HR returned to the baseline level within the first couple of minutes into the first recovery epoch (Fig. 4). Heart rates during the stress induction task were >120% times higher compared to baseline which are similar to those seen in prior studies exploring stress induction [56–58].

Table 1. Descriptive statistics for relevant demographic information

	Sensory type			
	Control	Audio only	Visual only	Visual and audio
Age(median(range))	31(23–62)	32(22–61)	27(26–62)	33(19–61)
Gender				
Female	12	13	13	13
Male	8	7	7	7
Race/Ethnicity				
White or Caucasian	10	15	12	13
Asian or Asian American	8	3	6	4
Other	1	1	1	1
Prefer Note to Answer	1	1	1	1
Education				
College Graduate	11	12	10	8
Some College or Technical School	1	1	3	3
Other	0	1	0	2
Prefer Not to Answer	8	6	7	7

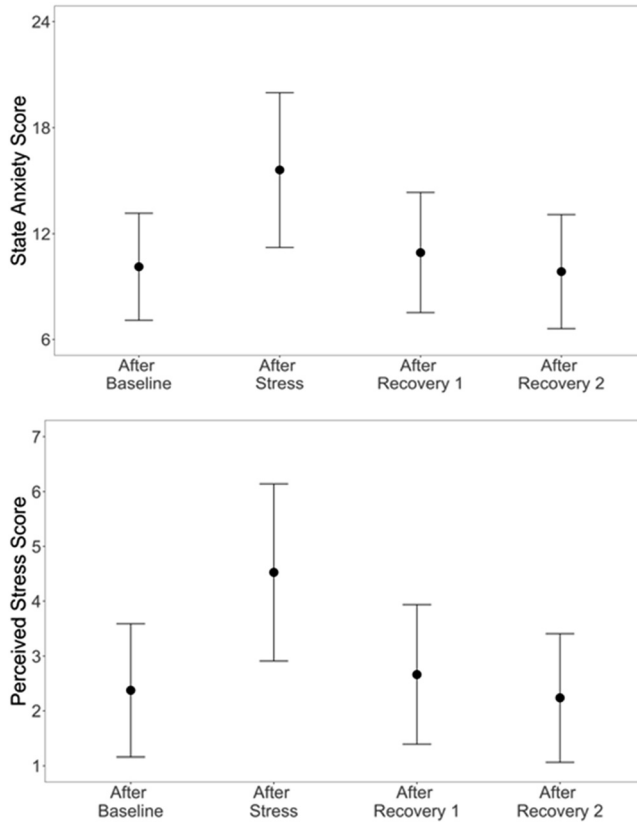

Fig. 2. Self-report of state anxiety (left) and perceived stress (right) level throughout the experimental session. Both levels significantly increased during the stress induction task and returned to the baseline levels by the recovery 1. For both scales, a greater number indicates a greater level of stress

We demonstrated a decrease in HRV with stress ($P < 0.05$, which is consistent with previous findings of stress induction). These changes in HRV (SDNN) returned to baseline post-intervention (Fig. 4). We found no significant differences in High frequency HF HRV nor in LF HRV power with stress induction.

As an exploratory analysis, we examined the time-series of the HF HRV power to determine when HRV deviated from baseline activity as an estimate of when participants showed signs of stress (Fig. 5). These data illustrate how the HF HRV power changes throughout the experiment session. We further measured the time relative to stress that each participant decreased from baseline epoch activity.

Mean stress onset of the participants was 165.94 ± 141.96 s (mean ± SD) relative to the start of the stress epoch. When examining the relationship between the stress onset time of HF HRV and the total duration of stress, later stress onset time negatively correlated with the total stress duration, $r = -0.73$, $P = 0.001$ (Fig. 6). Thus, individuals who experienced stress earlier also had a longer duration of stress and HF HRV was a persistent signal of stress lasting through

