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RESEARCH ARTICLE

Stress and decision making: neural correlates of the interaction between stress, executive functions, and decision making under risk

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Abstract Stress and additional load on the executive system, produced by a parallel working memory task, impair decision making under risk. However, the combination of stress and a parallel task seems to preserve the decision-making performance [e.g., operationalized by the Game of Dice Task (GDT)] from decreasing, probably by a switch from serial to parallel processing. The question remains how the brain manages such demanding decision-making situations. The current study used a 7-tesla magnetic resonance imaging (MRI) system in order to investigate the underlying neural correlates of the interaction between stress (induced by the Trier Social Stress Test), risky decision making (GDT), and a parallel executive task (2-back task) to get a better understanding of those behavioral findings. The results show that on a behavioral level, stressed participants did not show significant differences in task performance. Interestingly, when comparing the stress group (SG) with the control group, the SG showed a greater increase in neural activation in the anterior prefrontal cortex when performing the 2-back task simultaneously with the GDT than when performing each task alone. This brain area is associated with parallel processing. Thus, the results may suggest that in stressful dual-tasking situations, where a decision has to be made when in parallel working memory is demanded, a stronger activation of a brain area associated with parallel processing takes place. The findings are in line with the idea that stress seems to trigger a switch from serial to parallel processing in demanding dual-tasking situations.

Keywords Stress · Decision making under risk · GDT · 2-back task · Executive functions · Serial-to-parallel shift

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Introduction

Decision making is a key function in human everyday life. Sometimes, decisions are less important, without far-reaching consequences, and easy to make, such as which clothes to wear or which meal to cook. However, in some situations, people have to make decisions with potentially severe consequences, for example, a doctor in the operating room, a policeman during a street fight, or a stock market trader who has to decide which company shares to buy or to sell. These situations often elicit psychological stress, which could have an influence on the decisions people make. Additionally, these situations often require making more than one decision at the same time. In these situations, people have to make crucial decisions in a stressful setting while working on another problem simultaneously. It is important to understand what happens to peoples' decision-making performance in such situations.

The field of neuropsychological decision-making research distinguishes between decisions under ambiguity and decisions under risk (Brand et al. 2006). In decisions under ambiguity, no explicit information about the potential outcome and the possible consequences of different decisions is provided (operationalized by the Iowa Gambling Task (IGT); Bechara et al. 1994). People have

to rely on their hunches and guesses of what constitutes a good or bad decision (Bechara et al. 1997). In contrast, in decisions under risk, the decision maker has knowledge about the probabilities of different potential outcomes—or the probabilities are explicitly provided—and can largely estimate the possible consequences (Brand et al. 2006). An often used task to measure decision making under risk is the Game of Dice Task (GDT; Brand et al. 2005). In this computer-based task consisting of 18 trials, participants are asked to bet which number will be thrown by a single die in order to maximize their starting capital. The bet can be placed on a single number or on a combination of two, three, or four numbers. The difference between these options lies in the amount of money that can be won or lost (between €100 and €1,000) and in the winning probabilities that are associated with each option (between 16.67 and 66.67 %). While the single-number option and the combination of two numbers can be seen as disadvantageous or high-risk decisions (with winning probabilities below 34 %), the three- and four-number combinations are more advantageous or rather low-risk decisions (with winning probabilities from 50 % upward and a likely positive outcome in the long run). Although the options of three numbers are neither advantageous nor disadvantageous (as they have an expected value of zero), it should be mentioned that choosing these options every time would statistically lead to a positive final balance, given the starting capital of €1,000 (Bayard et al. 2011; Brand et al. 2009).

A recent study using this task investigated the interaction between stress, decision making under risk, and additional executive load (Pabst et al. 2013). The participants were divided into four groups: a stress group (SG) and a control group (CG) performing only the GDT (single-task condition) and a SG and a CG performing the GDT plus an additional working memory 2-back task (dual-task condition). In the 2-back task, participants have to indicate whether the current number seen on the screen is the same as the one shown two numbers before. Pabst and colleagues (2013) found that while stress led to diminished GDT performance in the single-task condition, in the dual-task condition stress seems to preserve the decision-making performance from decreasing, resulting in comparable GDT performances in the dual-task condition and in the single-task condition. However, when comparing the decision-making performance between the two CGs, they found that participants performing the additional 2-back task in parallel made more disadvantageous decisions than participants performing the GDT by itself. These results are in line with previous studies demonstrating negative influence of stress on GDT performance (Starcke et al. 2008) and diminished decision-making performance while performing a secondary executive task simultaneously (Starcke et al. 2011). Still, of more interest is the fact that stress combined with a parallel executive task seems to retain good decision-making performance. Due to the fact that the GDT and 2-back task require the same cognitive processing system (c.f. Starcke et al. 2011), system 2, both tasks should be processed serially (Evans 2003; Kahneman 2003), which means while concentrating on one task set, the information of the second task set is inhibited (Koch et al. 2010). This cognitive control mechanism enables subjects to shield one task from competing distractors by narrowing the subjects' attention to this particular task (see Easterbrook 1959). At the same time, it allows monitoring for potential second-task-associated action information (Miller and Cohen 2001; Plessow et al. 2011), in order to switch to the second task if necessary. Plessow et al. (2011) showed that under acute stress task shielding increases when performing a single task. However, when performing a dual task under acute stress, task shielding decreases in order to enable a cognitive shift from a serial to parallel goal monitoring (Plessow et al. 2012a, b). Plessow et al. (2012a, b) concluded that acute stress triggers a task-processing mode which is less resource-demanding (see also Arnsten 2009; Schwabe et al. 2010b). While in a single-task situation the less resource-consuming task-processing mode is associated with tonic task shielding, in dual-task situations it is associated with a reduction in task shielding that increases parallel processing (Lehle et al. 2009). Moreover, they found that this serial-to-parallel shift did not impair task performance (see also Schwabe et al. 2010a). Based on these findings, Pabst et al. (2013) argue that in their study stress may also have induced a cognitive shift from serial to parallel goal monitoring, but only in the dual-tasking condition where parallel performance is necessary, leading to preserved performance in the decision-making task. The question remains what happens in the brain in such demanding situations and which brain areas are involved.

