

How stereotype threat affects the brain dynamics of creative thinking in female students

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ABSTRACT

When people are placed in a situation where they are at risk of substantiating a negative stereotype about their social group (a scenario termed stereotype threat), the extra pressure to avoid this outcome can undermine their performance. Substantial and consistent gender disparities in STEM fields leave women vulnerable to stereotype threat, including the stereotype that women are not as good at generating creative and innovative ideas as men. We tested whether female students' creative thinking is affected by a stereotype threat by measuring power in the alpha frequency band (8–12Hz oscillations) that has been associated with better creative thinking outcomes. Counter to expectations that a stereotype threat would reduce alpha power associated with creative thinking, analyses showed increased alpha power following the introduction of the stereotype threat. This outcome suggests that women may have attempted to increase their internal attention during the task in order to disprove the stereotype. Behaviorally, this effort did not lead to changes in creative performance, suggesting that the stereotype threat decoupled alpha power from creative thinking outcomes. These results support a growing school of thought in the neuroscience of creativity literature that the alpha power often seen in conjunction with creative behavior is not necessarily related to the creativity processes themselves, but rather might be part of a larger network modulating the distribution of attentional resources more broadly.

1. Introduction

Creative thinking is a key ingredient for a successful career, with the need for generating novel and innovative solutions to real-world problems typically posing a greater challenge than finding simple correct solutions to schoolwork-type problem sets (e.g., Cropley, 2016; Puccio, 2017). A growing literature has used creativity (e.g., divergent thinking (DT); Guilford, 1967) tasks, in which people generate as many creative ideas for an open-ended prompt as possible, to examine neural processes associated with creative thinking. Work with EEG (electroencephalogram) recordings of ongoing neural oscillations show that increased creative ideation is associated with higher alpha power (centered around 10Hz; Fink and Benedek, 2014; Jausovec, 2000; Martindale and Mines, 1975). The present study examined whether creative ideation is sensitive to social factors, i.e., stereotype threat that has been

ubiquitously found to influence academic performance (Spencer et al., 2016). We focused on negative stereotypes regarding women's creative abilities, and how stereotype threat impacts neural and behavioral indices of creative ideation.

Research shows that women tend to be perceived as being less creative (Luksyte et al., 2017; Proudfoot et al., 2015) or brilliant (Leslie et al., 2015) than men. For example, Proudfoot et al. (2015) found that women are judged to be less creative than men (even when they produce identical output), that creativity is less strongly associated with stereotypically feminine qualities (e.g., cooperativeness, supportiveness) than with stereotypically masculine-agentic qualities (e.g., daring, self-reliance), and that stereotypically masculine behavior enhances men's perceived creativity, whereas identical behavior does not enhance women's perceived creativity. This is possibly related to the broader stereotype that women have less capacity for brilliance than men (Leslie

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et al., 2015), where brilliance would be required for generating innovative solutions. Collectively, these findings indicate that women could be vulnerable to stereotype threat regarding their abilities to think creatively. Stereotype threat is the social experience whereby members of gender, racial, ethnic, or cultural ethnic groups (that are often historically marginalized) perceive a risk of confirming a negative stereotype about their social group (Appel and Kronberger, 2012; Spencer et al., 1999, 2016; Steele, 1997; Steele and Aronson, 1995). Individuals targeted by a stereotype threat feel pressure to avoid being judged in light of the stereotype and worry that they inadvertently confirm it through their performance in that domain. This study addresses whether, and if so how, exposure to a stereotype threat impacts the neural and behavioral correlates of creative thinking in female engineering students.

We specifically targeted female engineering undergraduate students, as they operate in a STEM field with a relatively large gender disparity. In their review paper on differences in gender disparity across different STEM fields, Cheryan et al. (2017) identified negative stereotypes of women's abilities as one of the two main factors associated with the social-cultural environment that contribute to the relatively low representation of women in certain STEM fields (the second factor is scarcity of relatable female role models). Cheryan et al. (2017) also found that undergraduate women in STEM fields with the largest gender disparities (e.g., engineering, computer science, or physics) report greater concerns about being stereotyped negatively because of their gender than women majoring in STEM fields with no or smaller gender disparities, such as biology (Cheryan et al., 2017). Moreover, female engineering majors are more susceptible to stereotype threat, and score lower on engineering problems, when interacting with men displaying sexist behavior (Logel et al., 2009). The social environment can thus trigger and exacerbate stereotype threat, and its negative consequences on an individual's performance have important implications for educational or professional settings.

To measure brain activity during creative ideation, we modeled our design on previous studies using EEG and creative answer production (Fink et al., 2006; Fink et al., 2011; Jauk et al., 2012; Rominger et al., 2019; Schwab et al., 2014). Participants are provided a series of prompts and asked to speak out loud as many creative solutions as possible for each prompt (e.g., uses for a brick). Participants press a button before each verbal response to demarcate when the ideation event occurs. Brain oscillations (frequency band power or phase) just prior to these subject-delineated ideation events are later analyzed. Prior studies typically report higher alpha power being associated with better creativity outcomes. We will first review cognitive processes that have been associated with alpha waves and then turn to specific findings in the context of creative ideation relevant for the present work.

A robust and replicable EEG finding in divergent thinking tasks is the increase of brain oscillations in the alpha band (8–12 Hz) over frontal and temporo-parietal sites (Benedek et al., 2014). Unifying theories of alpha (Jensen et al., 2012; Jensen and Mazaheri, 2010; Klimesch, 2012) suggest alpha reflects inhibitory processing, and when tasks rely on focusing attention to external input (i.e., to incoming stimuli), the inhibition is lessened and alpha power decreases relative to a reference interval (i.e., alpha desynchronization). In contrast, when attention is focused inwards, external input is suppressed, and alpha increases (i.e., alpha synchronization) especially over posterior scalp locations (to suppress visual inputs). This general interpretation of alpha activity (Benedek et al., 2014, 2011; Jauk et al., 2012; Lustenberger et al., 2015; for review see Benedek, 2018; Benedek and Fink, 2019) has been proposed to account for the alpha changes found during creativity tasks.

The association between alpha and creative ideation is well established (Martindale and Hasenfus, 1978; Martindale and Mines, 1975). Between individuals, high-scoring individuals have higher alpha activity than lower-scoring individuals (Fink et al., 2009a; Fink et al., 2009b; Fink and Neubauer, 2008; Jaušovec, 2000; Martindale and Hasenfus, 1978; Martindale and Mines, 1975). Within individuals, tasks that

demand more creativity are associated with higher alpha activity (Jauk et al., 2012; Jaušovec, 1997), and higher-rated creative solutions are associated with higher alpha activity relative to lower-rated solutions (Fink and Neubauer, 2006; Grabner et al., 2007). Brain stimulation studies also highlight the functional role for alpha in creative ideation (Grabner et al., 2018; Lustenberger et al., 2015), with stimulation of frontal alpha increasing the number of ideas generated during the creativity tasks, particularly in individuals with higher creative potential (Grabner et al., 2018).

To our knowledge, no published studies have specifically examined the effects of stereotype threat on alpha power associated with creative ideation. However, Fink et al. (2011) found that alpha (10–12Hz) increases during ideation following a mood induction with positively valenced sound clips. The stereotype threat manipulation bears similarity to a negatively valenced mood induction – being told that members of your gender, racial, ethnic or cultural group are not good at something is by definition a negative experience, and worrying that one might inadvertently confirm this stereotype through their performance in that domain likely induces a negative mood. Thus, it is plausible that a stereotype threat manipulation also influences alpha power. Moreover, in a prominent model of mood and its effects on creative behavior, mood inductions that led to higher arousal levels (e.g., anger, happiness) were described as boosting ("activating") creativity whereas lower arousal moods had the opposite effect ("deactivating", e.g., from sadness, relaxation) (Baas et al., 2008, 2011; Dreu et al., 2008). Arousal has also been related to stereotype threat (e.g., Ben-Zeev et al., 2005; O'Brien and Crandall, 2003; Schmader et al., 2008). Depending on how students respond to stereotype threat, their creativity is hypothesized to be impacted. More specifically, if stereotype threat induces a low arousal level, then this would lead to less creative behavioral outcomes and lower associated alpha power. Indeed, the typical effect of stereotype threat is lower performance on a task (Grabner et al., 2018; Spencer et al., 2016), which would translate into fewer creative ideas, as well as lower quality ideas. Alternatively, if stereotype threat instead stirs the student, this could potentially lead to better creative outcomes (and higher alpha power).