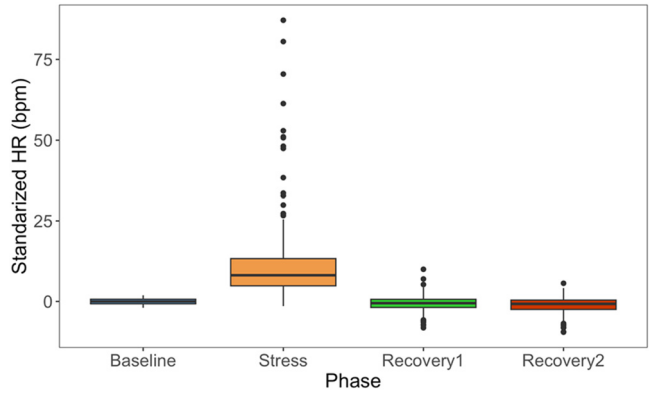

Fig. 3. Box and whisker representation of averaged heart rate values from Polar device for a given time. The *x*-axis is the intervention time (baseline, stress-induction, first recovery and second recovery and the *y*-axis is the heart rate (HR) normalized to a participant's baseline

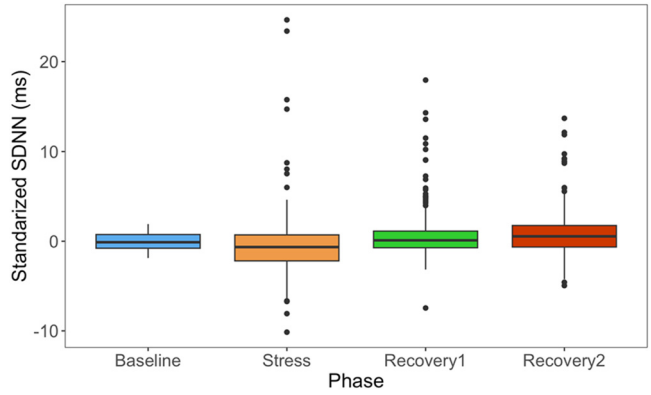

Fig. 4. Changes in median time-domain component of heart rate variability (HRV, SDNN) with a median and 25th and 75th percentile error bars. The *x*-axis is the intervention time (baseline, stress-induction, first recovery and second recovery and the *y*-axis is the HRV normalized to a participant's baseline

much of the stress epoch (as opposed to rapidly fluctuating above and below threshold). This approach provided a means of temporally characterizing how each person experienced stress throughout the experiment and suggests HF HRV power is a useful indicator of stress.

Beta power neural activity also increased during stress (Fig. 7), which is in agreement with previous work [12]. When analyzing across participants, beta power during stress was greater than baseline for the frontal electrodes (linear mixed-effects model, electrode F7: $P < 0.01$; electrode F8: $P < 0.02$) and for the occipital electrodes (electrode O1: $P < 0.001$; electrode O2: $P < 0.001$). However, for all electrodes there was no significant difference between the beta power during either recovery epoch and the baseline epoch, suggesting full recovery, post stress induction during both recovery periods.

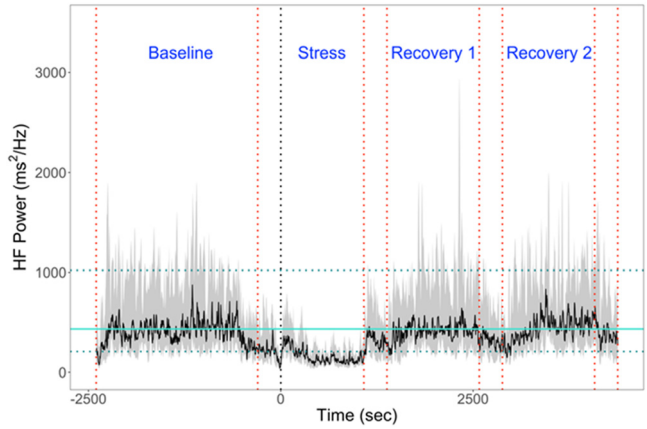

Fig. 5. Changes of high-frequency (HF) power throughout the experimental session. Time 0 indicates the start of the stress induction task. Median values are colored in black, 25th and 75th percentiles values are colored in gray, Median value from the entire baseline epoch is presented in horizontal turquoise line, dotted horizontal turquoise lines are represented 25th and 75th percentiles values from the baseline epoch

