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Separating EEG correlates of stress: Cognitive effort, time pressure, and social-evaluative threat

Nina M. Ehrhardt[1,2,3] (iD) | Julia Fietz[4,5] | Johannes Kopf-Beck[1] | Nils Kappelmann[4,5] | Anna-Katharine Brem[1,6]

[1]Max Planck Institute of Psychiatry, Munich, Germany

[2]Maastricht University, Maastricht, The Netherlands

[3]Department of Neurology, Universitätsmedizin Greifswald, Greifswald, Germany

[4]Department of Translational Research in Psychiatry, Max-Planck-Institute of Psychiatry, Munich, Germany

[5]International Max Planck Research School for Translational Psychiatry (IMPRS-TP), Munich, Germany

[6]Berenson-Allen Center for Noninvasive Brain Stimulation, Division of Cognitive Neurology, Department of Neurology, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA

Correspondence
Nina M. Ehrhardt, Department of Neurology, Universitätsmedizin Greifswald, Ferdinand-Sauerbruch-Straße, 17475, Greifswald, Germany.
Email: nina.ehrhardt@uni-greifswald.de

Present address
Anna-Katharine Brem, University Hospital of Old Age Psychiatry, University of Bern, Bern, Switzerland and Department of Neuropsychology, Lucerne Psychiatry, Lucerne, Switzerland

Abstract

The prefrontal cortex is a key player in stress response regulation. Electroencephalographic (EEG) responses, such as a decrease in frontal alpha and an increase in frontal beta power, have been proposed to reflect stress-related brain activity. However, the stress response is likely composed of different parts such as cognitive effort, time pressure, and social-evaluative threat, which have not been distinguished in previous studies. This distinction, however, is crucial if we aim to establish reliable tools for early detection of stress-related conditions and monitoring of stress responses throughout treatment. This randomized cross-over study ($N = 38$) aimed to disentangle EEG correlates of stress. With linear mixed models accounting for missing values in some conditions, we found a decrease in frontal alpha and increase in beta power when performing the Paced Auditory Serial Addition Test (PASAT; cognitive effort; $n = 32$) compared to resting state ($n = 33$). No change in EEG power was found when the PASAT was performed under time pressure ($n = 29$) or when adding social-evaluative threat (video camera; $n = 29$). These findings suggest that frontal EEG power can discriminate stress from resting state but not more fine-grained differences of the stress response.

KEYWORDS

EEG, frontal alpha activity, frontal beta activity, Paced Auditory Serial Addition Test, stress

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1 | INTRODUCTION

The incidence of stress-related disorders such as depression, anxiety, and cardiovascular disease is rising. Reliable tools to measure physiological stress responses are needed to allow for early detection of stress-related conditions and monitoring of stress responses throughout treatment (Al-Shargie et al., 2018; Arza et al., 2018). Neural activity, assessed via electroencephalography (EEG), has been suggested as a marker of stress. Its high temporal resolution and direct measurement of neural processes (Cohen, 2004) could be advantagous over the current gold standard, neuroendocrine stress response measurements (e.g., cortisol), that are temporally delayed.

In line with the role of the prefrontal cortex (PFC) in stress response regulation (Herman et al., 2003; McEwen & Gianaros, 2011), changes in the rhythmicity of EEG activity in the PFC have been suggested as stress markers (Alonso et al., 2015; Al-Shargie et al., 2018; Lewis et al., 2007). Specifically, (a) alpha power (8–13 Hz) is thought to decrease because of its association with relaxation and inverse relation to cognitive activity (Klimesch, 1999), while (b) beta power (13–30 Hz) is thought to increase in response to stress (Tran et al., 2007) due to its association with information processing and anxiety (Stern & Engel, 2013). Studies to date largely confirm this hypothesis of oscillatory changes in frontal alpha (decrease) and beta (increase) power during or after applying stressors such as exam stress (Lewis et al., 2007), sleep deprivation (Alonso et al., 2015), and during the presentation of negative images (Seo & Lee, 2010), and also so-called cognitive stressors such as the Stroop task (Alonso et al., 2015), mental arithmetic (Al-Shargie et al., 2016, 2018), and combinations thereof (e.g., a cognitive task in combination with a stressful public speaking task) (Secerbegovic et al., 2017). However, other frequency bands might also capture stress signatures. Stress differentially affects frontal midline theta (FMT) activity, which has been related to cognitive processes. FMT is decreased (Gärtner et al., 2014) and delayed (Gärtner et al., 2015) during working memory processes in response to stress, whereas it increases after negative feedback following stress (Paul et al., 2018). Combining changes in low frequencies with higher frequencies, Minguillon et al. (2016) have shown that frontal relative gamma power correlates with stress. Additionally, gamma power is increased among patients with depression, compared to controls, and similarly in students during examination stress (Strelets et al., 2007), also pointing towards increased gamma activity due to stress.