In the present study, we used a population likely vulnerable to stereotype threat targeting creative thinking (undergraduate female engineering students) and asked them to perform two standard creative thinking tasks before and after exposure to a gender-related stereotype threat. Participants completed two standard DT tasks, the Alternate Uses Task (AUT) and the Utopian Situations Task (UST), both of which require participants to think of unusual solutions and unique responses to prompts, while their ongoing EEG is recorded. In the AUT, participants are given a prompt item of a familiar object (e.g., a brick) and are instructed to produce as many novel alternate uses of that object as possible within a time limit (Guilford, 1967). The UST gives participants a prompt of an imaginary situation ("What would happen if no one could speak anymore?") and requires the participant to provide an explanation of what might happen if that situation were real (Wallach and Torrance, 1968; Wilson et al., 1954). We use these two different creativity tasks so that our results more broadly reflect creative thinking, rather than risk that the results are task dependent (see Hass and Beaty, 2018, for direct task comparisons). Following prior work in this domain, ongoing EEG activity was recorded while participants performed the tasks, and the alpha power around the time of response was examined as an index of creative thinking (Beaty et al., 2018).

If stereotype threat negatively impacts the ability to perform creatively – either in number of ideas produced (fluency) or in the quality of ideas themselves (originality), an alpha decrease might be expected (Dreu et al., 2008; Fink et al., 2011). Alternatively, if stereotype threat is actually stirring rather than discouraging, then stereotype threat delivery might lead to an alpha power increase along with improvement in creative thinking efforts (either in idea fluency or originality). Finally, building on prior work reporting increased alpha power is associated with more original ideas (e.g., Fink et al., 2009b; Fink and Neubauer,

2006; Grabner et al., 2007), we also correlated alpha power to idea originality and fluency and expected a positive association based on past work.

2. Methods

2.1. Participants

Twenty-seven female undergraduate students from a large American university gave informed consent to participate in the experiment that was approved by the university's IRB. Four participants were excluded from the analysis due to a technical error with the recording of verbal responses. The final sample included 23 female undergraduate students majoring in engineering ($M_{age} = 19.1$; $SD = 0.89$). One participant was further excluded from EEG analyses due to noisy data. After informed consent, participants completed a demographic questionnaire. All participants were right-handed native speakers of English, had normal or corrected-to-normal vision, and reported no history of neurological impairment.

2.2. Experimental tasks

While EEG was recorded, participants performed two experimental tasks: the Alternate Uses task (AUT) and the Utopian Situations task (UST). In the AUT, participants were asked to generate novel, unusual uses of common objects. Experimental stimuli consisted of eight items: brick, foil, hanger, helmet, key, magnet, pencil, and pipe. In the UST, participants were asked to come up with unusual and original solutions to hypothetical situations. Experimental stimuli consisted of eight hypothetical situations (e.g., *What would be the consequences, what would happen, if energy was unlimited? What would be the consequences, what would happen if nobody could speak anymore?*). Stimulus presentation was controlled by E-prime (version 2.0, Psychology Software Tools, Inc.). The experimental procedure was similar for both tasks, and was modeled after previous work (Fink and Neubauer, 2006). Participants first saw a fixation cross for 6 s, which served as the pre-stimulus baseline (reference) period that preceded each test item. Subsequently, a test item appeared on the screen for 2.5 s (AUT) or 8 s (UST), giving participants sufficient time to read and encode the item. The item was replaced by a question mark signaling the start of the ideation period. Participants generated ideas in silence and pressed a middle button on the response box when they were ready to produce the idea out loud. Following the button press, a picture of a microphone appeared on the screen signaling participants could start vocalizing the idea. When they finished speaking, participants pressed the button, after which the question mark reappeared on the screen signaling the start of the next ideation period (see Fig. 1). The experimental session was preceded by practice trials for both experimental tasks (AUT: chair; UST: *What would be the consequences, what would happen, if the continents were connected by land?*). Participants' verbal responses were recorded by E-prime. Participants spent app. 20 min on each task.

2.3. Procedure

Participants were seated approximately 100 cm away from the screen in a dimly lit and sound-attenuated booth. During EEG cap preparation, participants completed a Language History Questionnaire and the Edinburgh Handedness Questionnaire (Oldfield, 1971). Next, two 2-min resting-state EEG sequences were recorded, the first with eyes closed, the second with eyes open. This was followed by two warm-up trials (one AUT trial, one UST trial) and the experimental tasks described above. In both tasks, participants had 2 min to generate ideas for each test item. Halfway through the experiment a male experimenter and a male undergraduate student entered the testing room and performed a scripted conversation with the female participant to induce a stereotype threat. Stereotype threat administration was brief and succinct, comparable to the standard breaks within experimental blocks. The stereotype threat was modeled after prior work (Adams et al., 2006; Johnson et al., 2012; Spencer et al., 1999), and was expressed as follows:

Experimenter: How are you doing so far?

Participant: [...]

Experimenter: We're looking at how you're doing. What we've been seeing so far is that women in particular are really struggling with this task, so please try to do the task to the best of your ability after the break.

Experimental tasks consisted of 2 blocks per task, for a total of 4 blocks. Stereotype threat was administered halfway the experiment, after participants had completed one block of each task. For example, a participant might have completed UST Block 1 and AUT Block 2, and then UST Block 2 and AUT Block 1. Block and task order was counterbalanced across participants. Each block consisted of four items and item presentation within each block was fully randomized.

After completing the EEG experiment, two 2-min resting-state EEG sequences (with eyes closed and eyes open, respectively) were recorded. Subsequently, participants completed the Stereotype Vulnerability Scale (SVS), a questionnaire used to assess an individual's pre-existing vulnerability to stereotype threat; this test has good psychometric properties $\alpha > .80$ or better (Barnard et al., 2017; Spencer et al., 1999; Steele et al., 2002). Participants also completed the self-efficacy scale that measures the belief that one has the capacity to be successful at a particular task (Bandura et al., 1999), and the Big Five Inventory (Goldberg, 1992) that measures the personality traits including openness to experience which has been linked to alpha activity during creative idea generation (Fink et al., 2007). Finally, participants were debriefed about the aim of the experiment and compensated for their time with either course credit or money.

2.4. Assessments of AUT and UST performance

Five independent and trained raters judged the originality of the generated ideas on a five-point Likert scale ranging from 1 (not original) to 5 (very original). Raters were instructed that a given answer was to be considered original when it was novel/unique and when it was principally possible. They were also asked to use the complete scale range as

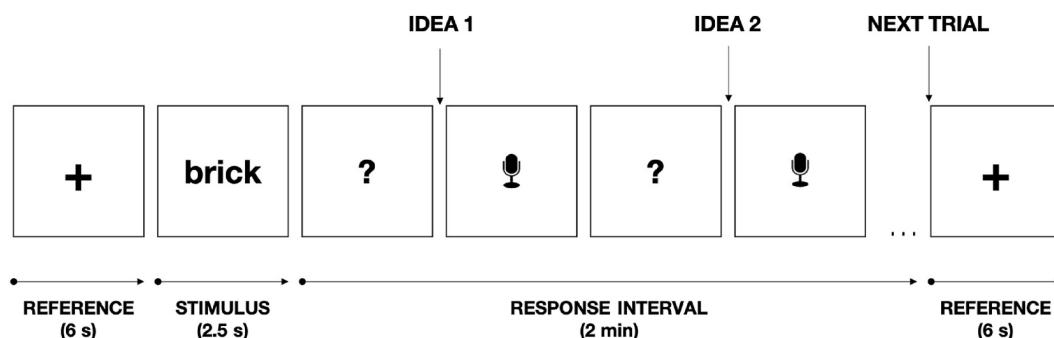


Fig. 1. Schematic time course of the experimental procedure.

far as possible. The originality ratings showed satisfactory inter-rater reliability for both the AUT and the UST tasks ($ICC_{AUT} = 0.64$; $ICC_{UST}(C,5) = 0.74$). As a result, all ratings were averaged across raters, resulting in one originality metric per participant and per item in the pre-threat and post-threat conditions.

2.5. Behavioral data analysis

We used R [Core Team \(2020\)](#) for all statistical analyses. Behavioral data analysis focused on fluency (i.e., the number of generated ideas) and originality of generated ideas in both the AUT and the UST combined.¹ The behavioral data were analyzed with two repeated measures ANOVAs with stereotype threat (pre-threat, post-threat) as a within-subject factor.