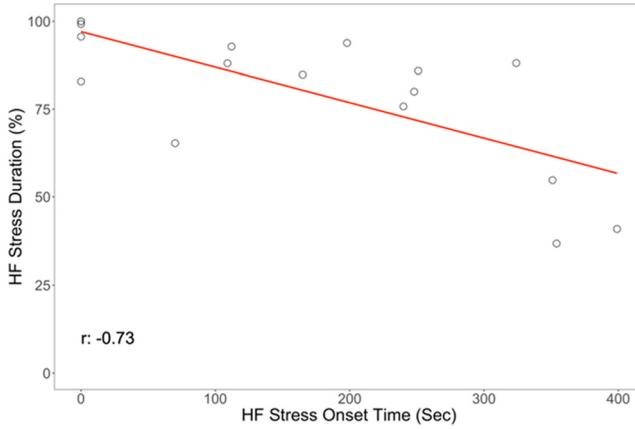

Fig. 6. Correlation between onset time of high-frequency (HF) heart rate variability (HRV) and duration of HF HRV below the threshold. Time 0 indicates the start of the stress induction task

We demonstrated no significant impact on working memory performance using the current stress-induction model (Fig. 8). Recent studies have found working memory is impaired by acute stress [20]. Here, participants completed the Operation SPAN (OSPAN) and Symmetry SPAN (SSPAN) working memory assessments to determine how performance changes before and after stress [48, 49]. Although the unit score for both OSPAN and SSPAN tasks decreased after the stress epoch compared to baseline, this decrease was not statistically significant (linear mixed effects model, $P > 0.5$ for all).

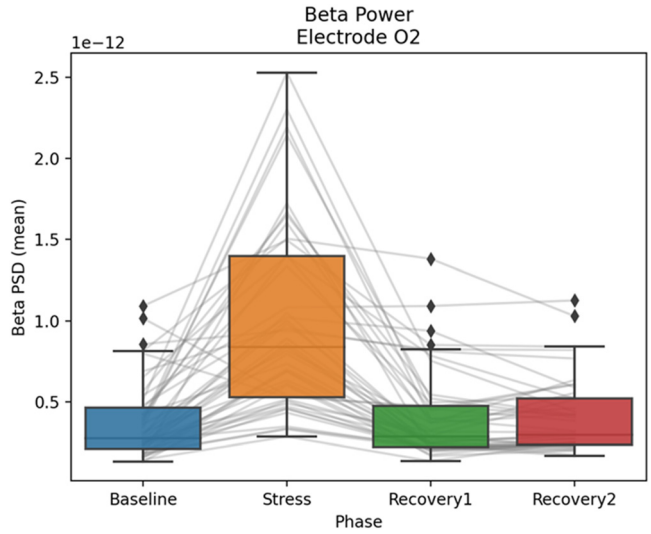

Fig. 7. Beta power measured during baseline, stress, recovery 1, and recovery 2 epochs. Boxplots for stress (orange), recovery 1 (green), and recovery 2 (red) show the increase in activity during the stress epoch. Individual traces are depicted in gray in the background to show the individual trends

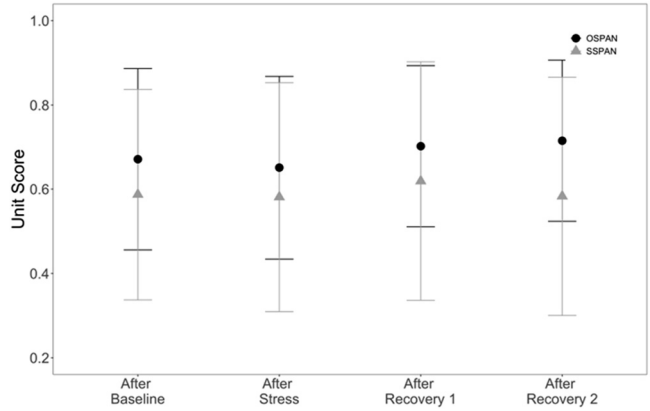

Fig. 8. Changes in working memory performance after baseline, stress, recovery 1, and recovery 2 epochs. Black circles indicate OSPAN unit scores, gray triangles indicate SSPAN unit scores

We found no statistical difference between anxiety scores (Fig. 9), HR normalized for baseline HR (Fig. 10), beta power neural activity (Fig. 11), nor working memory (Fig. 12) between the control, visual, auditory, or visual and auditory interventions.

