

Positive future thinking without task-relevance increases anxiety and frontal stress regulation

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ABSTRACT

Negative anticipatory biases can affect the way we interpret and subjectively experience events. Through its role in emotion regulation, positive future thinking may provide an accessible way to attenuate these biases. However, it is unclear whether positive future thinking works ubiquitously, independent of contextual relevance. Here, we used a positive future thinking intervention (task-relevant; task-irrelevant and control condition) prior to a social stress task to adapt the way this task was experienced. We assessed subjective and objective stress measures and also recorded resting state electroencephalography (EEG) to assess intervention related differences in the level of frontal delta-beta coupling, which is considered a neurobiological substrate of stress regulation. Results show that the intervention reduced subjective stress and anxiety, and increased social fixation behavior and task performance, but only if future thinking was task-relevant. Paradoxically, task-irrelevant positive future thoughts enhanced negative perceptual biases and stress reactivity. This increase in stress reactivity was corroborated by elevated levels of frontal delta-beta coupling during event anticipation, which suggests an increased demand for stress regulation. Together, these findings show that positive future thinking can mitigate the negative emotional, behavioral and neurobiological consequences of a stressful event, but that it should not be applied indiscriminately.

1. Introduction

Anticipatory anxiety and stress are as much a part of everyday life as they are of certain mental disorders. Such anxiety is associated with negatively biased expectations and interpretations that can cause emotional distress (Butler & Mathews, 1987; Mathews & MacLeod, 2002). Expectations have an important role in guiding behavior and the interpretation of novel information. They are typically shaped by prior experience (Gilboa & Marlatt, 2017), which provides a perceptual filter that influences attention (Hutchinson & Turk-Browne, 2012; Ryan & Shen, 2020), perception (Dijkstra et al., 2021; Mather & Sutherland, 2011) and ultimately memory (Audrain & McAndrews, 2020; Masís-Obando et al., 2021). Negative expectations do not just protect an individual from threat but also help moderate emotional responses to unpleasant situations, or prevent them altogether (Miloyan et al., 2016). However, it can bias processing of novel experiences, so negativity can over time become disproportionate to the situation (Clark & Beck, 2010).

Expectations of an event may be expressed and evaluated through

episodic future thinking. This involves the mental simulation, or pre-experiencing, of future events by recombining elements from previous experiences (Addis et al., 2008). Future thinking is important for a range of cognitive functions including planning, likelihood estimation, decision making, and emotion regulation (Schacter et al., 2017). Its role in emotion regulation is also reflected on a neural level. Future simulation relies on functional connectivity between the hippocampus and prefrontal cortex during event construction (Benoit et al., 2014; Campbell et al., 2018; Demblon et al., 2016), an area that has been related to emotion regulation processes and cognitive control. Because episodic future thinking takes a role in both the expression of anticipatory bias and the regulation of the accompanying emotional response, it may provide an accessible way to attenuate negatively biased cognitions.

Indeed, recent work shows that future thinking can positively bias the interpretation of neutral narratives (Devitt & Schacter, 2018), and inhibit the recollection of contextually similar scenarios (Ditta & Storm, 2016). Furthermore, increasing the level of episodic detail with which future events are simulated enhances emotion regulation strategies and improve psychological well-being towards worrisome future events

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(Jing et al., 2016, 2017). Beyond future thinking, positive imagery interventions have been developed to reduce anticipatory anxiety and stress (Pile et al., 2021). Interventions that use personally or contextually relevant imagery appear to produce consistent effects (e.g. Landkroon et al., 2021; Renner et al., 2019). However, it is unclear whether they work ubiquitously, independent of context or trait predisposition, and if these effects go beyond subjective experience. Of particular interest is whether task-relevance is indeed a boundary condition for the effect of positive interventions, and whether trait anxiety may limit efficacy as it is associated with deficits in emotion regulation (Cho et al., 2019; Liu et al., 2018).

Here, we addressed those questions by having participants imagine positive future events before being subjected to the Trier Social Stress Test (TSST; Kirschbaum et al., 1993), which is an aversive task that involves an impromptu presentation in front of a jury panel. To address the notion that efficacy might depend on task-relevance of the intervention, we compared no-intervention controls to participants who imagined either positive task-relevant or task-irrelevant future events. The goal was to mitigate the negative emotional response that is generally triggered by the TSST using positive future thinking, and skew subjective perception towards more positive interpretations of this stressful task. We expected both intervention groups to benefit from the intervention compared to controls, but expected that the task-relevant group would show the most improvement. We used a combination of self-report measures, eye tracking, and electroencephalography (EEG) to assess intervention-related differences in stress reactivity and emotion regulation.

Emotion regulation depends on connectivity between the pre-frontal cortex and limbic areas, like the hippocampus and amygdala (Banks et al., 2007). Cross-frequency coupling, or the interaction between two different neural oscillation frequencies, can be used as a measure for such functional connectivity (Canolty & Knight, 2010). Of interest is the level of coupling between delta (1–4 Hz), associated with affective processing and anxiety (Knyazev, 2007; Knyazev et al., 2005), and beta (14–30 Hz) oscillations, associated with cognitive control (Buschman & Miller, 2007; Engel & Fries, 2010). Frontal delta-beta amplitude-amplitude coupling has been proposed as a marker for trait level stress regulation efficiency, as it could differentiate between low and high levels of social anxiety in anticipation of a social stressor (Poppelaars et al., 2018). Furthermore, and of particular interest for this study, frontal delta-beta phase-amplitude coupling (PAC) has been proposed as a neural marker for emotion and stress regulation (Schutter & Knyazev, 2012; Schutter et al., 2006). Earlier reports, that used a similar task design as the current study, showed that in individuals with low levels of social anxiety delta-beta PAC typically increases when state nervousness and anxiety increase (Knyazev, 2011; Poppelaars et al., 2018). Therefore, delta-beta PAC specifically could be a viable measure for differences in stress and emotion regulation in a low anxiety sample like we present here. However, these earlier studies do not include measures that reflect whether higher PAC is associated with more effective regulation of stress, merely that PAC increases as a response to stress. Thus, it remains unclear whether increases in delta-beta PAC during stress anticipation are reflective of adaptive stress regulation, or rather stress reactivity.