2.6. Electrophysiological recording and analysis

An elastic cap (Brain Products ActiCap, Germany) with 31 active Ag/AgCl electrodes was placed on the participant's head. Electrode locations consisted of five sites along the midline (Fz, FCz, Cz, Pz, Oz) and 26 lateral electrodes (FP1/2, F7/8, F3/4, FC5/6, FC1/2, T7/8, C3/4, CP5/6, CP1/2, P7/8, P3/4, O1/2, PO9/10); see also [Jończyk et al. \(2020\)](#). In order to monitor vertical eye movements/blink, bipolar recordings were made above and below the left eye, and the outer canthus of each eye. Electrodes were referenced to a vertex reference (electrode FCz) and re-referenced offline to an average of the left and right mastoids. The electroencephalogram (EEG) was amplified by a NeuroScan Syn-Amps RT amplifier using a 0.05 Hz–100 Hz bandpass filter and continuously sampled at a rate of 500 Hz. Electrode impedances were kept below 5 kΩ. EEG data analyses were performed using EEGLAB (v14.1.1; [Delorme and Makeig, 2004](#)) toolbox in Matlab R2017a (The MathWorks, Inc.). Continuous EEG data was band-pass filtered using an infinite impulse response (IIR) filter between 1 Hz (transition bandwidth: 0.3 Hz; order: 6.0) and 55 Hz (transition bandwidth: 1.0 Hz; order: 12.0). Unsystematic artifacts in continuous EEG data caused by muscle activity or eye movements were manually detected and removed. Bad channels were identified via visual inspection and using the TrimOutlier plugin (Lee & Miyakoshi; <https://scn.ucsd.edu/wiki/TrimOutlier>), by excluding channels with a standard deviation $< 1 \mu$ and $> 100 \mu$ ($M = 1.96$, min = 1, max = 4). Continuous data were re-referenced to the algebraic mean of activity over the left (M1) and right (M2) mastoids and subjected to Independent Component Analysis (ICA) using the extended infomax algorithm (Lee et al., 1999) implemented in EEGLAB. To get a more detailed insight into the brain dynamics underlying creative ideation under threat, we performed analyses (1) at the sensor level, and (2) at the level of independent component (IC) clusters. For the sensor level analysis, ICs containing ocular, muscle artifacts, and line noise were removed from the data ($M = 6.01$; min = 2, max = 8). Following ICA, missing channels were interpolated using the spherical spline method implemented in EEGLAB. EOG and mastoid channels were dropped from further analyses. For the IC cluster analysis, we analyzed the results of ICA for each of our participants and isolated ICs with the highest alpha power. This analysis allowed us to identify and separate independent EEG source contributions of alpha oscillations that are typically blurred in scalp electrode data, thus allowing to explore their dynamics with greater precision (Makeig et al., 2004). Comparing ICs across participants requires that ICs from different participants should be grouped into functionally equivalent clusters of ICs. To

achieve this, we used the DIPFIT plugin in EEGLAB (v.3; [Oostenveld and Oostendorp, 2002](#)) to model each independent component as an equivalent current dipole within a boundary element head model based on the MNI (Montreal Neurological Institute, Quebec, Canada) brain. We clustered independent components across all 22 participants included in the analysis, based on similarities in scalp topography, spectra, and 3D dipole locations using a k-means clustering algorithm available in EEGLAB. 3D dipole densities were then plotted by the NIMA plugin ([Bigdely-Shamlo et al., 2013](#)). This resulted in three alpha-related (8–12 Hz) brain clusters: (1) left posterior alpha (containing ICs from 16 participants); (2) right posterior alpha (containing ICs from 17 participants); and (3) central posterior alpha (containing ICs from 18 participants). For both sensor-level and IC cluster level analyses, we computed task related power (TRP) changes for each electrode and trial in the lower (8–10 Hz) and upper (10–12 Hz) alpha band during creative ideation periods (e.g., [Fink and Neubauer, 2006](#); [Fink et al., 2009a](#)) before and after the administration of stereotype threat. The analysis was based on a 4000 ms time segment (the reference interval) that corresponded to the middle of the 6000 ms reference period, and a 4000 ms time segment between –3000 and 1000 ms surrounding the button press. Longer epochs were selected for the analysis to avoid the contamination of edge artifacts. Bad epochs were rejected based on visual inspection ($M = 8.47\%$; min = 0%, max = 13.75%). Time-/frequency decomposition was applied to the activities of the activation and reference intervals using sinusoidal wavelet transforms (newtimef function in Matlab; wavelet scale expansion factor of 0.8), with 3 cycles at the lowest frequency (2 Hz), increasing linearly up to 22.5 cycles at the highest frequency (30 Hz). This approach offers reasonable time and frequency stability at all computed frequencies. To establish the changes in the activation period (pre- and post-threat) relative to the power during the baseline period (reference interval), we computed the percentage change value at each time-frequency point at an electrode/cluster relative to a baseline power, following [Cohen \(2014\)](#):

$$prctchange_{tf} = 100 * (\text{activity}_{tf} - \text{baseline}_{tf})/\text{baseline}_{tf}$$

Hence, a decrease in alpha power from the baseline to the activation period would be reflected in negative TRP percentage values (i.e., event-related alpha desynchronization; ERD), while an increase in alpha power from the baseline to the activation period would be reflected in positive TRP percentage values (event-related alpha synchronization; ERS).

Here, we focus on the relative difference in TRP between pre-threat and post-threat ideation periods in the critical activation period from –1500 ms to –500 ms prior to button press. TRP values in the lower alpha band (8–10 Hz) and upper alpha band (10–12 Hz)² were each analyzed by means of a Repeated Measures (RM) ANOVA, with STEREOTYPE THREAT (pre vs. post), HEMISPHERE (left vs. right), AREA (anterior-frontal (FP1, F3, F7, FP2, F4, F8), fronto-central (FC1, FC5, FC2, FC6), centrotemporal (C3, T7, C4, T8), centro-parietal (CP1, CP5, CP2, CP6), parietal (P3, P7, P4, P8), parieto-occipital (PO9, O1, PO10, O2)), and BLOCK HALF (first half, second half) as within-subject variables. We also ran correlation analyses looking into possible lower and upper alpha power modulations as a function of idea originality and ideational fluency (see [Fink et al., 2009b](#); [Fink and Neubauer, 2006](#); [Grabner et al., 2007](#)). For the independent component analysis, TRP values in the lower

¹ A separate ANOVA including Task as a factor showed that, irrespective of the stereotype threat, ideas were more original in the AUT ($M = 2.57$, 95% CI [2.52,2.61]) rather than UST ($M = 2.14$, 95% CI [2.10,2.18]), $F(1,22) = 107.38$, $p < .001$, $\hat{\eta}_G^2 = .342$, 90% CI [.093,.551]. There was no effect of task for ideational fluency ($M_{AUT} = 7.55$, 95% CI [7.22,7.88]; $M_{UST} = 7.40$, 95% CI [7.07,7.73]), $F(1,22) = 0.44$, $p = .512$, $\hat{\eta}_G^2 = .002$, 90% CI [.000,.090].

² Across studies, the alpha band has often been divided into upper (10–12 Hz) and lower (8–10 Hz) alpha frequency, and upper alpha has been associated with specific task demands while lower alpha has been associated with more general cognitive processes. Upper and lower alpha is highly correlated in simple tasks, with increasing dissociation between the effect patterns in upper and lower alpha bands in more complex tasks ([Fink et al., 2005](#)). Similar results across upper and lower alpha bands have been reported in creativity studies ([Fink et al., 2009](#); [Fink et al., 2009](#); [Jauk et al., 2012](#)), with some reports of increased alpha in the upper band ([Fink et al., 2011](#); [Jaarsveld et al., 2015](#)).

and upper alpha band of the three alpha-related brain clusters were analyzed with an RM ANOVA, with STEREOTYPE THREAT (pre vs. post) as a within-subject factor. A Greenhouse-Geisser correction was applied where applicable and *p*-values obtained from post-hoc comparisons were adjusted using the Holm correction.

3. Results

3.1. Behavioral ratings: idea originality and fluency

Idea originality. Idea originality did not differ between the post-threat ($M = 2.33$, 95% CI [2.29,2.37]) and pre-threat ($M = 2.38$, 95% CI [2.34,2.43]) conditions, $F(1, 22) = 3.11, p = .092, \hat{\eta}_G^2 = .011$, 90% CI [.000, .165]. The Pearson's product-moment correlation between idea originality in the pre-threat and post-threat conditions combined and openness to experience was positive but failed to reach statistical significance, $r = .34$, 95% CI [−.08,.66], $t(21) = 1.66, p = .112$. Also, participants' score on the stereotype threat vulnerability scale did not correlate with the originality of ideas generated after the administration of stereotype threat, $r = .19$, 95% CI [−.25,.56], $t(20) = 0.86, p = .402$.

Idea fluency. The number of ideas did not differ between post-threat ($M = 7.64$, 95% CI [7.30,7.97]) and pre-threat ($M = 7.31$, 95% CI [6.99, 7.63]) conditions, $F(1, 22) = 3.14, p = .090, \hat{\eta}_G^2 = .008$, 90% CI [.000, .152]. Participants' score on the stereotype threat vulnerability scale did not correlate with the number of ideas generated after the administration of stereotype threat, $r = .17$, 95% CI [−.27,.56], $t(20) = 0.79, p = .436$.