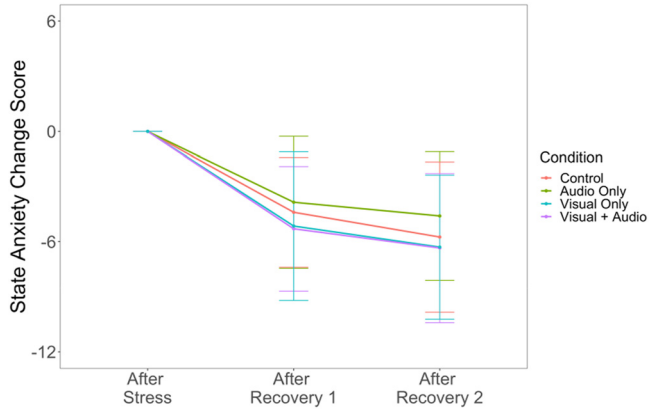

Fig. 9. Normalized changes in state anxiety score (SAS) (*y*-axis) following stress, during recovery 1, and during recovery 2 (*x*-axis). The red line indicates the control condition, the blue line represents the audio only intervention, the green line indicates the visual only intervention and the violet line indicates the audio and visual intervention combined

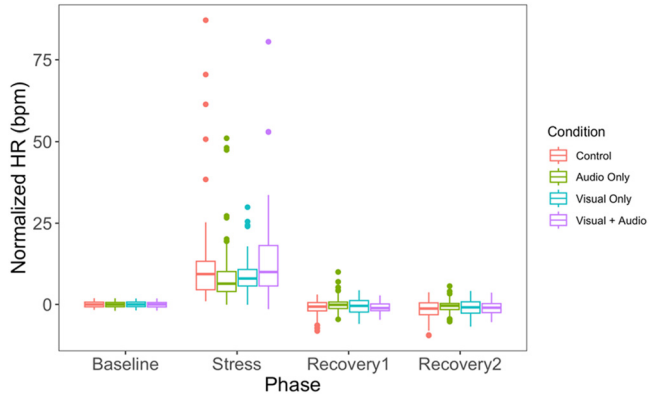

Fig. 10. Normalized changes in heart rate (HR) (*y*-axis) following stress, during recovery 1, and during recovery 2 (*x*-axis). The red line indicates the control condition, the blue line represents the audio only intervention, the green line indicates the visual only intervention and the violet line indicates the audio and visual intervention combined

DISCUSSION

In this study, we examined how recovery from stress can be influenced by visual and auditory interventions. For this, we assessed an individual's perceptions of stress and anxiety and quantified changes in heart rate, heart rate variability, neural activity, and working memory performance after acute stress. Using the well-validated TSST, individuals' perception of stress increased during the stress induction task which was to be expected [59]. When analyzing each

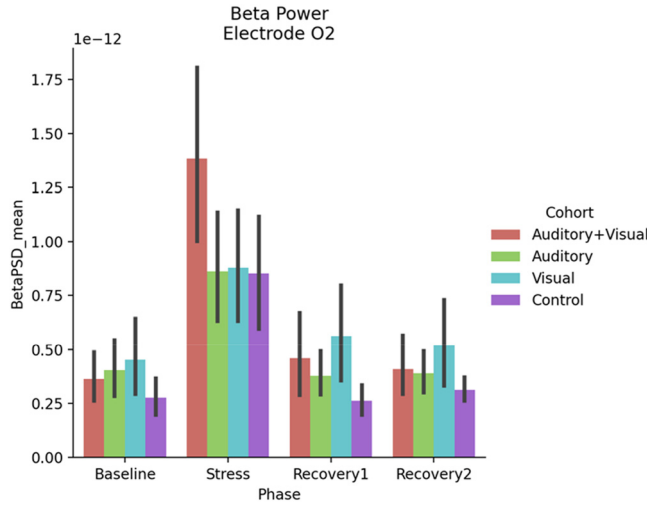

Fig. 11. Normalized changes in beta neural power (*y*-axis) with baseline and following stress, during recovery 1, and during recovery 2 (*x*-axis). The red line indicates the control condition, the blue line represents the audio only intervention, the green line indicates the visual only intervention and the violet line indicates the audio and visual intervention combined