2. Methods

2.1. Participants

We tested 65 students recruited at the Utrecht University campus, none of whom self-reported any current psychiatric impairment (i.e. no current diagnosis with an anxiety (related) disorder, major depressive disorder, or manic episode. Furthermore, female participants were required to be on hormonal birth control to control for potential bias in the hormonal stress response due to fluctuations of female hormones (Espin et al., 2013). Participants were randomly assigned to one of three

experimental groups: task-irrelevant positive, task-relevant positive and control. All participants provided written informed consent. A power analysis (G*Power Version 3.1; Faul, Erdfelder, Buchner, & Lang, 2009) based on prior research (Devitt & Schacter, 2018; Ditta & Storm, 2016) showed that a sample size of at least 18 per group was necessary to detect an effect of the positive future intervention on task appraisal (power = 0.80, $\eta_p^2 = 0.16$). Taking potential missing values into account, we aimed to test 20 participants per group. They were remunerated with money or course credit for their participation. The study was approved by the institutional ethical review board at Utrecht University (FETC19–053).

Three participants were excluded due to technical problems that forced us to quit the test session prematurely. This led to a sample size of 62 before data pre-processing (21 task-irrelevant, 21 task-relevant, 20 control). Furthermore, 6 participants (4 task relevant, 1 task-irrelevant and 1 control) were excluded from the eye-tracking analyses due to missing data (see Eye tracking pre-processing for further details on exclusion criteria), and 3 participants (one of each group) were excluded from the EEG analysis due to poor data quality.

2.2. Procedure

Data acquisition took place over two consecutive days. The first session took place in the lab between 12:00 and 18:00 to limit variability in stress reactivity due to the circadian cortisol rhythm. Participants started by filling out a battery of trait and state questionnaires followed by 5 min of eyes closed resting state EEG. This was followed by the positive future thinking intervention (see Positive Future Thinking), and then the Trier Social Stress Test (see TSST). For the control group, the order of these two tasks was reversed. Regardless of experimental group, the TSST was always directly followed by a questionnaire on task appraisal and memory for the preceding event. The second session consisted of a follow up questionnaire that consisted of the same items as the Task Appraisal Self-Report and a debriefing. This session was completed at home.

Positive Future Thinking. Participants were subjected to a positive future thinking intervention either before (task-irrelevant and task-relevant) or after (control) the TSST. For all groups, the intervention consisted of vividly imagining 15 positive episodic future events that could occur within the next five years of their lives. Participants were instructed to imagine the event in as much detail as they could, and to envision scenarios that evoked a highly positive emotion. For each trial, participants were shown a positively valenced cue word, e.g. successful or confident (see Materials section for the full list), that they could use as a starting point to imagine an event. All participants, irrespective of intervention group, were shown the same 15 cue words (one for each of the 15 trials), but the order was randomized between participants. Participants in all conditions were instructed to imagine a different event for each trial. While the cue words ensured differentiation to some degree, we asked participants to type a short title (3 – 5 words) for each event to ensure task compliance and diversity in the imagined events.

In the task-relevant condition, participants were instructed to imagine positive future events that could occur within the next 5 years based on the displayed cue word that involved them giving an oral presentation in front of 2 or more people. For example, for the cue word ‘successful’ someone might envision themselves giving a poster presentation at a conference and successfully convincing a skeptical researcher. To allow more diversity between scenario’s any event involving some type of public speaking, such as receiving an award or a thesis defense, was accepted as ‘presenting’ as long as they were the one speaking.

In the task-irrelevant condition, participants were instructed to imagine positive future events that could occur within the next 5 years based on the displayed cue word that they would generally experience to be positive. For example, for the cue word ‘successful’ someone might envision themselves getting the news that they finally got their dream apartment after much searching.

The task started with two practice trials to familiarize participants with the procedure. Practice trials were 3 min each, and required participants to describe the imagined event. The experimenter would use questions from the Autobiographical Interview to guide the participant to envision an event that had the appropriate level of episodic detail and emotional intensity. For the remaining 13 trials, per trial one cue word was presented in the middle of the screen for 45 s. The experimenter was in the room with the participant during the intervention to further ensure that participants adhered to the task instructions. Trials were separated by a 5 s break, and a longer break of one minute halfway down the task.

TSST. The presentation part of the Trier Social Stress Test (Kirschbaum et al., 1993) was used as the aversive episodic event that all participants were subjected to. Right before onset of the task, participants were informed that they would have to give an impromptu 5 min presentation as if it were a job interview in front of a jury panel, whom they would be able to see through a video call. Participants were led to believe that the jury panel would be evaluating both their presentation and behavioral characteristics, and that their entire presentation would be recorded for subsequent analysis. In reality the 'video call' was a prerecorded video. To further standardize the presentation, all participants had to give a presentation on Climate Change and were given a list of 10 facts about this topic which they had to memorize and incorporate in their presentation. The specific topic was only revealed once they received the fact sheet.

The task could be divided in five phases: task instruction, fact sheet reading, mental preparation, presentation and recovery. EEG was recorded during the mental preparation and recovery phase, and eye tracking was recorded during the presentation phase.

After the task instruction, participants were given 2 min to study the fact sheet followed by 5 min to mentally prepare their presentation. The fact sheet was not available during the preparation time and participants were not allowed to talk or take notes. Following the preparation time, participants completed the PASA questionnaire (Gaab et al., 2005) to assess anticipatory stress and could click to place the video call to the jury panel to start their presentation. During the presentation, the test leader scored the amount of facts from the fact sheet that were included in the presentation. If participants ran out of material, the test leader could give predefined content prompts (e.g. What have you done to impact or benefit the environment?). After 5 min of presentation time, the experiment continued automatically to a 5 min recovery phase where participants had to sit in silence and fixate on a fixation cross. Following the recovery phase, all participants completed the STAI-S, and a set of 11 visual analogue scales at assessing subjective task appraisal.