Previous studies investigating frontal EEG power examined different stressors, but neither the assessed stressors nor included standardized stress tasks such as the Trier Social Stress Task (Kirschbaum et al., 1993) or the Montreal Imaging Stress Task (Dedovic et al., 2005) distinguish between potentially different stress-related effects such as cognitive effort, time pressure, and social-evaluative threat. Social-evaluative threat refers to the possibility of being judged negatively (e.g., feedback, public speaking task), while time pressure represents uncontrollability as the situational outcome cannot be influenced (Dickerson & Kemeny, 2004). This raises the question which portions of the stress response are actually reflected in the reported oscillatory changes (Al-Shargie et al., 2016; Secerbegovic et al., 2017). This is particularly relevant when applying cognitive stressors, as both alpha (Klimesch, 1999) and beta power (Stern & Engel, 2013) decrease and increase, respectively, with cognitive activity. Changes in the theta band are investigated in relation to a cognitive process affected by stress, effects of stress on alpha and beta activity are directly assessed, and more commonly mixed with cognitive proportions of stress than effects on gamma activity. Therefore, previous results, especially regarding alpha and beta power, applying cognitive stressors might reflect differences in cognitive effort rather than stress itself.

The EEG response to social-evaluative threat and time pressure is especially interesting as these stressors are commonly encountered in daily life and, therefore, possess high external validity. They are also relevant for stress-related disorders such as depression and anxiety and have been linked to symptom severity (Hofmann, 2007; Kupferberg et al., 2016; Ramos-Cejudo & Salguero, 2017; Yılmaz et al., 2011).

We aimed to investigate the brain correlates of stress by studying differential effects of cognitive effort, time pressure, and social-evaluative threat on EEG oscillations. A cognitive task (i.e., the Paced Auditory Serial Addition Test, PASAT) was applied as a stressor and sequentially complemented with time pressure and social-evaluative threat as additional stress-inducing components. We focused on the effects of alpha and beta power as these are commonly investigated in the stress literature with mixed cognitive and other stressors. As frontal alpha and beta activity are mainly associated with cognitive processing, we hypothesized that power in the alpha band decreases and power in the beta band increases when performing the PASAT compared to resting state, and further decreases (alpha) or increases (beta) when performing the task under time pressure, but not when social-evaluative threat, a more affective stressor, is added.

2 | MATERIALS AND METHODS

2.1 | Participants

Thirty-eight healthy participants (19 women) between 18 and 50 years (25.76 ± 6.03) were recruited in Munich, Germany, through flyers and online platforms at the Ludwig-Maximilians University Munich, Technical University

Munich, and the Max-Planck Institute of Psychiatry. The majority (n = 36) of the sample was right-handed. Twenty-nine participants were native German speakers (mean education 16.53 ± 3.04 years). Exclusion criteria were acute or chronic medical conditions, current or past neurologic or psychiatric disorders, taking medication that might alter the EEG measures (e.g., anxiolytics, antidepressants), or insufficient proficiency in German. Participants underwent all experimental conditions (within-subject design), were naïve to the purpose of the experiment, participated voluntarily, and provided written informed consent. At the end of the visit, participants were debriefed and received 10€ as reimbursement. The study was conducted in accordance with the declaration of Helsinki, except pre-registration, and approved by the ethics committee of the Ludwig-Maximilians University Munich, Germany.

2.2 | Materials and design

The German version of the PASAT (Gronwall & Sampson, 1974) was applied to induce stress. It involves listening to a sequence of digits and adding the current number to the previous digit. It is perceived as stressful (Tombaugh, 2006) and has previously been used as a stressor (Lejuez et al., 2003). The PASAT was performed in three conditions with 60 trials each (see Figure 1).

In the cognitive effort condition, the PASAT was performed with a 3-s inter-stimulus interval (ISI). In the time pressure condition (PASAT + time), the PASAT was performed with a shorter, hence more stressful, time limit. This shorter ISI of 1.2 s produces a lower percentage of correct responses ranging from 50% to 60% (Tombaugh, 2006), indicating that performance is unpredictable and—due to the continuous nature of the task—uncontrollable. In the time pressure + social-evaluative threat condition (PASAT + time + social-evaluative threat), a camera was placed in front of the participant (replacing the fixation point) and evaluation of performance and behavior was announced to impose additional social-evaluative threat.