3.2. Electrophysiological results

3.2.1. Sensor-level analysis

In the lower alpha range, the ANOVA revealed a main effect of threat, $F(1, 21) = 19.41, p < .001, \hat{\eta}_G^2 = .051$, 90% CI [.000, .260], with greater alpha Event-Related Synchronization (ERS) after the administration of stereotype threat ($M_{\text{pre-threat}} = -8.77$, 95% CI [−23.16,5.61]; $M_{\text{post-threat}} = 10.00$, 95% CI [−4.38,24.39]). Also, the main effect of hemisphere, $F(1, 21) = 9.20, p = .006, \hat{\eta}_G^2 = .021$, 90% CI [.000, .201], showed greater alpha ERS in the right ($M = 6.55$, 95% CI [−7.75,20.85]) compared to left ($M = -5.32$, 95% CI [−19.62,8.98]) hemisphere. An area-by-hemisphere interaction, $F(2.74, 57.61) = 3.15, p = .036, \hat{\eta}_G^2 = .004$, 90% CI [.000, .000], showed greater alpha ERS in the right vs. left frontocentral ($M_{\text{right}} = 7.88$, 95% CI [−7.15,22.92]; $M_{\text{left}} = -4.51$, 95% CI [−19.55,10.52]), centrot temporal ($M_{\text{right}} = 6.76$, 95% CI

[−8.28,21.79]; $M_{\text{left}} = -12.07$, 95% CI [−27.11,2.96]), centroparietal ($M_{\text{right}} = 9.26$, 95% CI [−5.78, 24.30]; $M_{\text{left}} = -5.12$, 95% CI [−20.16,9.92]), and parietal ($M_{\text{right}} = 8.08$, 95% CI [−6.96,23.11]; $M_{\text{left}} = -6.08$, 95% CI [−21.12,8.95]) areas. The threat-by-block interaction was not significant, $F(1, 21) = 1.77, p = .198, \hat{\eta}_G^2 = .004$, 90% CI [.000, .126], ruling out the possibility that alpha power increased as a function of time on task. Finally, we compared alpha power in the block directly preceding (block 2) and directly following (block 3) the stereotype threat. This one-way ANOVA was significant, $F(1, 21) = 4.46, p = .047, \hat{\eta}_G^2 = .032$, 90% CI [.000, .227], and showed an increase in alpha power in block 3 ($M = 3.87$, 95% CI [−10.08,17.81]) rather than block 2 ($M = -7.58$, 95% CI [−21.53,6.37]). This result demonstrates that alpha power increased after the administration of stereotype threat.

In the upper alpha range, the RM ANOVA showed a main effect of threat, $F(1, 21) = 15.42, p = .001, \hat{\eta}_G^2 = .053$, 90% CI [.000, .263], with greater upper alpha ERS after the administration of stereotype threat ($M_{\text{pre-threat}} = -15.67$, 95% CI [−29.51,-1.83]; $M_{\text{post-threat}} = 3.75$, 95% CI [−10.09,17.59]). The main effect of hemisphere, $F(1, 21) = 11.43, p = .003, \hat{\eta}_G^2 = .022$, 90% CI [.000, .203], showed greater alpha ERS in the right ($M = 0.14$, 95% CI [−13.33,13.61]) compared to left ($M = -12.06$, 95% CI [−25.53,1.42]) hemisphere. An area-by-hemisphere interaction, $F(2.66, 55.86) = 4.06, p = .014, \hat{\eta}_G^2 = .005$, 90% CI [.000, .000], showed greater alpha ERS in the right vs. left centrot temporal ($M_{\text{right}} = 0.25$, 95% CI [−14.51,15.00]; $M_{\text{left}} = -19.35$, 95% CI [−34.10,-4.60]), centroparietal ($M_{\text{right}} = 6.20$, 95% CI [−8.56,20.95]; $M_{\text{left}} = -9.21$, 95% CI [−23.97,5.54]), and parietal ($M_{\text{right}} = 9.05$, 95% CI [−5.71, 23.80]; $M_{\text{left}} = -8.90$, 95% CI [−23.65,5.85]) areas. The threat-by-block interaction was significant, $F(1, 21) = 4.34, p = .050, \hat{\eta}_G^2 = .009$, 90% CI [.000, .160]. Before the stereotype threat, alpha ERS was somewhat greater in block 1 ($M = -12.41$, 95% CI [−27.36,2.54]) than in block 2 ($M = -18.93$, 95% CI [−33.88,-3.98]), $t(38.70) = -1.92, p = .063$. By contrast, after the stereotype threat, greater alpha ERS was observed in block 4 ($M = 8.12$, 95% CI [23.07,-6.83]) rather than block 3 ($M = -0.62$, 95% CI [14.33,-15.56]), $t(38.70) = -4.40, p < .001$. Finally, a direct comparison of upper alpha power in the block directly preceding (block 2) and directly following (block 3) the stereotype threat was significant, $F(1, 21) = 15.28, p = .001, \hat{\eta}_G^2 = .085$, 90% CI [.000, .308], and showed an increase in alpha power in block 3 ($M = -0.62$, 95% CI [−14.10,12.87]) rather than block 2 ($M = -18.93$, 95% CI [−32.42,5.44]). This result supports the finding from lower alpha range, demonstrating an increase in alpha power directly after the stereotype threat. Other comparisons did not differ from chance ($p_s > .05$; see Fig. 2).

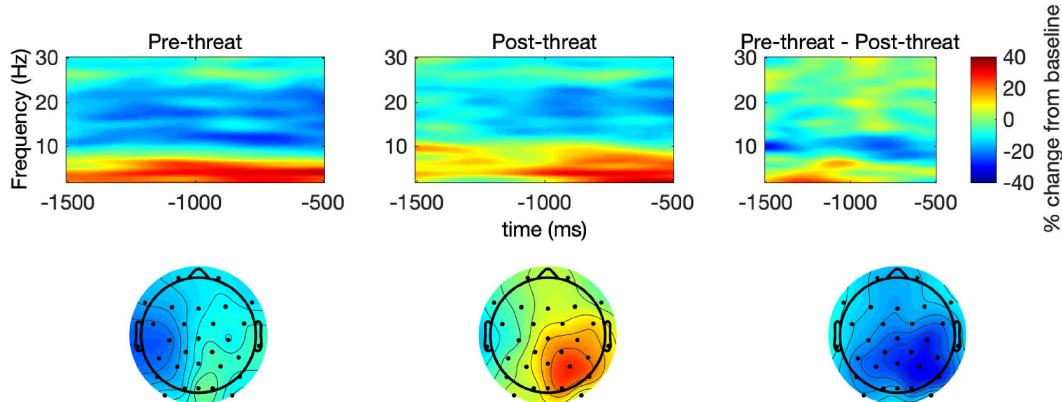


Fig. 2. Task-related changes in EEG alpha activity before stereotype threat (pre-threat; left panel), after stereotype threat (post-threat; middle panel), and their difference (pre-threat - post-threat; right panel). Scalp maps reflect topographical distribution of the effects in the −1500 to −500 ms time window and in the 8–12 Hz alpha range. Red regions indicate increases in alpha power relative to the reference period; blue regions indicate decreases. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.2. Correlational analyses

Participants' ideational fluency did not correlate with alpha power in the pre-threat and post-threat conditions either in the lower alpha range, $r = .19$, 95% CI [−.11, .46], $t(42) = 1.26$, $p = .215$, or in the upper alpha range, $r = .24$, 95% CI [−.06, .50], $t(42) = 1.60$, $p = .117$.

In the same vein, idea originality did not correlate with alpha power in the pre-threat and post-threat conditions either in the lower alpha range, $r = -.05$, 95% CI [−.34, .25], $t(42) = -.31$, $p = .755$, or in the upper alpha range, $r = -.18$, 95% CI [−.45, .12], $t(42) = -.120$, $p = .238$.

3.3. Independent-component analysis

For the left posterior alpha IC, the ANOVA showed a main effect of threat in the lower alpha range, $F(1, 15) = 8.86$, $p = .009$, $\eta^2_G = .031$, 90% CI [.000, .266], with greater alpha ERS in the post-threat ($M = -10.55$, 95% CI [10.85, −31.95]) than in the pre-threat ($M = -24.67$, 95% CI [−3.28, −46.07]) condition. Similarly, the effect of threat was significant in the upper alpha range, $F(1, 15) = 5.05$, $p = .040$, $\eta^2_G = .039$, 90% CI [.000, .280], with greater alpha ERS in the post-threat ($M = -11.53$, 95% CI [9.67, −32.72]) than in the pre-threat ($M = -27.24$, 95% CI [−6.05, −48.44]) condition (see Fig. 3).