Neuroimaging studies investigating the underlying neural mechanisms of decision making under risk found that the dorsolateral prefrontal cortex (dlPFC) in particular, the anterior cingulate cortex (ACC), and parts of the posterior parietal lobe are involved in decision making under risk (Ersche et al. 2005; Forbes et al. 2006; Labudda et al. 2008; Manes et al. 2002; Rao et al. 2008; Rubinsztein et al. 2001; Wilbertz et al. 2012). Those areas are also crucially involved in executive functioning (Gläscher et al. 2012; Jurado and Rosselli 2007; Lie et al. 2006), which are important for decision making under risk (e.g., Brand et al. 2008; Schiebener et al. 2011). However, the orbitofrontal/ventromedial prefrontal cortex and limbic-related structures are also activated during decision making under risk (Clark et al. 2008; Ernst et al. 2004; Forbes et al. 2006; Jurado and Rosselli 2007; Rogers et al. 1999a, b, 2004; Xue et al. 2010). These findings fit nicely with the results of a recent functional magnetic resonance imaging

(fMRI) study by Gläscher et al. (2012), demonstrating that the aforementioned brain areas are involved in two functional–anatomical pathways: a cognitive one, which includes the dlPFC and the ACC, and a value-based one, which includes, among others, the orbitofrontal/ventromedial prefrontal cortex. These findings support the assumption by Brand et al. (2006) that beyond the necessity of the cognitive pathway, emotional processing is also involved in decision making under risk. Studies comparing the decision-making performance of healthy controls with patients who have lesions or dysfunctions to limbic and prefrontal brain areas support these findings by demonstrating that these patients made more disadvantageous decisions in the GDT (Brand et al. 2005, 2007; Delazer et al. 2007; Drechsler et al. 2008; Euteneuer et al. 2009; Fond et al. 2012; Svaldi et al. 2012).

Studies addressing the neural correlates of stress revealed heterogeneous findings. Some studies found that stress leads to deactivation in brain regions such as the orbitofrontal cortex (Pruessner et al. 2008; Tillfors et al. 2001) and other regions associated with the limbic system, e.g., hippocampus and hypothalamus (Dedovic et al. 2009; Pruessner et al. 2008), ACC (Åhs et al. 2006; Pruessner et al. 2008), and dlPFC (Åhs et al. 2006; Oei et al. 2007; Pruessner et al. 2008; Qin et al. 2009). In contrast, other studies demonstrated an increase in some of the same brain regions during stress exposure: ACC and dlPFC (Dedovic et al. 2009; Tillfors et al. 2002; Wang et al. 2005), and limbic-related structures, e.g., the hippocampus, the amygdala, the thalamus, and the insular cortex (Ito et al. 2003; Tillfors et al. 2002; Wang et al. 2005). Results are not consistent, and it remains unclear whether stress leads to an increased or decreased activation of prefrontal and limbic structures. Apart from this, it is assumable that because decision making and stress reactions are associated with overlapping brain areas, stress can modulate decision making as discussed before (see also the review by Starcke and Brand 2012). However, no study investigated the underlying neural correlates of the interaction between stress, decision making, and an additional executive load. What are the neural correlates of the suggested shift to a parallel goal monitoring and thus to advantageous decision making in dual-task situations as described by Pabst et al. (2013)?