2.3. Materials and stimuli

2.3.1. Cue words intervention

Cue words were selected from a subset 25 positively valenced cue words that are commonly used as part of the Autobiographical Memory Task (Williams & Broadbent, 1986). An independent student sample ($N = 21$) rated all 25 words on subjective valence and arousal, as well as ease of simulation for both generally positive events and events involving an oral presentation. Words that rated highest across all four measures were selected for use. The following 15 cue words were used in all three conditions: successful, confident, friendly, enthusiastic, proud, smart, cheerful, respected, liked, peaceful, relaxed, interested, happy, comfortable, admired.

2.3.2. Baseline self-report

Measures of key traits underlying the current tasks (i.e. anxiety, stress, memory and imagery) were taken to assess a priori group differences, as well as a baseline measure for state anxiety. Specifically we assessed state and trait anxiety levels using the State Trait Anxiety Inventory (STAI-S and STAI-T; Spielberg et al., 1970), trait worry using the Penn State Worry Questionnaire (PSWQ; Meyer et al., 1990), stress

reactivity using the Perceived Stress Scale i.e., standard deviation units; (PSS; S. Cohen et al., 1983), and vividness of mental imagery using the Vividness of Visual Imagery Questionnaire (VVIQ; McKelvie, 1995). Scores for all questionnaires were computed using their respective scoring manual.

2.3.3. Task-appraisal self-report

A second battery of questionnaires was administered right after the recovery phase of the TSST to assess post event state anxiety and task appraisals. For state anxiety we again used the STAI-S.

For post-event task appraisals, we used a combination of the visual analogue scales that are part of the Primary Appraisal and Secondary Appraisal scale (PASA; Gaab et al., 2005) and items that were designed specifically for this study. The first part of the PASA was administered right before the presentation phase of the TSST, and consists of 16 items on anticipatory stress that are rated on a 6 point Likert-scale (1 strongly disagree – 6 strongly agree).

The second part of the PASA is administered after the stress-inducing event (in this case the TSST presentation) and consists of four visual analogue scales (0 not at all – 100 totally) on the level of experienced stress during and level of experienced control over the event. We elaborated on this scale with 7 more items. Of the novel items, two related to the level of physical and emotional discomfort ("The past situation was embarrassing for me" and "I felt physically uncomfortable in the past situation") and two to confidence in their own performance ("I think my presentation went well" and "If I were asked to give the presentation again I would do it exactly the same way"). These items were rated on the same scale as the original PASA items (i.e., 0 not at all – 100 totally). Furthermore, three items assessed subjective appraisal of the jury panel. Of these three, one used the original scale ("I thought the jury panel was intimidating") and two were rated from negative to positive (0–100; "I think the judges evaluated my presentation" and "I felt the facial expressions of the jury panel were"). After reverse scoring positively worded items, all ratings were summed and averaged with the three jury-items forming their own category.

2.3.4. TSST video

In the original protocol for the TSST (Kirschbaum et al., 1993), the presentation participants give is held in front of a live audience of judges that are in the same room with the participant. However, several video based adaptations of this procedure have been developed over the years to accommodate the use of specific measures or manipulations. These adapted versions, even animated VR environments (e.g. Zimmer et al., 2019), are generally found to be equally as effective as the original in-vivo setup. Here, we opted to use a pre-recorded video of the jury panel both to standardize the experience between participants and to accommodate the recording of EEG and eye-tracking during the TSST.

Three actors were recruited as jury members. Actors were instructed to wear professional attire. The recording started with a brief introductory statement ("Welcome, thank you for preparing this presentation. You may start now.") by the head jury member, seated in the middle, to sell the idea of a live video connection. This was followed by 5 min of silent observing as if the jury were actually listening to a presentation. As per the official TSST protocol, the jury was asked to refrain from giving verbal or non-verbal feedback during the entirety of the recording. However, taking notes and attentive listening were encouraged. Jury members looked directly into the camera to make it look like they were making eye contact from the participants perspective. After 5 min the head jury member notified the participant that their presentation time was up and that they would disconnect the call ("Well time is up, thank you for your presentation. We will now close this connection."). Following this statement, one of the other jury members pressed a button on their laptop and the video switched to a black screen.

2.4. Eye tracking recording and pre-processing

Eye tracking was recorded using a Tobii T120. Calibration was done right before the task instructions of the TSST, using a 9 point fixation calibration.

Pre-processing of the eye tracking signal was performed in Tobii Studio. First, participants were rejected if gaze detection was less than 60% during the presentation phase. For the remaining dataset, areas of interest (AOI) were set as ellipses around the faces of the three jury members. The number of fixations and fixation duration (in ms) were calculated for all AOI's and non-AOI using the automatic detection mechanism in Tobii Studio. The average fixation duration and total amount of fixations on each area were calculated per 1 min interval to assess changes in fixation behavior throughout the 5 min presentation.

2.5. EEG recording and software

EEG recording was done using 64 Ag/AgCl electrodes placed in an extended 10–20 montage and collected at a 1024 Hz sampling rate using the ActiveTwo BioSemi system (BioSemi, The Netherlands). Biosemi Common Mode Sense (CMS) active electrode and Driven Right Leg (DRL) passive electrode replaced the conventional ground electrode, and CMS was used as the online reference. Vertical EOG was measured with two Ag-AgCl electrodes placed above and below the right eye. Offline pre-processing of the EEG time series was performed using MATLAB (The Mathworks, Version 9.6.0.1472908, R2019a) with EEGLAB (Version 2020).

2.6. EEG pre-processing

The EEG signal was downsampled to 512 Hz. Data was re-referenced to the average of all 64 electrodes and offline band-pass filtered between 1 and 40 Hz (24 dB/oct), with a 50-Hz notch filter (zero-phase shift). Noisy channels were interpolated. Ocular artefacts were removed from the non-resting state data (mental preparation and recovery) using the ocular correction ICA method in EEGLAB. For each condition, data was then segmented into 8-second non-overlapping epochs (4096 time samples), to have sufficient low-frequency cycles to detect dPAC (Aru et al., 2015). The first and last 15 epochs of both tasks were manually inspected for gross artifacts and excluded if necessary. Out of those, three early and three late clean epochs were selected for use in further analysis. These three early and three late epochs of the resting state, mental preparation, and recovery were exported to ASCII files for further analyses. The focus of this study includes frontally mediated delta-beta PAC, to allow comparisons with relevant studies (Harrewijn et al., 2016; Poppelaars et al., 2018) and to reduce the risk of the multiple comparisons problem. F3, Fz and F4 were selected for further analysis. PAC analyses were performed as in Poppelaars et al. (2018) using custom scripts. The selected EEG epochs were down-sampled to 128 Hz, and band-pass filtered separately for delta (1–4 Hz) and beta (14–30 Hz) using a Butterworth IIR bandpass filter by using a zero phase-shift filtering method (with a filter order of 8 for delta and 34 for beta; which doubled after using both a forward and a backward filter). A Hilbert transform was applied to the delta and beta filtered epochs to isolate the phase and amplitude information (Abrahams & Papoulis, 1984). The first and last 16 samples – equal to the order of the lower frequency's filter (cf., Knyazev, 2011) – were cut from each epoch to remove edge artefacts originating from filtering (Aru et al., 2015; Kramer et al., 2008).