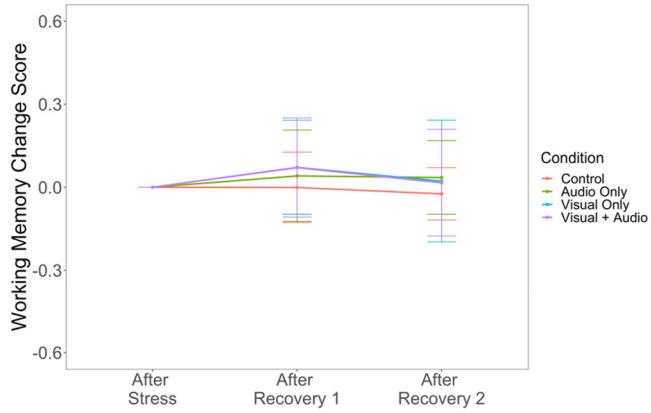

Fig. 12. Change in working memory score (*y*-axis) following stress, during recovery 1, and during recovery 2 (*x*-axis). The red line indicates the control condition, the blue line represents the audio only intervention, the green line indicates the visual only intervention and the violet line indicates the audio and visual intervention combined

physiological measure separately, neural activity (beta power) and HR each increased in response to the stressor, consistent with prior studies [60, 41, 57]. Temporal- and frequency-domain metrics of HRV decreased in response to stress, again consistent with prior studies

[61, 41, 62]. Thus, physiological and perceptual changes in response to acute social stress were accurately detected using the different wearable devices implemented here.

Previous work using relaxation rooms have been studied in stressful working environments, with some positive data [63, 30]. Similar to the present study, previous findings have shown that acute room usage leads to a decrease in perceived stress in nursing units [63]. A similar trial found that a 15-min exposure time reported a reduction in stress following room usage in a setting that utilized biophilic elements in clinicians during the COVID-19 Pandemic [30]. Further, a review of 14 articles demonstrated that the use of respite rooms resulted in improvements in feelings of stress during the COVID-19 pandemic [64]. In this review, the authors also describe that approximately 50% of clinicians who had an acute benefit of the respite rooms in these previous studies believed that long-term use would result in a decrease in burnout. While the present study is merely a start as to the environmental components of relaxation rooms that may guide relaxation, more robust work is needed to determine if there is minimal viable intervention that may be most effective.

Beta power over the occipital lobe has been shown to relate to visual attention and fatigue [65]. Neural activity from the occipital electrodes has been shown to increase in beta activity for fatigued doctors after working over 30 h of a call shift [66]. Here, we found that beta activity from occipital electrodes significantly correlated with individuals' perception of stress. Consistent with prior studies, we also found that beta activity from frontal electrodes increased in response to stress [12]. Interestingly, one's perception of stress did not correlate with frontal beta power. This could suggest that increases in frontal or occipital activity in response to stress are a good indicator that stress is occurring, however frontal activity is not an accurate indicator of one's awareness of stress.

We observed similar trends for cardiac activities. We found that increased HR was correlated with increased perceived stress levels as previous studies have demonstrated [57, 67]. Time-domain HRV metrics such as RMSSD and HF HRV power have been shown to decrease after stress [41]. As an exploratory analysis, we examined the time-series of the HF HRV power to determine when HRV deviated from baseline activity as an estimate of when individuals showed signs of stress. To our knowledge, few studies have examined the overall time course in which HRV power changes in response to stress. We further measured the time relative to stress that each participant decreased from baseline epoch activity. We used the 25th percentile of the HF HRV activity during the baseline epoch as our lower threshold as a measure of stress onset. Here, we defined stress onset to occur at the first instance when the HF HRV time-series decreased below this threshold for 60 s (the HF HRV time-series was sampled at 1 s intervals or 1 Hz). We also measured how long participants experienced stress based on how long the HF HRV was below this threshold. These measurements provided us with an estimate of when each participant began to experience stress and how long they experienced stress during the experiment.

Further, our data demonstrated that individuals who experienced stress earlier also had a longer duration of stress and HF HRV was a persistent signal of stress lasting through much of the stress epoch (as opposed to rapidly fluctuating above and below threshold). This approach provided a means of temporally characterizing how each person experienced stress throughout the experiment and suggests HF HRV power is a useful indicator of stress. One factor that could affect how participants performed the assessments was whether their job function was typically stressful, and they were accustomed to performing in these conditions. We ran the same linear

mixed effect model and found that including the job-related stress scale scores (which were assessed via survey at baseline) did not result in a significant difference due to stress ($P > 0.5$).

Previous studies have also demonstrated that stress can adversely affect working memory performance [20]. However, we did not find these a statistically significant result on these effects in this study. The lack of an effect of stress on working memory performance is potentially due to the task being too easy for participants to complete, or to the relatively small sample size. We examined whether participants were accustomed to working under stressful conditions in their job, but that did not significantly influence the cognitive performance unit scores over the course of the experiment. Additionally, we looked at how long it took each participant to perform the task and interestingly we found participants completed the tasks faster after stress. Previous studies have also found that participants react faster after a stressor, however this is often accompanied by an increase in performance errors [68]. Here, we did not detect any decrease in performance which further suggests the task was likely too easy to complete [67]. Future studies could potentially be performed to ensure that cognitive assessments are sufficiently difficult to be able to detect a change in performance after stress.