The present study was conducted in order to close this gap. We used the same task paradigm used in the study by Pabst et al. (2013), but modified for fMRI. In one group, stress was induced before the scans, while a second group served as CG. In order to compare GDT performance with GDT plus 2-back performance, all participants had to perform single-task and dual-task conditions. At behavioral level, we assumed to replicate the findings by Pabst and colleagues that acute stress in combination with a parallel executive task leads to preserved decision-making performance. Concerning the neural correlates, we hypothesized for the CG that dorsolateral prefrontal areas as well as parts of the ACC would be activated in particular during the GDT plus 2-back task (contrasts: GDT plus 2-back>; GDT plus 2-back > GDT; GDT plus 2-back > 2-back; GDT plus 2-back < GDT; GDT plus 2-back < 2-back), given that these regions are activated when a person processes gains/losses in combination with winning probabilities and also in a working memory paradigm (Labudda et al. 2008, 2010; Owen et al. 2005). Of special interest was the comparison between the SG and the CG, concerning the difference in activations between a dual-task condition and a single-task condition. We hypothesized that stress would lead to changes in neural activity in brain areas also involved in task performances, i.e., dorsolateral prefrontal areas and parts of the ACC. Moreover, we assumed that the shift from serial to parallel processing is associated with the same brain areas. This was assumed because those regions are known to be involved in the executive control mechanisms (Alvarez and Emory 2006; D'Esposito et al. 1995), which in turn are presumed to be engaged in the serial-to-parallel shift. Studies with similar types of stressors (Åhs et al. 2006) as well as comparable points in time when the stressor takes place (before fMRI and before a cognitive task, Åhs et al. 2006; Oei et al. 2007; Qin et al. 2009) displayed deactivation in the dlPFC and ACC. However, because several studies were also able to demonstrate an increase in these brain areas during stress (Dedovic et al. 2009; Tillfors et al. 2002; Wang et al. 2005), the neural activity changes will be analyzed in both directions (contrast for increase in activation: SG > CG, GDT plus 2-back > GDT alternatively 2-back; contrast for decrease in activation: CG > SG, GDT plus 2-back > GDT alternatively 2-back).

Methods

Participants

We examined 38 right-handed, healthy participants. The participants were randomly assigned to either the SG ($n = 19$) or the CG ($n = 19$). Exclusion criteria, as determined by telephone screening, were history of or current neurological or psychiatric diseases, acute or chronic diseases, and stressful life circumstances. Smokers and participants with current intake of medication, body mass index above 30 kg/cm^2 or lower than 18 kg/cm^2, recent immunization, hormonal contraceptive, or pregnancy were excluded because these criteria influence the measurement of stress hormones. Further exclusion criteria concerned issues interfering with the magnetic field of the fMRI, such

as active implants, mechanical contraception, or any metal objects that were not removable from the body. A further exclusion criterion was claustrophobia. Additionally, participants were requested not to engage in exhausting physical activities at least 24 h before the testing, to refrain from drinking alcohol at least 24 h before the testing, and to wake up at least 2 h before the testing. Furthermore, all participants were instructed not to eat or drink anything other than water 1 h before and during the study. All participants were recruited by advertisements and were paid €10/h for participation. Student participants obtained credits for courses. Participants gave written informed consent prior to the investigation. After participation, they were fully debriefed about the goal of the study. The study was approved by the ethics committee of the German Society of Psychology. Due to problems in data acquisition, because of software malfunctions, artifacts in salivary samples, and one participant dropping out of the scanning session, the final groups consisted of $n = 16$ in the SG and $n = 17$ in the CG. The two groups did not differ regarding gender (SG: 9 men and 7 women, CG: 8 men and 9 women, $\chi^2 = 0.28$, $df = 1$, $p = .598$) or age ($M_{SG} = 23.69$, $SD_{SG} = 5.00$, $M_{CG} = 24.06$, $SD_{CG} = 5.07$, $t = 0.21$, $df = 31$, $p = .834$). Moreover, all participants started the experiment between 9:30 am and 6:00 pm, and there was no significant difference in starting time between the groups ($\chi^2 = 2.22$, $df = 3$, $p = .528$). There was also no difference between groups in the number of participants who started in the mornings (9:30 am and 11:40 am) and those who started in the afternoons (1:20 pm and 3:00 pm) ($\chi^2 = 0.79$, $df = 1$, $p = .373$).

Stress induction

Stress was induced using the Trier Social Stress Test (TSST; Kirschbaum et al. 1993). This test is an established procedure that induces moderate psychosocial stress and a distinctive activation of the hypothalamus–pituitary–adrenal (HPA) axis. In the TSST, participants had to deliver a free speech (after a preparation time of 5 min) followed by a demanding arithmetic task in front of a selection committee, each part lasting 5 min. The members of the committee were dressed in white lab coats and were introduced as psychologists who are specially trained to analyze speech and non-verbal behavior. Furthermore, it was announced that the speech will be video recorded. During the whole speech, the committee acted in a cold and non-responsive manner. In the no-stress control condition, the standardized control version of the TSST (placebo TSST; Het et al. 2009) was used. Here, participants also had to deliver a speech but not in front of a committee. They were alone in a room, not video recorded, and the arithmetic task was easier.