To account for common practice effects in the PASAT (Tombaugh, 2006), and to prevent carry-over effects of stress, the three different PASAT conditions were performed in counterbalanced order. Participants were randomly assigned to one of six possible orders. Due to the longer ISI, the PASAT-only condition yielded 3 min of data, while the shorter ISI in the PASAT + time and the PASAT + time + social-evaluative threat condition resulted in 72 s of data. However, each condition contained the same amount of trials and was of sufficient duration for analysis.
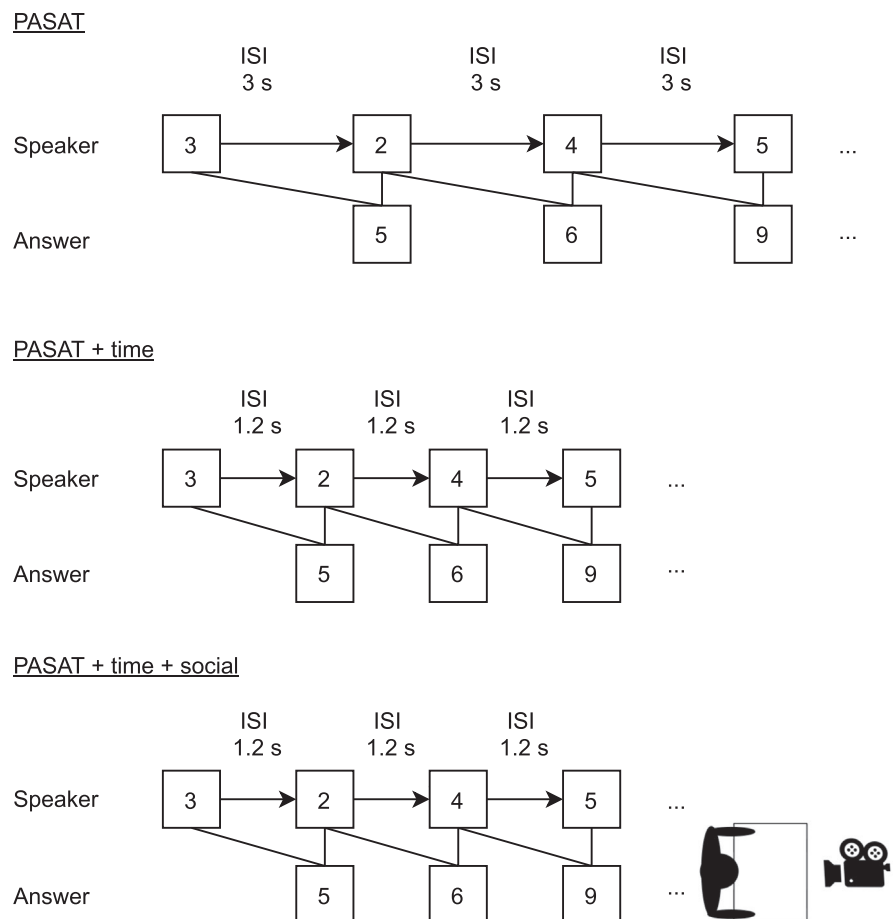

FIGURE 1 Paced Auditory Serial Addition Test (PASAT) conditions. In the cognitive-load condition, the PASAT was performed with a 3-s inter-stimulus interval (ISI). In the time pressure condition (PASAT + time), the ISI was set to 1.2 s. In the social-evaluative threat condition (PASAT + time + social), the ISI remained at 1.2 s, a video camera was placed in front of the participants, and evaluation of the video material was announced

2.3 | Procedure

The study procedure is depicted in Figure 2. Participants were seated in a comfortable chair with their hands resting in their lap. Resting-state frontal EEG (eyes-closed) was measured during a 3-min period and the PASAT was explained and practiced (10 trials without time limit). Next, the three experimental conditions (PASAT; PASAT + time; and PASAT + time + social-evaluative threat) were performed in counterbalanced order while participants were asked to fixate a point. After resting state and each of the PASAT conditions, participants rated subjective stressfulness, difficulty, and concentration on a visual analogue scale (VAS).