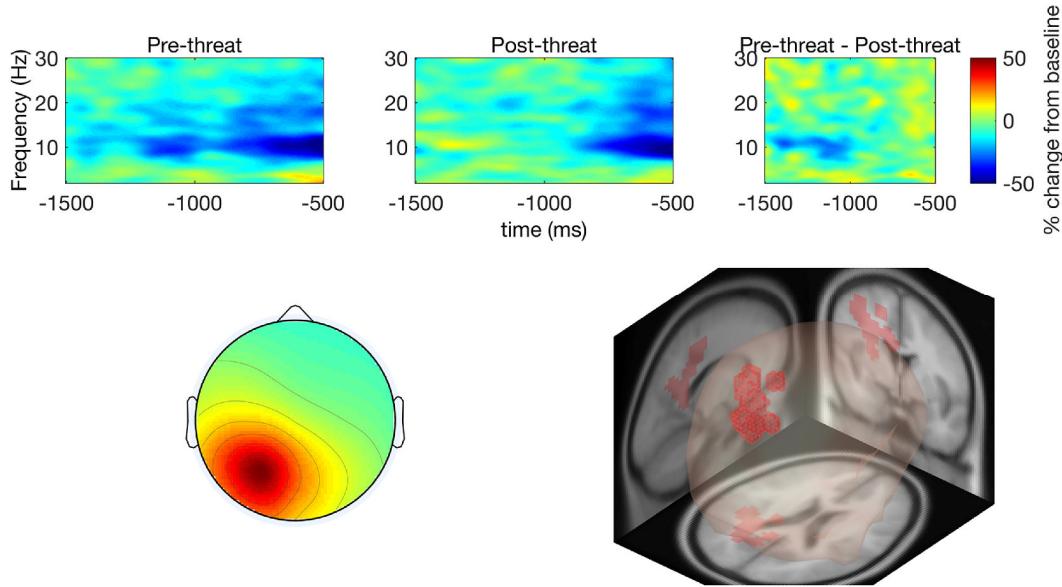


Fig. 3. Left Posterior Alpha IC cluster. Task-related changes in EEG alpha activity before stereotype threat (pre-threat; left panel), after stereotype threat (post-threat; middle panel), and their difference (pre-threat - post-threat; right panel) for the left posterior alpha IC cluster. Red regions indicate increases in alpha power relative to the reference period; blue regions indicate decreases. The lower panel features cluster topography in the -1500 to -500 ms time window and in the 8–12 Hz alpha range as well as dipole density. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

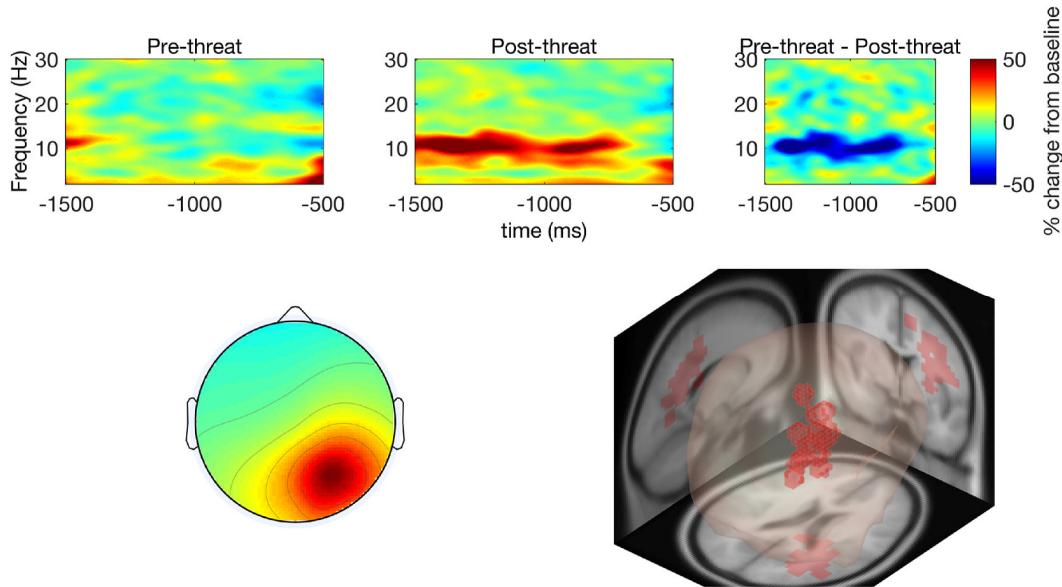


Fig. 4. Right Posterior Alpha IC cluster. Task-related changes in EEG alpha activity before stereotype threat (pre-threat; left panel), after stereotype threat (post-threat; middle panel), and their difference (pre-threat - post-threat; right panel) for the right posterior alpha IC cluster. Red regions indicate increases in alpha power relative to the reference period; blue regions indicate decreases. The lower panel features cluster topography in the -1500 to -500 ms time window and in the 8–12 Hz alpha range as well as dipole density. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

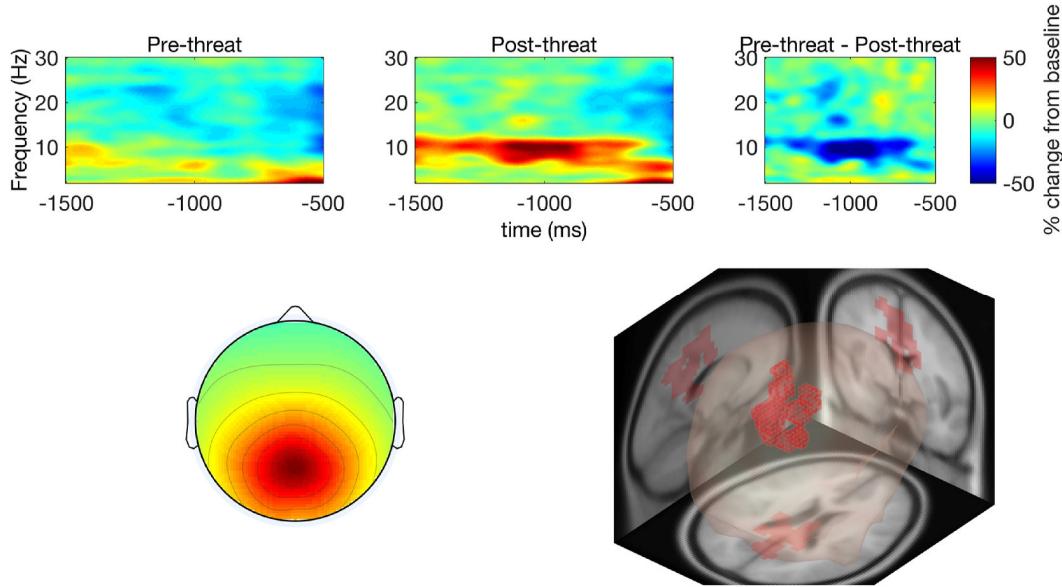


Fig. 5. Central Posterior Alpha IC cluster. Task-related changes in EEG alpha activity before stereotype threat (pre-threat; left panel), after stereotype threat (post-threat; middle panel), and their difference (pre-threat - post-threat; right panel) for the central posterior alpha IC cluster. Red regions indicate increases in alpha power relative to the reference period; blue regions indicate decreases. The lower panel features cluster topography in the -1500 to -500 ms time window and in the 8–12 Hz alpha range as well as dipole density. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

For the right posterior alpha IC, the ANOVA showed a main effect of threat in the lower alpha range, $F(1, 16) = 10.86, p = .005, \eta_G^2 = .138, 90\% \text{ CI } [.000, .403]$, with greater alpha ERS after the administration of stereotype threat ($M_{\text{pre-threat}} = -2.83, 95\% \text{ CI } [21.62, -27.27]$; $M_{\text{post-threat}} = 35.13, 95\% \text{ CI } [59.58, 10.69]$). In the upper alpha range, the main effect of threat only approached significance, $F(1, 16) = 3.38, p = .084, \eta_G^2 = .075, 90\% \text{ CI } [.000, .329]$, with slightly greater alpha ERS after the administration of stereotype threat ($M_{\text{pre-threat}} = -4.47, 95\% \text{ CI } [31.88, -40.83]$; $M_{\text{post-threat}} = 36.15, 95\% \text{ CI } [72.51, -0.20]$); see Fig. 4).

Finally, for the central posterior alpha IC, the ANOVA showed a main effect of threat in the lower alpha range, $F(1, 17) = 8.83, p = .009, \eta_G^2 = .117, 90\% \text{ CI } [.000, .372]$, with greater alpha ERS after the administration of stereotype threat ($M_{\text{pre-threat}} = -5.20, 95\% \text{ CI } [25.62, -36.02]$; $M_{\text{post-threat}} = 39.81, 95\% \text{ CI } [70.63, 8.99]$). Likewise, the effect of threat was significant in the upper alpha range, $F(1, 17) = 5.94, p = .026, \eta_G^2 = .062, 90\% \text{ CI } [.000, .302]$, with greater alpha ERS after the administration of stereotype threat ($M_{\text{pre-threat}} = -4.49, 95\% \text{ CI } [28.36, -37.33]$; $M_{\text{post-threat}} = 29.16, 95\% \text{ CI } [62.00, -3.69]$, see Fig. 5).