Measurements of stress response

Salivary cortisol

Endocrine indicators of stress were acquired by collecting salivary cortisol. A rise of cortisol concentration indicates the stress response due to HPA axis activity (see Dickerson and Kemeny 2004). Saliva was sampled five times (see the "Procedure" subsection below) using Salivette collection devices (Sarstedt, Nuembrecht, Germany) and was sent to the laboratory of Prof. Kirschbaum in Dresden, Germany, for analysis. An immunoassay (IBL, Hamburg, Germany) was used to measure free cortisol.

Positive and Negative Affect Schedule (PANAS)

The PANAS (Watson et al. 1988) was administered to measure the self-experienced stress level. In the German version of the PANAS, participants were asked to rate ten items for positive affect (e.g., "elated" and "excited") and ten items for negative affect (e.g., "distressed" and "hostile") on a five-point scale from 1 (*very slightly or not at all*) to 5 (*extremely*). The answers were added up to a positive affect score and a negative affect score, both ranging from 10 (minimum) to 50 (maximum).

The fMRI paradigm

In the fMRI within-subject design, three different experimental tasks were used: an fMRI version of the original GDT (see description in Brand et al. 2005), the GDT plus a parallel 2-back task (c.f. Starcke et al. 2011), and a single 2-back task (c.f. Schoofs et al. 2008). The experimental conditions are described in detail below. All experimental conditions had the same visual input in terms of screen organization and screen content. When performing the GDT alone, the interface of the 2-back task was frozen, showing one number that did not change. In contrast, when performing the 2-back task alone, the GDT interface was frozen, although the dice cup was being shaken. In the GDT plus 2-back task, the whole screen was activated. Each experimental condition lasted 144 s (for a detailed description of the tasks, see below). Moreover, two control tasks were used to normalize the blood-oxygenation-level-dependent (BOLD, Ogawa et al. 1990) signal (back to baseline) and to avoid carry-over effects of activation between the experimental conditions. In the high-level control task, participants were asked to indicate in which line a number or a number combination was highlighted. The duration was 144 s, and the task was performed twice. The order of the tasks was pseudo-randomized to minimize adaption to the tasks. The low-level control task lasted 30 s and was administered before an instruction window appeared (for 10 s) that

provided a short summary of the ensuing experimental task and the upcoming high-level control task. Additionally, the low-level control task was administered after the last task in the scanning session. The total duration of the study was 26.5 min. The two orders of the tasks were counterbalanced across groups. The fMRI data of each task were assembled, and the behavioral data for each task were averaged for both runs for analysis. To register the answers of the participants, they held two four-touch keypads in their hands. The keypad in the left hand was associated with the 2-back task and with the low-level control task. The keypad in the right hand was associated with the GDT and the high-level control task. To indicate the answers for the GDT plus 2-back task, both keypads had to be used simultaneously.

Experimental conditions

We designed an fMRI version of the GDT based on the original GDT (see description in the "Introduction" as well as in Brand et al. 2005) to measure decision making under risk for the first experimental condition. The goal of this task was to increase the fictitious starting capital of €1,000. A virtual die was thrown 18 times, and the participants were asked to guess each time which number would be thrown. Participants could bet either on one single number or on combinations of two, three, or four numbers, each associated with different winning probabilities: The choice of a single number provided a €1,000 gain/loss (winning probability 1:6); the choice of one of the other combinations provided a €500 gain/loss for two numbers (winning probability 2:6), a €200 gain/loss for three numbers (winning probability 3:6), and a €100 gain/loss for four numbers (winning probability 4:6). Even though the options were permanently shown on the screen, in this fMRI version of the GDT the participants were able to choose only one option of each possible category (one for each degree of risk). The available options were highlighted and pseudo-randomized across trials. This was performed to reduce the complexity of the game as well as to reduce artifacts in brain activation due to finger/hand movements, which would have been likely if participants had to select one of the alternatives with the mouse, as it is the case in the original GDT. In our fMRI version, participants had to indicate their answer on a four-touch keypad in the right hand, where each button was associated with one category. Furthermore, the decision time was limited to 4 s. If participants did not decide within the 4-s limit after the dice cup had started to shake, this trial was counted as a skip. In this case, "failure—no selection" appeared on the screen. After each decision or non-selection, the feedback (the amount of the gain/loss or the failure message) was given for 4 s before the next trial started immediately. This time interval corresponds to the average processing time reported in previous studies with the GDT. The time limit was set to ensure that all tasks were of equal duration, as mentioned above. In contrast to the original version of the GDT, it was possible to skip a trial in the current version if the participant did not indicate a decision on the keypad within 4 s. Therefore, the number of played rounds may differ between participants.