2.4 | EEG data acquisition and processing

Frontal EEG signals were measured using a Starstim wireless EEG system (Neuroelectrics). We chose this system as it is easy and quick to set up, an important prerequisite for clinical tools to detect stress-related conditions and monitor stress responses throughout treatment. As hypotheses pertained to frontal brain activity, six electrodes (1.4 cm^2, Ag/AgCl coated) were inserted into a neoprene cap on positions F7, F3, Fz, FPz, F4, and F8 according to the international 10-10 system of electrode placement after the scalp was cleaned with abrasive gel (Nuprep, Weaver and Company). Gel-filled electrodes (SignaGel, Parker) were used to minimize impedance. A diagonal setup was used to measure vertical and horizontal eye movements with two additional electrodes placed next to the right and left eye. Two electrodes behind the right ear served as reference electrodes. The signal quality index of the Neuroelectrics system, taking into account drift, offset, line, and main noise, was kept below 0.7 indicating medium-to-good signal quality (Neuroelectrics, 2019). EEG data were sampled at a frequency of 500 Hz and processed using custom Matlab scripts (The Mathworks; see Supporting Information) and EEGLab (Delorme & Makeig, 2004). A high-pass filter was applied at 0.5 Hz to reduce slow drifts and a notch filter of 50 Hz was applied to remove line noise. No low-pass filter was applied (see Supporting Information Methods for sensitivity analyses with a bandpass filter between 0.5 and 48 Hz). Independent components analysis (ICA) was used to manually remove components representing eye blink artifacts. Because ICA is less reliable with a small number of electrodes, the data were visually inspected for remaining blinks and other artifacts. Recordings from conditions in which <70% of the data remained after artifact rejection were excluded from further analysis. On average, 96% artifact-free data of the resting-state condition, 89% of the PASAT condition, 85% of the PASAT + time condition, and 86% of the PASAT + time + social-evaluative threat condition were retained. The amount of rejected data differed between conditions ($F(1,88) = 9.08$, $p < 0.001$) with resting state differing significantly from the task conditions ($t(37)$'s > 4.62, p's < 0.001). EEG data of four individuals were removed due to reduced data quality across conditions. Data from individual conditions in 10 participants were removed due to low data quality or exceedance of our artifact rejection threshold (one resting condition, two PASAT conditions, five PASAT + time conditions, and five PASAT + time + social-evaluative threat conditions). This resulted in $n = 33$ for Resting state, $n = 32$ for the PASAT condition, $n = 29$ for the PASAT + time condition, and $n = 29$ for the PASAT + time + social-evaluative threat condition. Excluded participants did not differ significantly from the rest of the sample regarding age, gender, VAS, and task performance and sensitivity analyses performed without them left our main findings substantially unchanged (see Table S3). Remaining data were segmented into non-overlapping epochs of 1 s. Then, frequency band power was extracted from electrodes F7, F3, Fz, FPz, F4, and F8 according to standard frequency bands: alpha (8–13 Hz) and beta (13–30 Hz) with the FieldTrip toolbox (Oostenveld et al., 2011) using Fast Fourier Transform with a Hanning window to decrease leakage. Next, mean power for alpha and beta activity during each condition was calculated and log-transformed to correct for non-normal distribution of power values due to the power law (Kiebel et al., 2005).

2.5 | Statistical analysis

To account for missing data due to artifacts in the EEG recordings and non-independence of measurements due to a within-subjects design, mixed linear models (Baayen et al., 2008)
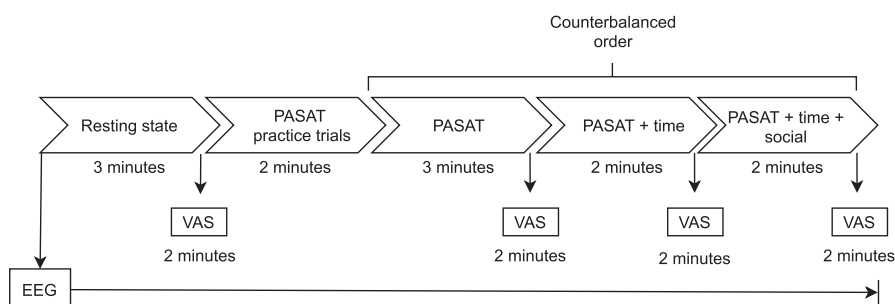