2.7. Debiased phase-amplitude coupling analysis

PAC analyses between delta phase and beta amplitude were performed using the debiased PAC (dPAC) method (Cox et al., 2014; van Driel et al., 2015) with custom-written scripts (as in Poppelaars et al., 2018), to fit the current data specifications and research interests.

Delta-beta dPAC and the accompanied Z-values were calculated for each participant and electrode, over the six epochs, and were thereafter averaged over three frontal electrodes (F3, Fz and F4), yielding one dPAC and Z-value per participant, per condition. dPAC was calculated by removing the phase clustering from the traditional PAC method (cf., Canolty et al., 2006) via a simple linear subtraction (cf., Cox et al., 2014; van Driel et al., 2015). PAC can be defined as:

$$PAC = \sum_{t=0}^n \alpha_t e^{i\varphi_t}$$

where α_t represents the amplitude of the modulated frequency (i.e., beta amplitude), and φ_t represents the phase of the modulating frequency (i.e., delta phase), t is time, and n is the total number of time samples. The phase clustering (PC) is calculated by averaging the complex vector of phase angles ($e^{i\varphi_t}$), from which the magnitude (or strength) and angle of clustering can be determined:

$$PC = \frac{1}{n} \sum_{t=1}^n e^{i\varphi_t}$$

It should be noted that by not including the beta amplitude α , all complex numbers have the same length, and, therefore, all angles have the same weight in the averaging process. This allows for determining the average angle, or PC. For dPAC, the aforementioned complex numbers, $\alpha_t e^{i\varphi_t}$ (combining beta amplitude α and delta phase φ) are averaged for all time samples, correcting the phase angle of the complex numbers by the earlier obtained PC:

$$dPAC = \frac{1}{n} \sum_{t=1}^n \alpha_t (e^{i\varphi_t} - PC)$$

The dPAC value is expressed as the magnitude of the averaged complex number, where zero indicates no coupling, and values greater than zero indicate coupling. The significance of the coupling was established by comparing the dPAC values to surrogate dPAC values that were obtained via a non-parametric permutation testing approach (Maris & Oostenveld, 2007) by randomly shuffling epochs for phase information, while amplitude remained intact. This shuffling process was repeated 1000 times, yielding a distribution of surrogate dPAC values as expected under the null hypothesis of no coupling. This method not only allows for significance testing but also accounts for possible outliers (van Driel et al., 2015). Significant dPAC was determined by comparing dPAC to their surrogate counterparts ($dPAC_{null}$) to obtain Z-values (dPACz):

$$dPACz = \frac{dPAC - \text{mean}(dPAC_{null})}{\text{std}(dPAC_{null})}$$

These Z-values were used for hypothesis testing due to their straightforward interpretation i.e., standard deviation units; (i.e., standard deviation units; Cohen, 2014).

3. Results

3.1. Subjective measures

3.1.1. No baseline group differences

Participants started with a baseline assessment of state and trait anxiety levels (STAI; Spielberg et al., 1970), as well as trait based levels of worry (PSWQ; Meyer et al., 1990), stress reactivity (PSS; S. Cohen et al., 1983) and imagery ability (VVIQ; McKelvie, 1995). Group comparisons (see Table 1) revealed no significant baseline differences on any of the measures: trait anxiety (STAI-T), $F(2, 61) = 0.073$, $p = .93$, state anxiety (STAI-S), $F(2, 61) = 1.07$, $p = .350$, worry (PSWQ), $F(2, 61) = 0.092$, $p = .912$, stress reactivity (PSS), $F(2, 61) = 1.939$, $p = .153$, and visual imagery ability (VVIQ), $F(2, 61) = 1.000$, $p = .374$. This suggests that the randomization of participants across conditions was successful.

Table 1

Demographics and Baseline Questionnaire scores (Means and SD) per experimental group.

	Task-Irrelevant	Task-Relevant	Control	Total
N participants (F/M)	21 (16 F/5 M)	21 (12 F/9 M)	20 (13 F/7 M)	62 (41 F/21 M)
Age	23.5 (3.1)	23.5 (2.5)	24.5 (3.6)	23.8 (3.1)
STAI-State Baseline	31.7 (4.4)	34.6 (9.7)	31.9 (6.1)	32.7 (7.1)
STAI-Trait	38.3(8.3)	38.7 (9.9)	37.7 (8.3)	38.2 (8.8)
PSWQ	46.5 (10.5)	46.7 (13.6)	45.2 (11.8)	46.2 (11.9)
PSS	16.1 (5.5)	16.2 (6.1)	12.9 (6.6)	15.1 (6.2)
VVIQ	58.4 (13.7)	55.8 (7.7)	60.3 (8.8)	58.2 (10.5)

Note. No significant group differences were found for any of the measures.

3.1.2. Task-irrelevant positive future thinking leads to more stress reactivity during anticipation

After the anticipation phase (see Fig. 1B), we assessed subjective levels of anticipatory stress using the Primary Appraisal (situational threat and challenge) and Secondary Appraisal (situational control and self-confidence) scale (PASA; Gaab et al., 2005). A positive Stress Index (primary – secondary) reflects that the perceived threat or challenge outweighs the perceived ability to control the situation. We found a significant main effect of group, $F(2, 59) = 4.815$, $p = .012$, $\eta_p^2 = .14$, that was driven by a higher Stress Index in the task-irrelevant group compared to both the task-relevant and control group (see Fig. 1C).