When analyzing the temporal changes in HR and HRV, we noticed that there were increases in HR and decreases in HRV during the cognitive assessments that were less than those observed during the stress induction task. This could have been indicative of different stress responses to different types of stress. The main stressor in the TSST is a socially evaluative situation during which one needs to speak in front of an audience. We included cognitive assessments to also track how performance changes throughout the task, but this also introduced a different form of stress, i.e., mental stress. Qualitatively, we noticed that physiological responses occurred during the cognitive assessments but were not the same response. There were consistent physiological responses to the mental stress of the cognitive assessments, but participants did not report significantly higher anxiety or stress compared to baseline after performing these assessments. Additionally, the increase in HR when performing the task appeared to be reproducible each time the tasks were completed (Fig. 5) whereas previous studies have suggested that repeated exposure to the TSST can reduce the observed effects to the stressor [69]. By having the cognitive assessments before and after the stress test, distinguishing between the mental stress and social stress effects and evaluating their potential interactions is challenging. Future studies could analyze how different types of stress elicit different physiological responses to better understand the underlying physiological mechanisms governing stress as well as how they relate to perceptions of stress. These findings would be critical to advance understanding of how to detect different types of stress more effectively in real-world environments.

Participants' perceived stress followed a similar trend to their state anxiety levels ($P < 0.001$), with their perceived stress during the stress epoch greater than baseline ($P = 0.001$, Bonferroni-adjusted) but returning to levels similar to baseline by the first recovery epoch ($P > 0.05$). These results are consistent with prior studies where both perceived stress and state anxiety increased significantly throughout the stress task [60, 70, 71].

LIMITATIONS

This study does have a number of limitations. Most importantly, one consideration for this study, and any study using a laboratory-controlled stressor, is whether these findings will

translate to real-world exposure to chronic stress. Multiple factors play a role in the stress responsivity of each person which could be masked by the effects from the TSST. Prior studies have found that the age of participants plays a role on the stress responsivity of the TSST [72]. In addition, job function (e.g., managerial vs. non-managerial position) and personality [58] could impact their stress response as well. The participants in this study were relatively young working professionals and doing a job interview may be more salient to younger professionals compared to older professionals. While TSST is a useful tool to invoke acute stress, it remains unclear how individuals react to such events in the real-world as individuals experience stress multiple times throughout a day from different stressors.

An additional limitation is the sole focus on beta power from the EEG data. Unfortunately, after data filtering, this data (within the 15-30HZ) was most robust. While this has been to be robustly associated with changes in stress in meta-analyses, further work with a more thorough EEG analysis is warranted, particularly because alpha bands have been shown to be associated with HRV changes [12]. Also, the EEG data demonstrated a rapid recovery, even prior to the interventions that focused on altering environmental inputs. This suggests a potential limitation for this to capture a potentially lagging recovery time, given the rapid recovery response.

CONCLUSION

These data support previous work that the TSST is an adequate method of stress induction. We were able to assess self-reported stress and anxiety, stress indicators from the cardiac and central nervous systems. We did not find that this stress impacted cognitive function, even in times of measured stress. We found that all of measured indicators of stress returned to baseline quickly and that there was no difference between the initial or second 20 min of recovery. Further, we found no statistical difference in the selected stimuli for the visual and auditory stimuli in the present study which we hypothesized to enhance stress recovery, with similar measured values with control, visual, auditory, and visual and auditory interventions. It is important to note that, given the relatively small sample size, and selection of only two environmental variables that the lack of difference in visual vs. auditory stimuli should be interpreted as preliminary. For Instance, there may have been small differences that were not statistically captured in the present study. Or, importantly, there may be individual differences in self-selection of stimulation type that is optimal for a person's relaxation. For instance, perhaps nature-mimicking sounds are not ideal for everyone (they may prefer quiet, or soft music). Because this study only controlled for two environmental inputs, and those two were the same for all individuals, future studies could focus more on individualized relaxation rooms for recovery.

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of Interest poses no additional significant risk to the welfare of participants in this research project or to the integrity of the research.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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