FIGURE 2 Study procedures. EEG, electroencephalographic; PASAT, Paced Auditory Serial Addition Test; VAS, visual analogue scale

were used for hypothesis testing using *R* software (R Core Team, 2019) and the *lme4* package (Bates et al., 2015) (see Supporting Information for script). First, linear mixed models for each outcome variable (log-alpha and log-beta power) were estimated using maximum likelihood estimation. We compared linear mixed effects models with a random by-subject intercept only versus a model including condition as predictor and used likelihood ratio tests to test for the effect of condition. Here, condition was dummy coded with cognitive effort condition as reference category to examine the effect of time pressure and social-evaluative threat as additional stressors. Assumptions of normality, linearity, and homoscedasticity were evaluated. Order of condition was not included in the model due to identifiability problems. However, the data points in condition by order groups did not suggest that an effect of condition order on performance, VAS, or power values was likely (see Supporting Information). The final model was re-estimated using restricted maximum likelihood estimation. The *influence.ME* package (Nieuwenhuis et al., 2012) was used to test for outlying residuals and influential cases. Two influential cases for the difficulty model were identified but excluding them from the analysis did not change the pattern of results, generally indicating a highly stable pattern of results. Therefore, all participants were included in the reported results. Pairwise comparisons using the *glht* function of the *multcomp* package (Hothorn et al., 2008) were performed to examine differences between the conditions with Tukey's honestly significant difference (HSD), which corrects for multiple post-hoc testing and is a relatively conservative approach (Abdi & Williams, 2010). Comparison of cognitive effort and time pressure condition was performed for the effect of time pressure, while the comparison of time pressure with time pressure + social-evaluative threat indexed the effect of social-evaluative threat.

Similar mixed-effects analyses were performed with task performance, perceived stress, difficulty, and concentration (without prior log-transformations) for all participants ($n = 38$) to check whether the stress manipulation influenced these outcomes.

3 | RESULTS

3.1 | Task characteristics

Final mixed regression results for task performance and VAS are reported in Table S4 and we summarize results below.

3.1.1 | Task performance

Comparing the mixed regression models with and without condition as predictor showed that condition significantly predicted task performance ($\chi^2 = 156.49$, $df = 2$, $p < 0.001$).

Task performance was highest for the PASAT condition with an average of 78% ($SD = 17.47$) correct answers. Pairwise comparisons using Tukey's HSD revealed that task performance in conditions with added stressors was significantly lower (all $p < 0.001$) than in the PASAT condition with 34% ($SD = 15.16$) mean correct answers in the time pressure condition and 35% ($SD = 13.87$) mean correct answers in the social-evaluative threat condition. However, task performance was not significantly different between time pressure and additional social-evaluative threat conditions ($p = 0.871$).

3.1.2 | Visual analogue scales

Perceived difficulty, stress and self-reported concentration are illustrated in Figure 3.

Regarding perceived stress, the mixed regression models with and without condition as predictor significantly differed from each other ($\chi^2 = 155.17$, $df = 3$, $p < 0.001$). Pairwise comparisons with Tukey's HSD showed a significant difference in perceived stress between resting state and PASAT, PASAT + time, and PASAT + time + social-evaluative threat condition (all $p < 0.001$), such that resting state was perceived as less stressful than the PASAT conditions. Additionally, the PASAT + time and PASAT + time + social-evaluative threat conditions differed significantly from PASAT only (all $p < 0.001$), indicating that added stressors were perceived as more stressful than the PASAT-only condition. However, the PASAT + time and PASAT + time + social-evaluative threat conditions ($p = 0.457$) did not differ significantly from each other, showing that time pressure increased the perceived stressfulness of the PASAT, while social-evaluative threat did not.

Regarding task difficulty, we observed a similar pattern of results with conditions differing significantly ($\chi^2 = 233.77$, $df = 3$, $p < 0.001$). All pairwise comparisons between conditions, except PASAT + time versus PASAT + time + social-evaluative threat, indicated significant differences following Tukey's HSD (all $p < 0.001$) with difficulty increasing from Resting to PASAT to time pressure and social-evaluative threat.

Regarding concentration, we again observed significant differences between conditions ($\chi^2 = 33.28$, $df = 3$, $p < 0.001$). Pairwise comparisons revealed significant differences between Resting and all PASAT conditions (all $p < 0.01$). However, none of the PASAT conditions differed significantly from each other (all $p > 0.05$).