3.1.3. Task-relevant positive future thinking prevents event-related negativity and anxiety

Directly after the TSST, participants completed the STAI-S again to assess changes in State Anxiety following their presentation. A 2 (time: Baseline, Recovery) x 3 (Group: Task-irrelevant, Task-relevant, Control) mixed analysis of variance (ANOVA) revealed a significant interaction between time and group (see Fig. 1D), $F(2, 59) = 5.914$, $p = .005$, $\eta_p^2 = .167$. This interaction was explained by an increase in State Anxiety in the Control, $t(19) = -3.263$, $p = .004$, $d = 0.72$, and Task-Irrelevant group, $t(20) = -4.462$, $p = .000$, $d = 0.93$, but not in the Task-Relevant group, $t(20) = 0.243$, $p = .81$, $d = 0.05$.

Participants also completed an 11-item questionnaire that assessed their subjective appraisal of their performance and the event itself (i.e. the TSST presentation). Experimental groups differed significantly from each other in overall task appraisal (see Fig. 1F), $F(2, 59) = 7.608$, $p = .001$, $\eta_p^2 = .205$. Pairwise comparisons (Bonferroni corrected) showed that the Task-Relevant group ($M = 43.9$, $SD = 3.5$) appraised the task significantly more positively ($p = .001$) than the Task-Irrelevant group ($M = 63.3$, $SD = 3.5$), and at a trend level ($p = .088$) compared to the Control group ($M = 55.2$, $SD = 3.6$). These effects persisted in the follow-up measurement 24 h later.

3.2. Behavioral measures

3.2.1. Task-relevant positive future thinking boosts task performance

To assess whether the intervention enhanced task performance, we calculated the number of climate change facts that participants remembered to incorporate in their presentation. We found a significant effect of group $F(2, 59) = 3.481$, $p = .037$, $\eta_p^2 = .11$, that was explained by the task-relevant group ($M = 6.67$, $SD = 1.35$) presenting significantly more facts than the control group ($M = 5.15$, $SD = 2.01$), $t(39) = 2.849$, $p = .007$, $d = 0.89$. However, contrary to what might be expected based on the subjective data, the task-relevant group did not present more facts than the task-irrelevant group ($M = 6.1$, $SD = 2.11$), $t(39) = -1.041$, $p = .304$, $d = 0.46$.

3.3. Cross-frequency EEG measures

3.3.1. Delta-beta dPAC increases as a function of trait anxiety and stress

We expected that levels of frontal delta-beta phase-amplitude coupling (see Supplementary Fig. S2) would increase more for the intervention groups (Task-Relevant > Task-Irrelevant) leading up to the TSST compared to the control group, and wind down again during recovery. To assess this, we ran two linear mixed regression models, one for the upward slope (early baseline to late anticipation) and one for the downward slope (late anticipation to late recovery), using group and time as fixed factors and allowing random slopes per subject. Compared to the control group, delta-beta dPAC levels in the task-irrelevant group increased at trend level from early baseline into late anticipation ($\beta = 0.11$, $p = .09$) and decreased again from late anticipation to late recovery ($\beta = -0.17$, $p = .07$) (see Fig. 2A). This trend was not found for the Task-Relevant group.

Next, to assess the effect of trait vulnerability on emotion regulation and the interaction with the intervention groups, we included Trait Anxiety as a fixed effect in both models. Leading up to late anticipation, we found a significant interaction between group, time and trait anxiety levels, $F(2, 178.94) = 3.053$, $p = .04$ (see Fig. 2B and C). Trait anxiety significantly predicted increases in dPAC over time in the Task-Irrelevant group ($\beta = .019$, $p = .014$). From late anticipation to late recovery, higher levels of trait anxiety were also associated with a steeper, though not significant, decrease in dPAC in the Task-Irrelevant group ($\beta = -.02$, $p = .07$).

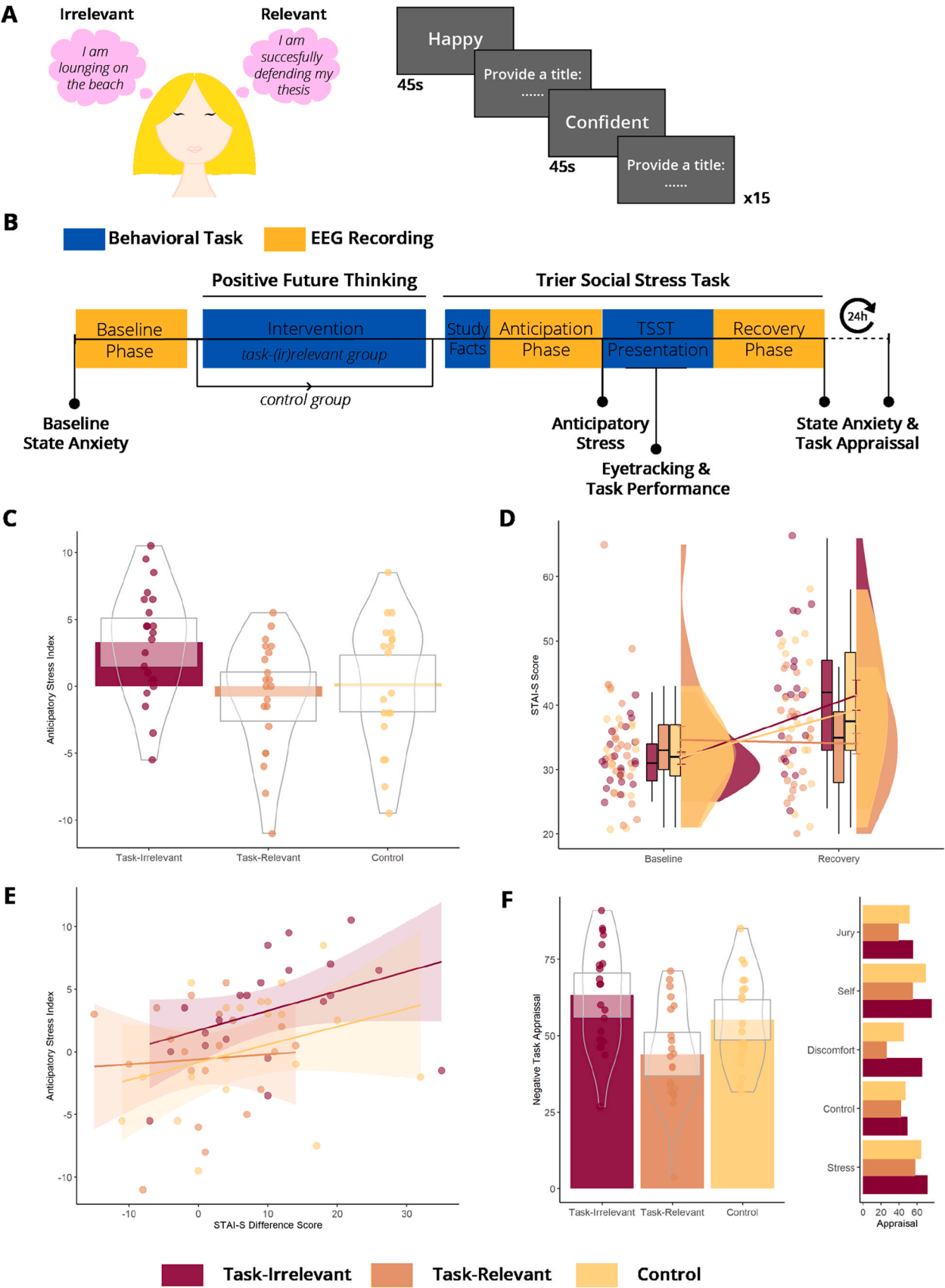
To explore whether delta-beta PAC coded for stress reactivity rather than emotion regulation, we used delta-beta dPAC scores during late anticipation as a predictor for changes in State Anxiety levels pre to post TSST (Recovery minus Baseline). The hypothesis here was that if delta-beta PAC reflects emotion regulation it should be negatively related to task-related changes in State Anxiety. Indeed, increased delta-beta coupling in the Task-Irrelevant group was negatively predictive of task-related increases in State Anxiety ($\beta = -12.3$, $p = .06$) (see Fig. 2D).