The second experimental condition was an fMRI version of the GDT with a parallel 2-back task (see Fig. 1). The goal of this condition was to perform as well as possible in each task and equally well on both tasks. The administered 2-back task was comparable to the high-load parallel executive task used by Starcke et al. (2011). Here, participants were asked to monitor the identities of numbers between 0 and 9. The numbers were presented in a pseudorandom sequence, and participants were asked to indicate with the keypad in the left hand whether the currently presented number was identical to the number presented two trials before. The stimuli were displayed for 500 ms with an interstimulus interval of 2,750 ms. Thus, participants had a time limit of 500 ms for making their response. The target stimuli (same stimulus as two trials before) were presented randomly with a probability of 33 % (c.f. Schoofs et al. 2008).

In the third experimental condition, participants had to work on the 2-back task alone.

Procedure and analysis

Procedure

The procedure was identical for the SG and the CG with one exception: The SG received the TSST (Kirschbaum et al. 1993) for stress inducement, whereas the CG received the placebo TSST (Het et al. 2009). After the participants had given written informed consent for the experiment, the practice part began. For each experimental condition, the participants received detailed instructions on the screen, followed by a short practice sequence for each task. The GDT was practiced alone for three trials and the 2-back task alone for 20 trials. For the GDT with parallel 2-back task, the GDT was practiced for three trials in parallel with the 2-back task for seven trials. Afterward, the PANAS was completed, and the first salivary sample (baseline) was taken. Subsequently, participants were brought to the room where the TSST or the placebo TSST took place, after which participants were asked to fill in the self-report again, and the second salivary sample was taken (+20 min). Next, participants were brought to the scanner room, and after a third salivary sample (+30 min), the fMRI procedure began. After the fMRI scanning (which in total lasted about an hour, including the experimental design plus shimming, anatomical scans, and preparation time), participants were asked to complete the PANAS and to give a fourth salivary

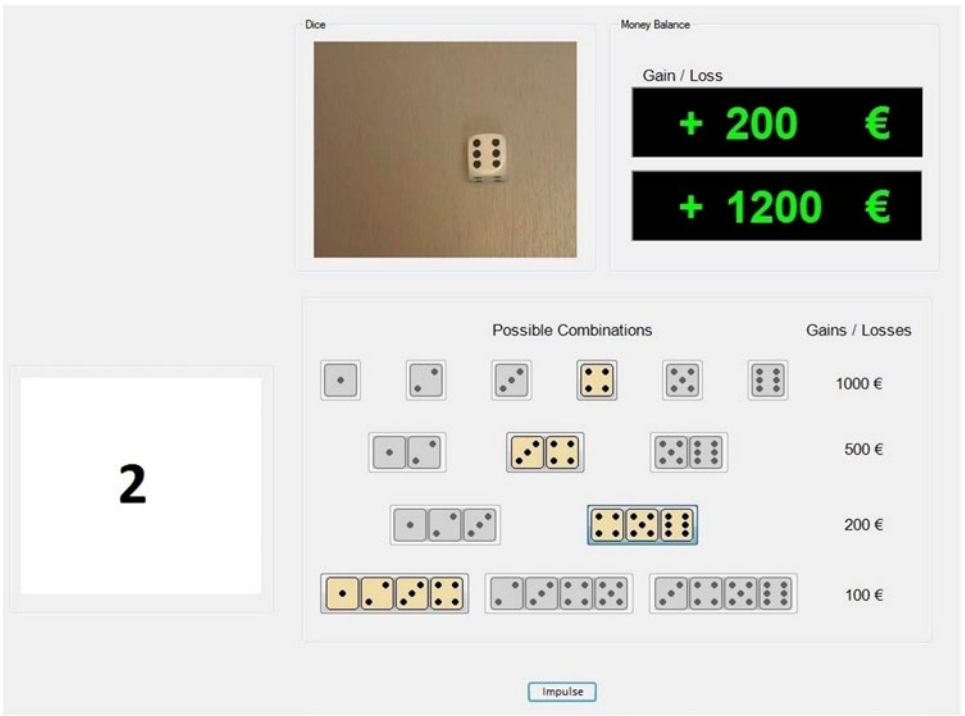

Fig. 1 The GDT plus 2-back task. On the right side of the screen, participants had to work on the GDT by betting which number will be thrown. They had to select one of the four highlighted possible combinations (one number, combination of two, three, or four numbers) with a four-touch keypad in the right hand. Afterward a die was thrown, followed by the feedback if the participants had won or lost. To the left side of the GDT interface, participants continuously had to monitor the numbers presented. Here, they had to indicate on a keypad in the left hand if the current number presented was already seen two trials before. For the single-task condition, either the right or left side of the screen was fixed. Thus, participants could only perform the GDT or the 2-back task by itself

sample (+95 min). The fifth salivary sample was taken during the debriefing (+105 min).

Functional MRI data acquisition

Functional MRI scanning was performed with a 7-tesla whole-body magnetic resonance imaging (MRI) system (Magnetom 7T, Siemens Healthcare, Erlangen, Germany) at the Erwin L. Hahn Institute for MRI, Essen, Germany. For this experiment, the scanner was equipped with a 32-channel transmit/receive head coil (Nova Medical, Wilmington, USA).