3.2 | EEG data

The mean power values of alpha and beta activity for each condition are depicted in Figure 4 and the final mixed regression models for log-alpha and log-beta are shown in Table 1.
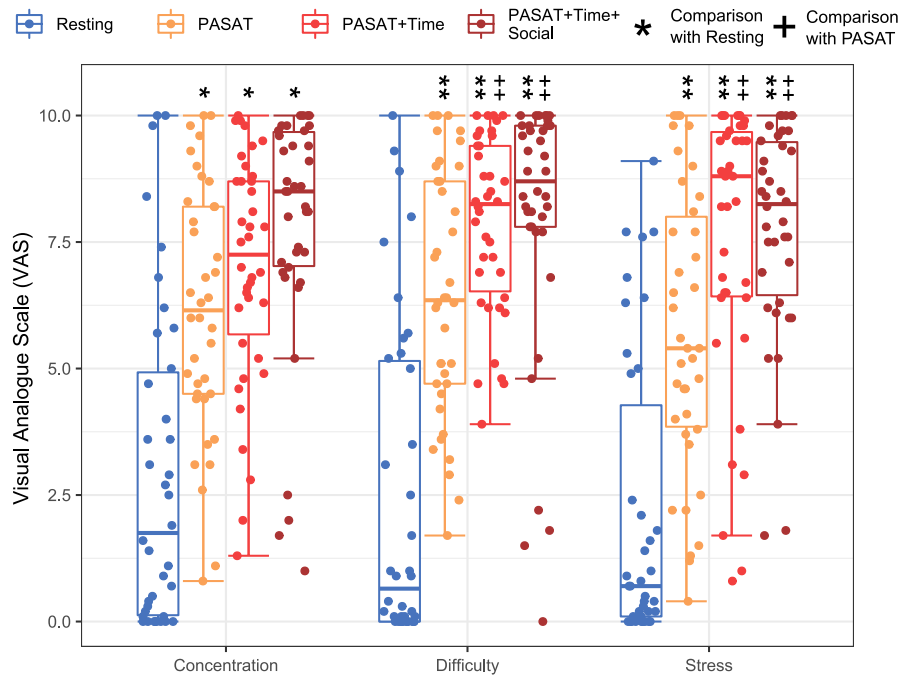
FIGURE 3 Mean perceived difficulty, perceived stress, and self-reported concentration for each condition with error bars indicating the first and third quartile. Outliers are defined as values above or below 1.5 times the interquartile range. *Note*. PASAT, Paced Auditory Serial Addition Test; VAS, visual analogue scale. PASAT + time = PASAT under time pressure. PASAT + time + social = PASAT under time pressure with social-evaluative threat. *Comparsion with resting state significant at $p < 0.01$, **comparison with resting state significant at $p < 0.001$, +comparison with PASAT significant at $p < 0.01$, ++comparison with PASAT significant at $p < 0.001$, and comparisons between PASAT + time and PASAT + time + social were not significant
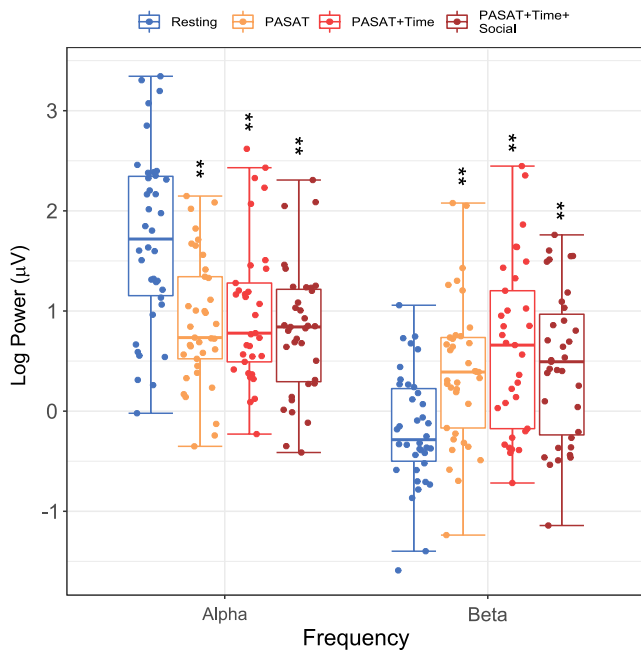

FIGURE 4 Boxplots of frontal alpha and beta power during each condition with error bars indicating the first and third quartile. Outliers are defined as values above or below 1.5 times the interquartile range. *Note*. PASAT, Paced Auditory Serial Addition Test. PASAT + time = PASAT under time pressure. PASAT + time + social = PASAT under time pressure with social-evaluative threat. **$p < 0.001$

3.2.1 | Frontal alpha activity

Condition significantly predicted log-alpha power ($\chi^2 = 75.14$, $df = 3$, $p < 0.001$). In line with our hypothesis, pairwise comparisons using Tukey's HSD revealed that alpha power in resting state differed significantly from alpha power in the PASAT ($p < 0.001$), the PASAT + time ($p < 0.001$), and the PASAT + time + social-evaluative threat conditions ($p < 0.001$), such that alpha power in resting state was significantly higher than in the different PASAT conditions. In contrast to our hypothesis on decreased alpha power under time pressure, the PASAT condition did not differ significantly from the PASAT + time condition ($p = 0.999$). As we expected, the PASAT + time and PASAT + time + social-evaluative threat conditions did not differ significantly from each other ($p = 0.912$). Analyses further exploring the finding that stress conditions do not differ from each other are reported in the Supporting Information Results.