4. Discussion

In this study, we investigated if positive future thinking can be used to attenuate negatively biased perception of a social stressor (TSST). Our data show that task relevance of the intervention, and not positivity alone, determines its benefit. Positivity without task relevance led to more negative task appraisal and a more severe stress reaction in response to the social stressor. This adverse effect of the task-irrelevant positive intervention may have been somewhat counteracted by the engagement of neural stress regulation mechanisms.

Our hypotheses regarding the working mechanism of the interventions were centered on the notion that positive future thinking promotes effective emotion regulation, as a way of planning ahead (i.e. the event will still be stressful but participants feel more in control). Instead, we found that when the intervention is task-relevant, it seemingly prevents the stress reaction that the TSST typically induces. Participants in the task-relevant group reported comparable levels of anticipatory stress to the control group and did not show a task related increase in state anxiety while both the control and task-irrelevant group did.

Perhaps anticipatory anxiety in the task-relevant imagery group did not translate into state anxiety increase during the TSST because the participants simulated and planned successful presentations scenarios. Another possible explanation for the discrepancy between task-relevant and irrelevant future thinking in terms of stress response is that the former intervention modulates memory schema activity. Higher-order conceptual knowledge is used as a perceptual filter that facilitates the interpretation of novel information as well as the selection of appropriate actions (Gilboa & Marlatte, 2017; Wang & Morris, 2010). Through future thinking, the task-relevant group may have instantiated



(caption on next page)

Fig. 1. Design and Subjective Data. **A)** Task design Positive Future Thinking intervention. Participants either imagined 15 generally positive future events (Task-Irrelevant Group) or 15 positive future events where they gave a presentation (Task-Relevant Group). Positively valenced cue words were presented to aid event construction. Participants were asked to provide a title for every imagined event to ensure task-compliance. **B)** Study design including timepoints at which specific measures were taken. **C)** Response distribution for Anticipatory Stress Index. Colored bars represent group mean, white squares show 95% CI, violins and points show distribution of individual participants. Positive scores reflect maladaptive stress while negative scores reflect adaptive stress. **D)** Between groups response distribution and group means of STAI-S scores at Baseline and post-TSST Recovery. Graph shows an increase in State Anxiety for the Task-irrelevant and Control group, but not for the Task-relevant group. Scores on the STAI-S range from 20 to 80. **E)** Correlation between Anticipatory Stress levels and task-related changes in State Anxiety. **F)** Subjective task appraisal scores separated by experimental group. Bars represent mean scores, violin and points show response distribution, boxes represent 95% CI. To the right, appraisal scores are separated by both experimental group and appraisal sub-scale. Scores ranged from 0 (not negative at all) to 100 (very negative).