4. Discussion

In this work we aimed to uncover the effects of stereotype threat exposure on neural and behavioral indices of creative ideation by measuring alpha power and behavioral outcomes of idea originality and fluency before and after female students were informed that women do not perform well on a task – invoking the stereotype that women are not good at creative thinking. The primary finding in terms of brain activity was that alpha power increased post-threat relative to pre-threat, in both upper and lower alpha frequency bands and across both sensor-level and independent component cluster-level analyses. The behavioral effects did not reach statistical significance but trended towards participants generating more ideas post-threat, with those ideas being less original than the pre-threat ideas had been. These results appear consistent with an interpretation that the stereotype threat manipulation stirred and motivated participants to try harder, leading to increased internal attention to focus on the task as reflected on alpha power, but that this effort did not lend itself to better behavioral performance.

The impact of stereotype threat on creative ideation had a few main potential outcomes depending on competing factors related to emotional reactivity and attentional focus. On one hand, stereotype threat could lead to disengagement on creative thinking tasks (if, for example, the threat had induced low-arousal negative and deactivating mood, see, e.g., Dreux et al., 2008), resulting in lower alpha power and potentially poorer behavioral outcomes. Alternatively, stereotype threat could have stirred and aroused participants, resulting in higher alpha power and potentially better behavioral outcomes. Our study found an increase in alpha power following stereotype threat, though this alpha increase was not paired with improvements in the level of creativity (originality) of the behavioral responses. Still, the delivery of stereotype threat did not lead to decreases in behavioral performance, as has been reported previously (Spencer et al., 2016). One potential explanation of our behavioral findings is that the women tested in this study were engineering majors, a field with high gender disparity (Cheryan et al., 2017). While exposure to a stereotype threat typically leads to distraction due to the psychological pressure not to conform to the stereotype, people who have higher coping skills do not tend to underperform with stereotype threat (see Spencer et al., 2016, regarding efficacy of a stereotype threat). The female engineering students who participated in our study may have relatively high coping skills, which is corroborated by the lack of correlations of Stereotype Vulnerability with idea originality post-threat. Students who are unable to cope with the challenges of being a female minority (and have high stereotype threat) among the engineering students might instead drop out of the major (Beasley and Fischer, 2012), or might be too busy trying to do their best in the major to come into a lab experiment for several hours of their day. Anecdotally, several participants spontaneously reported that they were inspired to do better on the task following the threat (trying to prove that women could do the task as well), in line with the participant group being resilient.

A second explanation of our behavioral findings is related to the delivery of the stereotype threat. A meta-analysis that examined how the salience of stereotype threat cues affects behavioral task performance in women and minorities reported that for women more subtle and implicit cues elicited the strongest negative effects on performance (Nguyen and Ryan, 2008). Blatant and explicit cues also were associated with

significant effects, but with reduced magnitude. In their seminal study of male and female negotiation strategies under stereotype threat conditions, Kray et al. (2001) demonstrated that explicit delivery of stereotypes could enhance female performance. The stereotype threat in the present study was quite direct and straightforward, and possibly too explicit to be behaviorally effective. If indeed the female engineering majors who participated in the experiment had relatively high coping skills, the stereotype threat may have motivated them to increase their attention on the task. Because the present study constitutes the first attempt to directly examine the effects of stereotype threat on creative ideation outcomes in female students, future research may seek to further unravel the precise conditions under which stereotype threat may affect behavioral outcomes of creative thinking in women majoring in STEM disciplines.

We now turn to elaborating on the neural findings, and the significant effects of stereotype threat on creative ideation as observed in both upper and lower alpha bands. Finding the same outcomes in both upper and lower alpha is not uncommon (Benedek et al., 2011; Fink et al., 2009a, 2006; Fink et al., 2005, 2011; Fink et al., 2009b; Fink and Neubauer, 2008; Grabner et al., 2007; Jauk et al., 2012; Jausovec, 2000; Rominger et al., 2019; Schwab et al., 2014). Some choose to not separate alpha bands at all (Benedek et al., 2014), or to use individually-defined alpha bands for each participant (Fink and Neubauer, 2006). Here, the only difference we report is that the right posterior alpha cluster reached significance for the effect of stereotype threat in lower but not upper alpha. At the sensor level, by contrast, we found an interaction between block and threat in upper alpha, but not in lower alpha. All other comparisons and correlational analyses otherwise yielded the same outcome in upper and lower alpha bands. To the extent that upper alpha is associated with more specific task demands and lower with more general cognitive activity, here, at least, we find no evidence of specific or general activity functioning independently under these task conditions. Although the cluster-based ROIs identified significant effects in both hemispheres, the alpha effects were stronger over right hemisphere sites in both the cluster-based and sensor-level analyses, consistent with prior literature (Benedek et al., 2014). There has been an emerging view in this area that alpha increase over right hemisphere sites might be due more to a domain-general focusing of internal attention that benefits creative thinking (Benedek, 2018; Stevens and Zabelina, 2019). That is, alpha power increase associated with better outcomes during creative ideation may be due to utilization of top-down exertion of executive control mechanisms that promote increases in internal attention during creativity tasks (cf., Jauk et al., 2012; Ritter et al., 2018). The alpha power increase after the stereotype threat might reflect a similar phenomenon.

The role of alpha power in cognition has been studied across many domains, including mental rotation (Hanslmayr et al., 2005), attention (Haegens et al., 2011), and working memory (e.g., Wianda and Ross, 2019), among others. Generally speaking, increases in alpha are hypothesized to reflect top-down processes including inhibitory control (for reviews, see Klimesch et al., 2007; Sadaghiani and Kleinschmidt, 2016). Accordingly, alpha increases have been reported when participants must withhold a response (Hummel et al., 2002). In the AUT and UST, the most obvious and commonplace responses are uncreative and must be suppressed in favor of more inventive and original answers. Thus, these creativity tasks require exertion of attentional control mechanisms. However, suppressing undesirable responses is not the same as being able to produce a creative response, so it might not be surprising that increases in alpha observed in the present study were not accompanied by more original ideation outcomes. It is possible that participants felt pressure to perform and expended more effort, drawing on domain-general attention focusing mechanisms (and increasing alpha power), but did not actually have the skills to convert the effort into domain-specific improvements in creative ideation. To better clarify the roles and potential interactions between attentional mechanisms, alpha power, and creativity, future research pursuing direct

measurements of attentional engagement throughout the experiment would be valuable.

We successfully demonstrated that the social intervention of stereotype threat can modulate alpha power during creative cognition. Future research is necessary to determine when and how alpha modulations will also be linked to behavioral outcomes in the context of stereotype threat and other social interventions, as they appear to be separable given the present findings. The specific critical mechanisms connecting stereotype threat to increased alpha remain an exciting venue for future research.

Credit author statement

Rafał Jończyk: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft preparation, Writing – review & editing; Danielle S. Dickson: Writing – original draft preparation, Writing – review & editing; Tarik S. Bel-Bahar: Formal analysis, Visualization, Writing – review & editing; Güll E. Kremer: Conceptualization, Funding acquisition, Methodology, Writing – review & editing; Zahed Siddique: Conceptualization, Funding acquisition, Methodology, Writing – review & editing; Janet G. van Hell: Conceptualization, Funding acquisition, Methodology, Writing – review & editing.

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References

- Adams, G., Garcia, D.M., Purdie-Vaughns, V., Steele, C.M., 2006. The detrimental effects of a suggestion of sexism in an instruction situation. *J. Exp. Soc. Psychol.* 42 (5), 602–615. <https://doi.org/10.1016/j.jesp.2005.10.004>.
- Appel, M., Kronberger, N., 2012. Stereotypes and the achievement gap: stereotype threat prior to test taking. *Educ. Psychol. Rev.* 24 (4), 609–635. <https://doi.org/10.1007/s10648-012-9200-4>.
- Baas, M., Dreu, C.K.W.D., Nijstad, B.A., 2008. A meta-analysis of 25 years of mood-creativity research: hedonic tone, activation, or regulatory focus? *Psychol. Bull.* 134 (6), 779–806. <https://doi.org/10.1037/a0012815>.
- Baas, M., Dreu, C.K.W.D., Nijstad, B.A., 2011. When prevention promotes creativity: the role of mood, regulatory focus, and regulatory closure. *J. Pers. Soc. Psychol.* 100 (5), 794–809. <https://doi.org/10.1037/a0022981>.
- Bandura, A., Freeman, W.H., Lightsey, R., 1999. Self-efficacy: the exercise of control. *J. Cognit. Psychother.* 13 (2), 158–166. <https://doi.org/10.1891/0889-8391.13.2.158>.
- Barnard, L., Burley, H., Olivarez, A., Crooks, S., 2017. Measuring vulnerability to stereotype threat. *Electron. J. Res. Educ. Psychol.* 6 (14) <https://doi.org/10.25115/ejrep.v6i14.1259>.
- Beasley, M.A., Fischer, M.J., 2012. Why they leave: the impact of stereotype threat on the attrition of women and minorities from science, math and engineering majors. *Soc. Psychol. Educ.* 15 (4), 427–448. <https://doi.org/10.1007/s11218-012-9185-3>.
- Beaty, R.E., Kenett, Y.N., Christensen, A.P., Rosenberg, M.D., Benedek, M., Chen, Q., Fink, A., Qiu, J., Kwapił, T.R., Kane, M.J., Silvia, P.J., 2018. Robust prediction of individual creative ability from brain functional connectivity. *Proc. Natl. Acad. Sci. USA* 115 (5), 1087–1092. <https://doi.org/10.1073/pnas.1713532115>.
- Ben-Zeev, T., Fein, S., Inzlicht, M., 2005. Arousal and stereotype threat. *J. Exp. Soc. Psychol.* 41 (2), 174–181. <https://doi.org/10.1016/j.jesp.2003.11.007>.
- Benedek, M., 2018. Internally directed attention in creative cognition. In: Jung, R.E., Vartanian, O. (Eds.), *The Cambridge Handbook of the Neuroscience of Creativity*. Cambridge University Press, pp. 180–194. <https://doi.org/10.1017/9781316556238.011>.
- Benedek, M., Fink, A., 2019. Toward a neurocognitive framework of creative cognition: the role of memory, attention, and cognitive control. *Curr. Opin. Behav. Sci.* 27, 116–122. <https://doi.org/10.1016/j.cobeha.2018.11.002>.
- Benedek, M., Bergner, S., Könen, T., Fink, A., Neubauer, A.C., 2011. EEG alpha synchronization is related to top-down processing in convergent and divergent thinking. *Neuropsychologia* 49 (12), 3505–3511. <https://doi.org/10.1016/j.neuropsychologia.2011.09.004>.
- Benedek, M., Schickel, R.J., Jauk, E., Fink, A., Neubauer, A.C., 2014. Alpha power increases in right parietal cortex reflects focused internal attention.