3.2.2 | Frontal beta activity

Condition also significantly predicted log-beta power ($\chi^2 = 36.92$, $df = 3$, $p < 0.001$). As hypothesized, beta power differed significantly between resting state and the PASAT, the PASAT + time, and the PASAT + time + social-evaluative

TABLE 1 Mixed regression models of log-transformed mean alpha power and beta power at electrodes F7, F3, Fz, FPz, F4, and F8 with random by-subject intercept with cognitive effort condition as reference category

Condition	Log-alpha power (μV)			Log-beta power (μV)		
	β	SE	Sig.[a]	β	SE	Sig.[a]
Intercept	0.81	0.12		0.25	0.11	
Rest	0.90	0.10	<0.001	−0.48	0.11	<0.001
PASAT + time	0.02	0.11	0.999	0.20	0.11	0.270
PASAT + time + social	−0.06	0.11	0.953	0.06	0.11	0.938

Note: PASAT + time = PASAT under time pressure. PASAT + time + social = PASAT under time pressure with social-evaluative threat.

Abbreviations: HSD, honestly significant difference; PASAT, Paced Auditory Serial Addition Test.

[a]The *p*-value for the pairwise comparison with the PASAT condition following Tukey's HSD correction.

threat conditions (all *p*'s < 0.001), such that beta power was significantly higher during the PASAT conditions compared to resting state. There was neither a significant difference between the PASAT and PASAT + time conditions (*p* = 0.270) nor between the PASAT + time and PASAT + time + social-evaluative threat conditions (*p* = 0.629). Additional analyses on the finding that stress conditions do not differ from each other are reported in the Supporting Information Results.

4 | DISCUSSION

Previous studies investigating EEG correlates of stress administered different stressors, including cognitive stressors, hereby neglecting that cognitive activity per se induces similar oscillatory changes. Previous measures also precluded a differentiation of more fine-grained effects of stress. The current study investigated frontal EEG activity in response to stress such as cognitive effort, time pressure, and social-evaluative threat. As hypothesized and in line with research showing that cognitive activity is related to a decrease in alpha and an increase in beta activity in task-related brain areas (Klimesch, 1999; Stern & Engel, 2013), we found significantly reduced alpha and significantly increased beta power following stress induced by a cognitive stressor (PASAT) compared to resting state. Other stressors (i.e., time pressure and social-evaluative threat) were not associated with changes in these EEG measures.

Regarding working memory, decreased frontal alpha power has been observed during encoding, while it increased during retention and manipulation of information in working memory (Sauseng et al., 2005; Wianda & Ross, 2019). An increase in alpha power has been interpreted as a possible mechanism of inhibition of task-irrelevant brain areas (Klimesch et al., 2007). The PASAT is not a suitable task to make a distinction between encoding and retention and the averaged power over the whole task likely represented a general decrease in alpha power in response to cognitive activity in the current study.

Adding time pressure or social-evaluative threat resulted in a similar oscillatory response to the cognitive task alone and

therefore did not reflect the self-reported increase in perceived stress. It cannot be ruled out that the alpha suppression and beta increase in response to the cognitive task alone were elicited by looking at the fixation cross rather than by performing the PASAT, possibly mixing the effects of eyes opening and task performance as there was no eyes-open resting-state condition to compare it to (Barry et al., 2007). However, a decrease in alpha activity with opening of the eyes is primarily observed in posterior regions (Klimesch et al., 2007). Additionally, in line with our results, an earlier study using a driving simulator task (Tran et al., 2007) reported a task-related decrease in frontal alpha activity compared to eyes-open resting state, while there was no significant difference when performing the task with versus without additional stressors. A recent study (Woody et al., 2018) differentiated the effects of social-evaluative threat from effects of cognitive effort on salivary cortisol measurements. Adding cognitive effort during the task of giving a speech (i.e., count the number of tones presented concurrently) did not add to the stress response, indicating that social-evaluative threat is likely central in eliciting a neuroendocrine stress response. This contrasts with our results showing that the central stressor is cognitive effort, while social-evaluative threat and time pressure did not further modulate the oscillatory pattern. The discrepant results between the studies possibly reflect the more passive nature of the added stressors (i.e., counting tones as a cognitive stressor and adding a camera as social-evaluative stressor), while the main stressors were active tasks (i.e., giving a speech as social-evaluative stressor and PASAT as cognitive stressor). These results underline that a distinction of different stress components is important.