Before the acquisition of the sequences, B0 shimming was performed using a vendor-provided gradient-echo sequence and an algorithm based on the work of Schär et al. (2004). For B1 field mapping and local flip angle optimization, a vendor-provided spin-echo type sequence was used. After a slice selective excitation, two refocusing pulses generated a spin-echo and a stimulated echo, respectively. The algorithm was mainly based on the work of Hoult (2000). Structural images ($0.7 \times 0.7 \times 0.7$ mm^3) were acquired using a modified T1-weighted three-dimensional magnetization-prepared rapid gradient-echo (MPRAGE) sequence: TR = 2,500 ms, TE = 1.54 ms, FOV = 270×237 mm^2, flip angle = 7° (c.f. Wrede et al. 2012). Whole functional MRI images were acquired with an optimized bold contrast-sensitive EPI sequence (c.f. Poser et al. 2010). For fMRI, two sessions, each lasting approximately 14 min, were conducted, which led to 790 mosaic images in total. Each mosaic image contains 144 images (mosaic 12×12). The following scan parameters were used: TR = 1,980 ms, TE = 22 ms, FOV = 256×253 mm, flip angle = 14°, 144 slices with a voxel size of $1.5 \times 1.5 \times 1.5$ mm^3, Grappa $R = 9$.

Image analysis

Functional images were analyzed using MATLAB (The MathWorks, Inc) and statistical parametric mapping (SPM8, Wellcome Department of Imaging Neuroscience, London, UK; http://www.fil.ion.ucl.ac.uk/spm) for all imaging, pre-processing, and voxel-based statistical analyses within the context of the general linear model (GLM). For movement correction, realignment was assessed using the default SPM8 algorithm, followed by spatial normalization to reduce anatomical differences. Therefore, a standard stereotactic space of SPM8, i.e., the Montreal Neurological Institute (MNI) brain and the default SPM8 settings for normalization, was used. To improve the signal and anatomical conformity, spatial smoothing was performed using a Gaussian kernel (5 mm full width at half-maximum). Based on prior hypotheses, we conducted region of interest (ROI) analyses in the prefrontal cortex, in particular in the dlPFC (Brodmann areas 9, 10, and 46), in the ACC (Brodmann areas 24 and 32), and in the parietal cortex (Brodmann areas 5 and 7). ROIs were defined using WFUPickatlas version 3.0.3 (Maldjian et al. 2003, 2004).

GLMs were applied to the time course of activation, where stimulus onsets were modeled as single-impulse

response functions. Linear contrasts of parameter estimates were defined to test specific effects. The resulting statistical maps were entered into second-level, t test random-effects group analyses. These analyses were conducted to identify significant differences between BOLD (Ogawa et al. 1990) responses for the planned linear contrasts between the SG and the CG. All effects were reported with a height threshold of $p \leq .001$, uncorrected with an extent threshold of $k \geq 10$ voxel as done in many previous studies (e.g., Ernst et al. 2004; Forstmann et al. 2006; Hsu et al. 2005; Kukolja et al. 2008; Otsuka et al. 2006; Van Snellenberg et al. 2007; Yarkoni et al. 2005). To obtain the associated anatomical structures of the maximum activation, the MNI-coordinates of this activity were transformed into Talairach and Tournoux space (Talairach and Tournoux 1988) using the correction procedure of Brett (1999). Subsequently, the transformed coordinates were put into the Talairach Daemon (Lancaster et al. 1997, 2000) to identify the anatomical structures.

Statistical analyses of the behavioral data

Statistical analyses of the behavioral data were carried out using the IBM SPSS Statistics software for Windows (Release 19.0; April 18, 2011; SPSS Inc. IBM, Chicago). Potential differences in gender distribution and the distribution of experimental starting time between groups were calculated using Pearson's χ^2 test. To compare the performance in the GDT, the 2-back task, and the GDT plus 2-back task between groups, t tests for independent samples as well as one-way analysis of variance (ANOVA) were used. For the stress response analyses, a between–within-subject ANOVA and an ANOVA with repeated measures were used. In case of a violation of the assumption of sphericity (Mauchly's test $p < .05$), the degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity. If necessary, Bonferroni correction was applied to adjust α for multiple comparisons. Simple effect tests were conducted in order to follow up possible main effects and interactions between task performances, affect, and cortisol concentration at different points in time. In order to analyze the relationship between increase in cortisol concentration and brain activation, Pearson's correlations were calculated.