Neuropsychologia 56, 393–400. <https://doi.org/10.1016/j.neuropsychologia.2014.02.010>.

Bigdely-Shamlo, N., Mullen, T., Kreutz-Delgado, K., Makeig, S., 2013. Measure projection analysis: a probabilistic approach to EEG source comparison and multi-subject inference. *Neuroimage* 72, 287–303. <https://doi.org/10.1016/j.neuroimage.2013.01.040>.

Cheryan, S., Ziegler, S.A., Montoya, A.K., Jiang, L., 2017. Why are some STEM fields more gender balanced than others? *Psychol. Bull.* 143 (1), 1–35. <https://doi.org/10.1037/bul0000052>.

Cohen, M.X., 2014. Analyzing Neural Time Series Data. The MIT Press. <https://doi.org/10.7551/mitpress/9609.001.0001>.

Core Team, R., 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. <https://www.R-project.org/>.

Cropley, D.H., 2016. Creativity in engineering. In: Corazza, G.E., Agnoli, S. (Eds.), *Multidisciplinary Contributions to the Science of Creative Thinking*. Springer Singapore, pp. 155–173. https://doi.org/10.1007/978-981-287-618-8_10.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134 (1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>.

Dreu, C.K.W.D., Baas, M., Nijstad, B.A., 2008. Hedonic tone and activation level in the mood-creativity link: toward a dual pathway to creativity model. *J. Pers. Soc. Psychol.* 94 (5), 739–756. <https://doi.org/10.1037/0022-3514.94.5.739>.

Fink, A., Benedek, M., 2014. EEG alpha power and creative ideation. *Neurosci. Biobehav. Rev.* 44, 111–123. <https://doi.org/10.1016/j.neubiorev.2012.12.002>.

Fink, A., Neubauer, A.C., 2006. EEG alpha oscillations during the performance of verbal creativity tasks: differential effects of sex and verbal intelligence. *Int. J. Psychophysiol.* 62 (1), 46–53. <https://doi.org/10.1016/j.ijpsycho.2006.01.001>.

Fink, A., Neubauer, A.C., 2008. Brain correlates underlying the generation of original ideas. *Int. J. Psychophysiol.* 69 (3), 178. <https://doi.org/10.1016/j.ijpsycho.2008.05.468>.

Fink, A., Grabner, R.H., Neuper, C., Neubauer, A.C., 2005. EEG alpha band dissociation with increasing task demands. *Cognit. Brain Res.* 24 (2), 252–259. <https://doi.org/10.1016/j.cogbrainres.2005.02.002>.

Fink, A., Grabner, R.H., Benedek, M., Neubauer, A.C., 2006. Divergent thinking training is related to frontal electroencephalogram alpha synchronization. *Eur. J. Neurosci.* 23 (8), 2241–2246. <https://doi.org/10.1111/j.1460-9568.2006.04751.x>.

Fink, A., Benedek, M., Grabner, R.H., Staudt, B., Neubauer, A.C., 2007. Creativity meets neuroscience: experimental tasks for the neuroscientific study of creative thinking. *Methods* 42 (1), 68–76. <https://doi.org/10.1016/j.ymeth.2006.12.001>.

Fink, A., Grabner, R.H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., Neuper, C., Ebner, F., Neubauer, A.C., 2009a. The creative brain: investigation of brain activity during creative problem solving by means of EEG and fMRI. *Hum. Brain Mapp.* 30 (3), 734–748. <https://doi.org/10.1002/hbm.20538>.

Fink, A., Graif, B., Neubauer, A.C., 2009b. Brain correlates underlying creative thinking: EEG alpha activity in professional vs. Novice dancers. *Neuroimage* 46 (3), 854–862. <https://doi.org/10.1016/j.neuroimage.2009.02.036>.

Fink, A., Schwab, D., Papousek, I., 2011. Sensitivity of EEG upper alpha activity to cognitive and affective creativity interventions. *Int. J. Psychophysiol.* 82 (3), 233–239. <https://doi.org/10.1016/j.ijpsycho.2011.09.003>.

Goldberg, L.R., 1992. The development of markers for the big-five factor structure. *Psychol. Assess.* 4 (1), 26–42. <https://doi.org/10.1037/1040-3590.4.1.26>.

Grabner, R.H., Fink, A., Neubauer, A.C., 2007. Brain correlates of self-rated originality of ideas: evidence from event-related power and phase-locking changes in the EEG. *Behav. Neurosci.* 121 (1), 224–230. <https://doi.org/10.1037/0735-7044.121.1.224>.

Grabner, R.H., Krenn, J., Fink, A., Arendasy, M., Benedek, M., 2018. Effects of alpha and gamma transcranial alternating current stimulation (tACS) on verbal creativity and intelligence test performance. *Neuropsychologia* 118, 91–98. <https://doi.org/10.1016/j.neuropsychologia.2017.10.035>.

Guilford, J.P., 1967. *The Nature of Human Intelligence*. McGraw-Hill.

Haegens, S., Handel, B.F., Jensen, O., 2011. Top-down controlled alpha band activity in somatosensory areas determines behavioral performance in a discrimination task. *J. Neurosci.* 31 (14), 5197–5204. <https://doi.org/10.1523/jneurosci.5199-10.2011>.

Hanslmayr, S., Sauseng, P., Doppelmayr, M., Schabus, M., Klimesch, W., 2005. Increasing individual upper alpha power by neurofeedback improves cognitive performance in human subjects. *Appl. Psychophysiol. Biofeedback* 30 (1), 1–10. <https://doi.org/10.1007/s10484-005-2169-8>.

Hass, R.W., Beaty, R.E., 2018. Use or consequences: probing the cognitive difference between two measures of divergent thinking. *Front. Psychol.* 9 <https://doi.org/10.3389/fpsyg.2018.02327>.

Hummel, F., Andres, F., Altenmüller, E., Dichgans, J., Gerloff, C., 2002. Inhibitory control of acquired motor programmes in the human brain. *Brain* 125 (2), 404–420. <https://doi.org/10.1093/brain/awf030>.

Jaarsveld, S., Fink, A., Rinner, M., Schwab, D., Benedek, M., Lachmann, T., 2015. Intelligence in creative processes: an EEG study. *Intelligence* 49, 171–178. <https://doi.org/10.1016/j.intell.2015.01.012>.

Jauk, E., Benedek, M., Neubauer, A.C., 2012. Tackling creativity at its roots: evidence for different patterns of EEG alpha activity related to convergent and divergent modes of task processing. *Int. J. Psychophysiol.* 84 (2), 219–225. <https://doi.org/10.1016/j.ijpsycho.2012.02.012>.

Jaušovec, N., 1997. Differences in EEG alpha activity between gifted and non-identified individuals: insights into problem solving. *Gift. Child. Q.* 41 (1), 26–32. <https://doi.org/10.1177/001698629704100104>.

Jaušovec, N., 2000. Differences in cognitive processes between gifted, intelligent, creative, and average individuals while solving complex problems: an EEG study. *Intelligence* 28 (3), 213–237. [https://doi.org/10.1016/s0160-2896\(00\)00037-4](https://doi.org/10.1016/s0160-2896(00)00037-4).