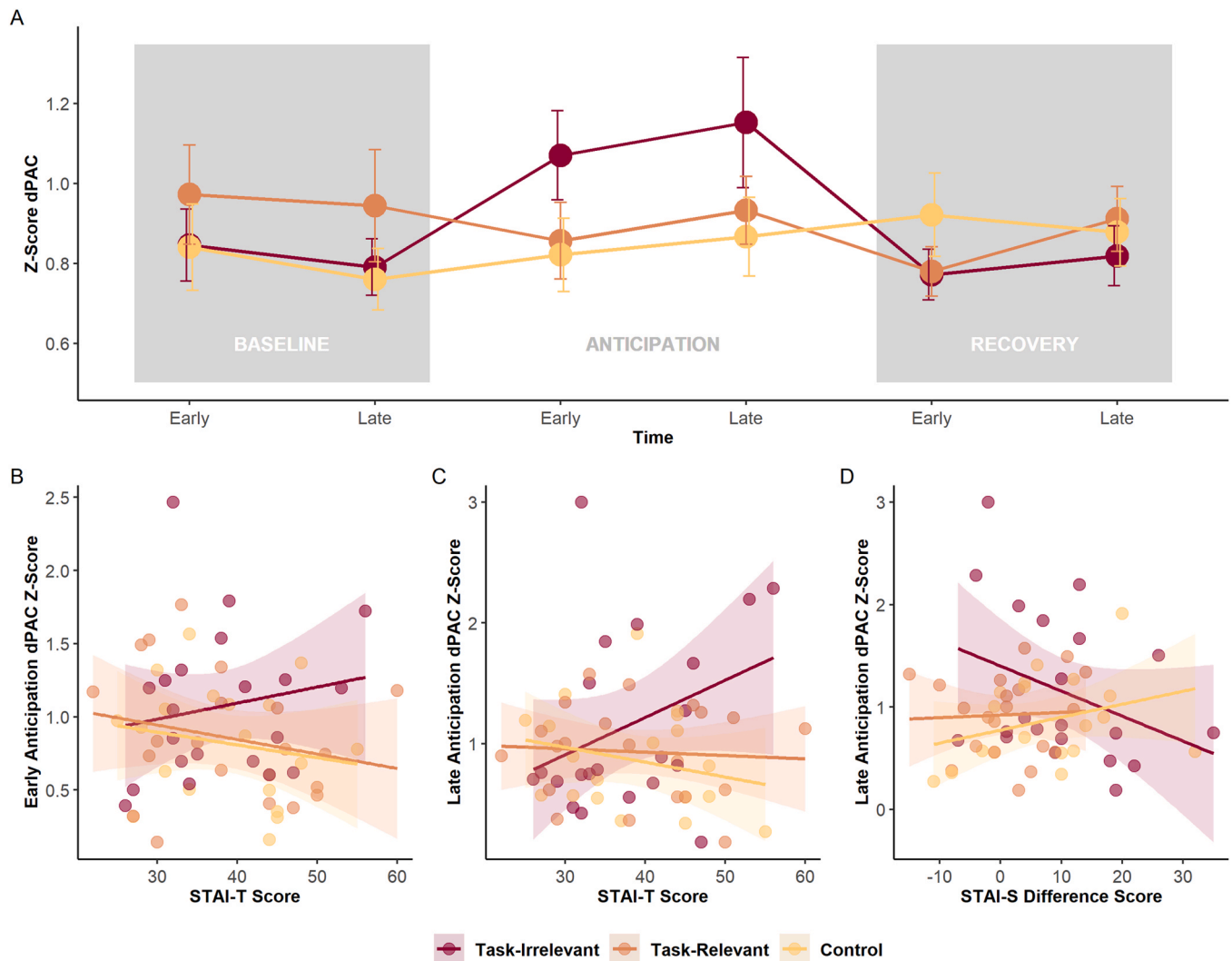


Fig. 2. Delta-beta phase amplitude coupling. **A)** Mean and SE of Z-scored delta-beta dPAC (average of electrodes Fz, F3 and F4) per experimental group. Line graph shows the progression of dPAC levels over the three phases of the experiment (Baseline, Anticipation and Recovery). Early and Late reflect an average dPAC level for the first (early) and last (late) 80 s of that phase. **B)** Scatter plot showing group differences in the correlation between Early Anticipation dPAC and Trait Anxiety scores. **C)** Correlation between Late Anticipation dPAC and Trait Anxiety scores **D)** Correlation between Late Anticipation dPAC and State Anxiety Difference scores (Recovery – Baseline).

contextually appropriate positive schema, which likely caused the interpretation of the new external information to assimilate into the active schema (Gilboa & Moscovitch, 2017; Tse et al., 2007). In the task-irrelevant group, the instantiated schema did not hold contextually relevant information that could help the individual deal with the stressor. Such incongruity may have prompted the reinstatement of the dominant schema for having to give a presentation in front of a jury (Frühholz et al., 2011; van Kesteren et al., 2020), which is negatively biased for many people. Furthermore, due to this incongruence, these participants may have felt less prepared to deal with the stressor, as suggested by heightened anticipatory stress and stronger engagement of

frontal emotion regulation compared to controls. Participants in the control group were also negatively affected by the stressor, but may have felt relatively more prepared during anticipation, because they were not distracted with irrelevant positive information beforehand.

This study has important implications and recommendations for psychological interventions that leverage positive imagery or simulation-based learning to reduce anxiety. First, positivity should not be applied indiscriminately. General positivity training may be beneficial in affective disorders like depression (Boland et al., 2018), where overall positivity tends to be reduced (Bjärehed et al., 2010), but it does not help to reduce anticipatory anxiety and (paradoxically) increases it.

However, similar to our findings, work on affective forecasting errors has shown that unmet positive expectations can negatively affect well-being (Wilson & Gilbert, 2005) and suggests that people may even downward adjust their subsequent future expectations as a result (Bertoni & Corazzini, 2018). This reality problem is something the positive psychology movement has also been criticized for in the past (Held, 2004). As data from our task-irrelevant group shows, by replacing negatively biased event anticipation with irrelevant positive information, the individual may feel less equipped to handle the situation. Second, the task-relevant positive future thinking intervention is effective even if it does not specifically address the upcoming stressful situation. That is, our task-relevant group imagined scenarios where they gave a presentation, but the presentations could concern anything from a wedding speech to a job application. This might be helpful in situations where individuals have a difficult time envisioning positive alternatives to a highly feared situation. Finally, due to its positive effects on state anxiety and task performance, task-relevant positive future thinking could be a useful tool to enhance both exposure willingness and efficacy in pathological anxiety (also see Landkroon et al., 2021).

This work extends findings on the transfer of valence through simulation-based learning. A recent study showed that future thinking can serve as a substitute for lived experience in updating pre-existing beliefs or attitudes. By imagining liked (or disliked) people together with a neutral location, participants changed their appraisal of the location towards the valence associated with the person (Paulus et al., 2022). Here, we show that such transfer of valence does not just apply to existing semantic representations, but also immediately affects the interpretation of new experiences that are semantically related. These positive effects on event appraisal remain at 24-hour follow-up. So, while it is unclear whether future thinking can establish long-term changes in pre-existing beliefs, the effects on information learned directly following the intervention are relatively stable.