Results

Stress response

Cortisol response to stress

As mentioned above, saliva was collected at five points in time. The +30-min point (before the beginning of the fMRI session) had to be excluded from further analyses because there was not enough saliva to analyze the cortisol concentration in eight samples, most likely because this salivary sample had only been taken about 10 min after the previous sample. At first, it was calculated whether there was an interaction between starting time (pm vs. am) and cortisol concentration for the four points in time (baseline, +20, +95, and +105 min) using a between- and within-subject ANOVA. The analysis revealed no significant main effect for the between-factor starting time (F (1, 31) = 1.38, $p = .249$, $\eta^2 = .04$), but a significant main effect for the within-factor time (*Greenhouse–Geisser* F (2.30, 71.34) = 6.78, $p \leq .001$, $\eta^2 = .18$). The interaction between starting time and time of measurement was also not significant (*Greenhouse–Geisser* F (2.30, 71.34) = 2.44, $p = .087$, $\eta^2 = .07$). Subsequently, a 4 (time) × 2 (group) repeated-measures ANOVA was computed with time as within-factor (baseline, +20, +95, +105) and group (SG vs. CG) as between-factor. The analysis revealed a significant main effect of group (F (1, 31) = 14.03, $p \leq .001$, $\eta^2 = .31$), a significant main effect of time (*Greenhouse–Geisser* F (1.78, 55.23) = 8.85, $p \leq .001$, $\eta^2 = .22$), and a significant interaction between time and group (*Greenhouse–Geisser* F (1.78, 55.23) = 10.52, $p \leq .001$, $\eta^2 = .25$). Further analyses revealed that at baseline the cortisol concentration did not differ between groups (t (31) = 0.52, $p = .604$, $d = 0.18$), but at all following points in time, the SG showed higher cortisol than the CG (directly after TSST: t (22.77) = 4.76, $p \leq .001$, $d = 1.67$; +95 min: t (18.21) = 5.05, $p \leq .001$, $d = 1.78$; +105 min: t (31) = 2.44, $p = .021$, $d = 0.84$).

In total, the SG had a significantly higher cortisol concentration after the TSST (+20 min) and throughout the fMRI paradigm than the CG. These results are summarized in Fig. 2.

Affect

A 3 (time) × 2 (group) repeated-measures ANOVA with time as a within-factor (before the TSST, directly after the TSST, and at the end of the fMRI session) and group as a between-factor (SG vs. CG) was performed separately for the positive and negative affect scales of the PANAS. For the positive affect, the main factor group did not reach significance (F (1, 31) = 0.13, $p = .725$, $\eta^2 = .01$). However, the main factor time was significant (F (2, 62) = 38.94, $p \leq .001$, $\eta^2 = .56$). The interaction between group and time was again not significant (F (2, 62) = 0.77, $p = .469$, $\eta^2 = .02$). Post hoc pairwise Bonferroni-corrected comparisons revealed that participants had a less positive affect at the end of the fMRI session ($M = 23.91$, SD = 7.21) than before the TSST ($M = 31.76$, SD = 5.79; $p \leq .001$, $d = 1.25$) or directly after the TSST ($M = 31.39$, SD = 6.11; $p \leq .001$, $d = 1.21$). However,

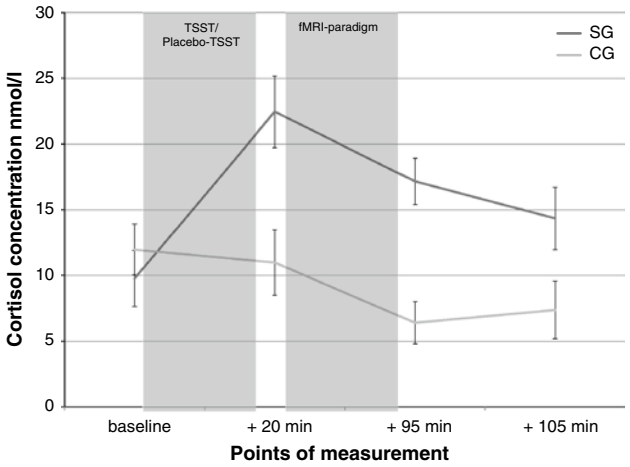

Fig. 2 Mean salivary cortisol as a function of time for the stress group (SG) and the control group (CG). The SG demonstrated a significantly higher cortisol concentration than the CG after the stress induction. The *gray bars* illustrate the points in time when the stress induction (TSST/placebo TSST) and the fMRI session took place. Note that the fMRI session including the behavioral tasks was during the high cortisol period of the SG. The *error bars* represent standard deviations

the positive affect did not differ between the points of measurement before the TSST and directly after the TSST ($p > .900$, $d = 0.08$). For the negative affect, neither main factor group (F (1, 31) = 0.01, $p = .930$, $\eta^2 \leq .01$) or time (F (2, 62) = 0.46, $p = .633$, $\eta^2 = .02$) nor the interaction between time and group (F (2, 62) = 2.02, $p = .141$, $\eta^2 = .06$) was significant.

In total, there were no significant differences in the self-reported affect between SG and CG (see Table 1).

Behavioral results

Table 2 shows that on a behavioral level, the performance in the GDT, the 2-back task, as well as the GDT plus 2-back task did not differ significantly between the SG and the CG.