Jensen, O., Mazaheri, A., 2010. Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Front. Hum. Neurosci.* 4 <https://doi.org/10.3389/fnhum.2010.00186>.

Jensen, O., Bonnefond, M., VanRullen, R., 2012. An oscillatory mechanism for prioritizing salient unattended stimuli. *Trends Cognit. Sci.* 16 (4), 200–206. <https://doi.org/10.1016/j.tics.2012.03.002>.

Johnson, H.J., Barnard-Brak, L., Saxon, T.F., Johnson, M.K., 2012. An experimental study of the effects of stereotype threat and stereotype lift on men and women's performance in mathematics. *J. Exp. Educ.* 80 (2), 137–149. <https://doi.org/10.1080/00220973.2011.567312>.

Jończyk, R., Kremer, G.E., Siddique, Z., Hell, J.G., 2020. Engineering creativity: prior experience modulates electrophysiological responses to novel metaphors. *Psychophysiology* 57 (10). <https://doi.org/10.1111/psyp.13630>.

Klimesch, W., 2012. Alpha-band oscillations, attention, and controlled access to stored information. *Trends Cognit. Sci.* 16 (12), 606–617. <https://doi.org/10.1016/j.tics.2012.10.007>.

Klimesch, W., Sauseng, P., Hanslmayr, S., 2007. EEG alpha oscillations: the inhibition timing hypothesis. *Brain Res. Rev.* 53 (1), 63–88. <https://doi.org/10.1016/j.brainresrev.2006.06.003>.

Kray, L.J., Thompson, L., Galinsky, A., 2001. Battle of the sexes: gender stereotype confirmation and reactance in negotiations. *J. Pers. Soc. Psychol.* 80 (6), 942–958. <https://doi.org/10.1037/0022-3514.80.6.942>.

Lee, T.-W., Girolami, M., Sejnowski, T.J., 1999. Independent component analysis using an extended infomax algorithm for mixed subgaussian and supergaussian sources. *Neural Comput.* 11 (2), 417–441. <https://doi.org/10.1162/08997669930016719>.

Leslie, S.-J., Cimpian, A., Meyer, M., Freeland, E., 2015. Expectations of brilliance underlie gender distributions across academic disciplines. *Science* 347 (6219), 262–265. <https://doi.org/10.1126/science.1261375>.

Logel, C., Walton, G.M., Spencer, S.J., Iserman, E.C., Hippel, W. von, Bell, A.E., 2009. Interacting with sexist men triggers social identity threat among female engineers. *J. Pers. Soc. Psychol.* 96 (6), 1089–1103. <https://doi.org/10.1037/a0015703>.

Luksyte, A., Unsworth, K.L., Avery, D.R., 2017. Innovative work behavior and sex-based stereotypes: examining sex differences in perceptions and evaluations of innovative work behavior. *J. Organ. Behav.* 39 (3), 292–305. <https://doi.org/10.1002/job.2219>.

Lustenberger, C., Boyle, M.R., Foulser, A.A., Mellin, J.M., Fröhlich, F., 2015. Functional role of frontal alpha oscillations in creativity. *Cortex* 67, 74–82. <https://doi.org/10.1016/j.cortex.2015.03.012>.

Makeig, S., Delorme, A., Westerfield, M., Jung, T.-P., Townsend, J., Courchesne, E., Sejnowski, T.J., 2004. Electroencephalographic brain dynamics following manually responded visual targets. *PLoS Biol.* 2 (6), e176. <https://doi.org/10.1371/journal.pbio.0020176>.

Martindale, C., Hasenfus, N., 1978. EEG differences as a function of creativity, stage of the creative process, and effort to be original. *Biol. Psychol.* 6 (3), 157–167. [https://doi.org/10.1016/0301-0511\(78\)90018-2](https://doi.org/10.1016/0301-0511(78)90018-2).

Martindale, C., Mines, D., 1975. Creativity and cortical activation during creative, intellectual and eeg feedback tasks. *Biol. Psychol.* 3 (2), 91–100. [https://doi.org/10.1016/0301-0511\(75\)90011-3](https://doi.org/10.1016/0301-0511(75)90011-3).

Nguyen, H.-H.D., Ryan, A.M., 2008. Does stereotype threat affect test performance of minorities and women? A meta-analysis of experimental evidence. *J. Appl. Psychol.* 93 (6), 1314–1334. <https://doi.org/10.1037/a0012702>.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the edinburgh inventory. *Neuropsychologia* 9 (1), 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4).

Oostenveld, R., Oostendorp, T.F., 2002. Validating the boundary element method for forward and inverse EEG computations in the presence of a hole in the skull. *Hum. Brain Mapp.* 17 (3), 179–192. <https://doi.org/10.1002/hbm.10061>.

O'Brien, L.T., Crandall, C.S., 2003. Stereotype threat and arousal: effects on women's math performance. *Pers. Soc. Psychol. Bull.* 29 (6), 782–789. <https://doi.org/10.1177/014616720329006010>.

Proudfoot, D., Kay, A.C., Koval, C.Z., 2015. A gender bias in the attribution of creativity. *Psychol. Sci.* 26 (11), 1751–1761. <https://doi.org/10.1177/0956797615598739>.

Puccio, G.J., 2017. From the dawn of humanity to the 21st century: creativity as an enduring survival skill. *J. Creativ. Behav.* 51 (4), 330–334. <https://doi.org/10.1002/jocb.203>.

Ritter, S.M., Abbing, J., Schie, H. T. van, 2018. Eye-closure enhances creative performance on divergent and convergent creativity tasks. *Front. Psychol.* 9 <https://doi.org/10.3389/fpsyg.2018.01315>.

Rominger, C., Papousek, I., Perchtold, C.M., Benedek, M., Weiss, E.M., Schwerdtfeger, A., Fink, A., 2019. Creativity is associated with a characteristic u-shaped function of alpha power changes accompanied by an early increase in functional coupling. *Cognit. Affect. Behav. Neurosci.* 19 (4), 1012–1021. <https://doi.org/10.3758/s13415-019-00699-y>.

Sadaghiani, S., Kleinschmidt, A., 2016. Brain networks and α -oscillations: structural and functional foundations of cognitive control. *Trends Cognit. Sci.* 20 (11), 805–817. <https://doi.org/10.1016/j.tics.2016.09.004>.

Schmader, T., Johns, M., Forbes, C., 2008. An integrated process model of stereotype threat effects on performance. *Psychol. Rev.* 115 (2), 336–356. <https://doi.org/10.1037/0033-295X.115.2.336>.

Schwab, D., Benedek, M., Papousek, I., Weiss, E.M., Fink, A., 2014. The time-course of EEG alpha power changes in creative ideation. *Front. Hum. Neurosci.* 8 <https://doi.org/10.3389/fnhum.2014.00310>.

Spencer, S.J., Steele, C.M., Quinn, D.M., 1999. Stereotype threat and women's math performance. *J. Exp. Soc. Psychol.* 35 (1), 4–28. <https://doi.org/10.1006/jesp.1998.1373>.

Spencer, S.J., Logel, C., Davies, P.G., 2016. Stereotype threat. *Annu. Rev. Psychol.* 67 (1), 415–437. <https://doi.org/10.1146/annurev-psych-073115-103235>.

Steele, C.M., 1997. A threat in the air: how stereotypes shape intellectual identity and performance. *Am. Psychol.* 52 (6), 613–629. <https://doi.org/10.1037/0003-066x.52.6.613>.

Steele, C.M., Aronson, J., 1995. Stereotype threat and the intellectual test performance of african americans. *J. Pers. Soc. Psychol.* 69 (5), 797–811. <https://doi.org/10.1037/0022-3514.69.5.797>.

Steele, C.M., Spencer, S.J., Aronson, J., 2002. Contending with Group Image: the Psychology of Stereotype and Social Identity Threat, vol. 34. Academic Press, pp. 379–440. [https://doi.org/10.1016/S0065-2601\(02\)80009-0](https://doi.org/10.1016/S0065-2601(02)80009-0).

Stevens, C.E., Zabelina, D.L., 2019. Creativity comes in waves: an EEG-focused exploration of the creative brain. *Curr. Opin. Behav. Sci.* 27, 154–162. <https://doi.org/10.1016/j.cobeha.2019.02.003>.

Wallach, M.A., Torrance, E.P., 1968. Torrance tests of creative thinking: norms – technical manual. *Am. Educ. Res. J.* 5 (2), 272. <https://doi.org/10.2307/1161826>.

Wianda, E., Ross, B., 2019. The roles of alpha oscillation in working memory retention. *Brain Behav.* 9 (4), e01263 <https://doi.org/10.1002/brb3.1263>.

Wilson, R.C., Guilford, J.P., Christensen, P.R., Lewis, D.J., 1954. A factor-analytic study of creative-thinking abilities. *Psychometrika* 19 (4), 297–311. <https://doi.org/10.1007/bf02289230>.