Our findings also extend earlier work on the relation between stress and frontally mediated delta-beta coupling. Functionally, delta-beta PAC has been positioned as a stress regulation mechanism. This assumption is fueled by previous research (Knyazev, 2011; Poppelaars et al., 2018) showing that coupling increases as a function of state nervousness during anticipation (but see Poppelaars et al., 2021), which our results corroborate. However, these earlier studies do not include measures that reflect whether higher PAC is associated with more effective regulation of stress, merely that PAC increases as a response to stress. This study shows that people with higher levels of delta-beta PAC during anticipation tend to have a lower or no increase in state anxiety following the stressor. While replication of these findings is certainly needed given the limited sample size, our data provide preliminary support for the notion that delta-beta PAC is reflective of adaptive stress regulation. However, as noted by others (Brooker et al., 2016; Harrewijn et al., 2016; Poppelaars et al., 2021), whether this mechanism is actually engaged seems to depend both on context and trait predisposition.

Elevations in delta-beta PAC during stress anticipation were limited to the task-irrelevant group (i.e. the group with the highest subjective levels of anticipatory stress), and were not statistically robust. The latter may in part be due to variability in trait anxiety within this group, which was positively correlated to levels of delta-beta coupling. So, only participants in the task-irrelevant group with high levels of trait anxiety increased in delta-beta PAC during anticipation. Since only a small percentage of our sample met these specific conditions, these analyses lack power and would require replication to verify the validity of the effect. However, similar moderating effects of trait anxiety have been found for other slow/fast wave EEG patterns, like delta-beta and theta-beta ratio, in relation to stress regulation and threat bias (Angelidis et al., 2018; Putman, 2011; van Son et al., 2018). This may suggest that some individuals with a trait vulnerability engage this frontal delta-beta PAC system to regulate stress when cognitive resources that help deal with the situation are low. It should be noted that increased activity does not automatically mean that emotion regulation is also effective (Kret

et al., 2011; Sylvester et al., 2012), as our data also suggest. Highly anxious individuals may exert more effort to regulate their emotions in response to stress but vary in their level of efficiency in doing so. This was also shown in an IAPS picture viewing task, in which individuals with high trait anxiety showed greater engagement of prefrontal emotion regulation systems to establish similar levels of emotional down-regulation as low-anxiety individuals (Campbell-Sills et al., 2011).

Our work complements existing work on frontal emotion regulation using other EEG-derived markers, like frontal alpha asymmetry. In contrast to the current experiment, where emotion regulation efficiency was assessed indirectly as a function of state anxiety changes, work on the up and down-regulation of emotion has shown a correlation to frontal asymmetry in the alpha frequency band. On a trait level, effective emotion regulation is related to greater left frontal alpha asymmetry (i.e. alpha power decreases from the left to right hemisphere) (Choi et al., 2016). Furthermore, similar to our results, frontal alpha asymmetry has been related to state dependent (only in high stress conditions) differences in emotion regulation (Goodman et al., 2012). Future work may focus on the independent contributions of these EEG derived markers of emotion regulation. One possibility is that alpha asymmetry, due to its role in the functional association between the frontal lobe and amygdala, is important for regulating emotional experience. Whereas delta-beta coupling may facilitate effective goal-directed behavior needed to manage the situation at hand, as suggested by its involvement in decision making (Riddle et al., 2022) and attentional control (Morillas-Romero et al., 2015).

While the use of delta-beta coupling in relation to emotion regulation and social anxiety is not new (Poppelaars et al., 2018, 2021), analyses typically focus on the contrast between two groups (e.g. high and low trait anxiety). Leveraging the temporal resolution of EEG, it is possible to track the functional dynamics of cortical-subcortical crosstalk measures, like delta-beta coupling, over time and in relation to specific task contexts (e.g., Brooker et al., 2016). We opted to average coupling over longer epochs, to ensure comparability to earlier work. However, delta-beta coupling dynamics can even be tracked on a millisecond scale using MEG (Arnal et al., 2015). Furthermore, recent work has shown that emotion (regulation) dynamics can be tracked using EEG microstates (Hu et al., 2023; Zerna et al., 2021). These efforts present exciting new ways to examine the precise temporal dynamics of EEG/MEG derived correlates of emotion regulation.

A limitation to the current work is the relatively small sample size, in particular for the eye-tracking data where a lot of data was lost due to quality issues. The power analysis for this study was based on the behavioral effect and therefore may not be representative for the eye-tracking and EEG data. Nevertheless, the study was adequately powered for the behavioral data, which show a consistent benefit of task-relevant positive future thinking over task-irrelevant future thinking or no intervention. Another limitation of this study is the absence of affect measures throughout the experiment. In following the TSST protocol (Kirschbaum et al., 1993) we included the Stress Index right before onset of the presentation, and added a second measure of State Anxiety directly following the TSST. To delineate the proposed mechanism behind the paradoxical effect of task-irrelevant positive future thinking, future research may use affect measures at different stages of the experiment to clarify how and when imagery exercises increase different facets of positive affect.

To summarize, positive future thinking can be an effective tool to induce a priori positive reappraisal of aversive situations and enhance task performance and goal-directed behavior. However, the contextual relevance of the imagined future scenarios to the aversive event is a clear boundary condition for this effect: when future thinking is incongruent with the aversive event, it can (paradoxically) increase stress and anxiety. Task-relevant positive future thinking may be used to increase willingness and efficacy of exposure therapy for pathological anxiety and could be an accessible way for people to deal with negative

anticipation in daily life. Over time, this could help to update the negative biases surrounding these situations, but this is an empirical question that awaits future research.

Ethics approval

The study was approved by the institutional ethical review board at Utrecht University (FETC19–053).

Open practices statement

The experiment reported in this article was not preregistered. Requests for raw data and materials can be e-mailed to the corresponding author. Pre-processed data that were used for the main analyses can be found at: https://osf.io/tj9q5/?view_only=1f28e17503104c3b8b8de42bae9fcac4.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

The authors affirm that human research participants provided informed consent for publication.

CRediT authorship contribution statement

NDM, LG and IME designed the study; NDM collected the data; NDM, DvS and LG analyzed the data; all authors interpreted the data; NDM wrote the first draft of the article, and DvS, LG and IME provided critical revisions. All authors approved the final version of the manuscript for submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All materials, code and data are made available on the Open Science Framework. A link is provided in the open practices statement.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.biopsycho.2023.108620](https://doi.org/10.1016/j.biopsycho.2023.108620).

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