Additionally, the effects of stress could possibly be observed only at specific time points after the stressful event. Regarding theta activity, this effect was stronger in late time windows after presentation of a stressful arithmetic task (Gärtner et al., 2014, 2015), suggesting an underlying cognitive effect. Unfortunately, the short ISI in our stress conditions prevented explorations of event-related frequency analyses, which have to be investigated in future studies with longer ISI (while maintaining the perceived stressfulness of the conditions).

Our findings demonstrate that while the tasks used were adequate to induce stress (reflected in the subjective measures), EEG measures are not appropriate to distinguish different stressors such as time pressure and social-evaluative threat from a cognitive stressor. This difference from previous studies, which did find an effect of stress on alpha and beta activity, could be due to the missing distinction between cognitive effort and other stressors.

4.1 | Limitations

We measured brain activity with six electrodes and used the Neuroelectrics' signal quality index, which considers drift, offset, line, and main noise, but does not provide a direct physical measure of impedance. This setup is advantageous for clinical use but limits the comparability with other studies using classical EEG setups, more electrodes, and impedance check. However, our findings reliably replicated overall resting versus stress effects, thus suggesting validity of our EEG setup. We observed differences in artifact rejection rates between resting-state and stress conditions. While our findings were robust across sensitivity analyses, these differences could have biased our results. Therefore, future studies should replicate our findings with classical setups and broader EEG coverage. Due to the reference electrode setup, laterality of alpha activity could not be investigated. Several studies investigating laterality of frontal alpha activity in response to stress reported increased right versus left frontal activation (Al-Shargie et al., 2018; Hamid et al., 2015; Lewis et al., 2007; Lopez-Duran et al., 2012; Zhang et al., 2018), suggesting that frontal alpha asymmetry could provide a measure of stress. However, other studies did not replicate this asymmetry (Alonso et al., 2015; Quaedflieg et al., 2015).

The stress conditions had two limitations. First, the 3-s interval in the cognitive effort condition was already perceived as stressful and might therefore already include a time pressure proportion. This could be controlled for by including several ISIs, no fixed ISI, or a less time-sensitive cognitive condition. Second, the social-evaluative threat condition was not perceived as stressful by all participants, indicating that the operationalization of this part might have depended too much on participant characteristics. More explicit social-evaluative stress involving more direct human interaction or active participation would have likely resulted in stronger effects. Additionally, a more objective measure of stressfulness such as cortisol could add valuable information. However, due to the counterbalanced within-subject design and as cortisol responses occur with delay, the conditions would not have been distinguishable in the current study.

Participants indicated to be less concentrated during the PASAT under time pressure, which might partly explain an increase in alpha activity. It is possible that participants therefore detached from the task, indicating that the chosen time pressure might have been too high. Future studies should analyze correct versus incorrect trials to better distinguish the effects of time pressure and cognitive effort. Although a camera could act as distraction, thereby also interacting with the cognitive stressor, this was not reflected in perceived difficulty ratings. Social-evaluative threat could therefore be distinguished from cognitive effort. Finally, because there was no condition with social-evaluative threat only, our design did not allow independent exploration of effects of time pressure and social-evaluative threat. Future studies could incorporate a condition with social-evaluative threat only to separate it from the effect of time pressure.

5 | CONCLUSION

In conclusion, we found a decrease in alpha and increase in beta activity in response to a stressful cognitive task. This is likely an effect of cognitive effort, rather than stress, as the addition of different stressors to the task, namely time pressure and social-evaluative threat, did not influence the EEG measures that have previously been proposed as measures of stress. A possible reason might be the missing distinction of stress and cognitive effort in previous research investigating stress and frontal EEG activity. Future studies should further investigate different components of stress and their interactions in healthy individuals and psychiatric patients with disorders known to be associated with disturbed stress responses.

AUTHOR CONTRIBUTIONS
Conception and design: A.-K.B., N.E., J.F.; Data acquisition: N.E.; EEG analysis: N.E., J.F., N.K.; Statistical analysis: N.E., N.K., J.F.; Writing of the first draft: N.E.; Writing—review and editing: N.K., A.-K.B., J.K.-B., J.F.

PEER REVIEW
The peer review history for this article is available at https://publons.com/publon/10.1111/ejn.15211.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Nina M. Ehrhardt https://orcid.org/0000-0002-8653-4323

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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