Imaging data

To investigate the underlying neural correlates of the GDT plus 2-back task, we analyzed the brain areas involved in the dual-task compared with the single-task performance (see Table 3 for the CG and Table 4 for the SG). The following contrasts were calculated for each group separately: *GDT plus 2-back* > *GDT* and *GDT plus 2-back* > *2-back* as well as *GDT plus 2-back* < *GDT* and *GDT plus 2-back* < *2-back*. Concerning the CG, there was significantly more activation in parts of the cingulate gyrus as well as in the medial frontal gyrus during the dual task compared with the GDT.

Table 1 Means and standard deviation of the PANAS at the three points of measurement

Points of measurement	Stress group *M* (SD)	Control group *M* (SD)
Positive affect scale		
Before the TSST (baseline)	32.00 (5.79)	31.53 (5.97)
Directly after the TSST (+20 min)	31.13 (5.81)	31.65 (6.56)
After the fMRI session (+95 min)	22.88 (7.82)	24.88 (6.68)
Negative affect scale		
Before the TSST (baseline)	13.94 (2.91)	14.12 (2.52)
Directly after the TSST (+20 min)	15.19 (3.89)	13.76 (2.99)
After the fMRI session (+95 min)	13.06 (2.21)	14.53 (4.99)

However, there was also a significant decrease in activation in the cuneus during the dual-task condition compared with the GDT. Moreover, when comparing the dual-task condition with the 2-back task condition, there was a significant increase in activation in inferior and superior parietal areas (see Table 3). Concerning the SG, the analyses revealed significantly more activation during the dual task compared with the GDT in a part of the dorsolateral prefrontal area (middle frontal gyrus, BA 9), in supplementary motor areas (paracentral lobe and precentral gyrus), as well as in the superior parietal lobe. Compared with the 2-back task, there was an increased activation in superior as well as inferior parietal areas, in parts of the supplementary motor area (postcentral gyrus), and in the superior frontal gyrus.

The main focus lay on the interaction effect between stress, decision making, and additional executive load. Therefore, the contrasts *GDT plus 2-back* > *GDT* and *GDT plus 2-back* > *2-back* were also compared between SG and CG, in order to see whether there was an increase (*SG* > *CG*) or a decrease in activation (*SG* < *CG*) due to acute stress (see Table 5). The analyses revealed a significant increase in activation (*SG* > *CG*) in the superior frontal gyrus as well as in the supplementary motor area (paracentral gyrus; see Fig. 3) during the GDT plus 2-back compared to the GDT. All other contrasts did not survive the height and extent threshold.

Additionally, the activation during the GDT solely, the 2-back task solely, and the GDT plus 2-back task was compared between the two groups (see Table 6). Only the comparison concerning the GDT (performed solely) activation survived height and extent threshold, revealing an increase in activation in the superior frontal gyrus during acute stress. Additionally, the precuneus was less activated during acute stress compared with the control condition.

Table 2 Comparison of the task performance between stress and control groups

Task scores	Stress group *M* (SD)	Control group *M* (SD)	*t*	*df*	*p*	*d*
GDT						
Rounds	17.81 (0.31)	17.74 (0.50)	0.53	31	.602	0.17
Risky choices in %	33.56 (20.98)	23.58 (20.35)	1.39	31	.175	0.48
2-Back task						
Rounds	47.94 (0.25)	47.79 (0.73)	0.75	31	.462	0.27
Correct responses in %	84.13 (15.54)	86.74 (17.03)	0.46	31	.650	0.16
Reaction time[a]	591.13 (111.08)	612.10 (173.58)	0.41	31	.684	0.14
GDT plus 2-back						
GDT: rounds	16.84 (1.21)	17.00 (0.90)	0.42	31	.675	0.15
GDT: risky choices in %	28.75 (24.23)	22.26 (24.78)	0.76	31	.453	0.26
2-Back: rounds	47.59 (0.42)	47.44 (1.01)	0.57	21.53	.574	0.18
2-Back: correct responses in %	70.62 (12.21)	70.91 (14.42)	0.06	31	.950	0.02
2-Back: reaction time[a]	753.42 (238.71)	685.26 (153.02)	0.97	25.30	.341	0.34

[a] In ms

Table 3 Comparison between dual-task activation and single-task activation in the control group

Contrast	Nearest brain region	Laterality	*k*	MNI-coordinates			Peak *t*	*p*
				x	*y*	*z*		
GDT plus 2-back > GDT	Limbic lobe, cingulate gyrus (BA[a] 24)	L	172	−5	−1	49	4.83	≤.001
		R	172	8	−4	48	4.53	≤.001
	Frontal lobe, medial frontal gyrus (BA[a] 6)	R	172	6	4	52	3.40	≤.001
GDT plus 2-back < GDT	Occipital lobe, cuneus (BA[a] 19)	R	15	29	−87	28	4.13	≤.001
GDT plus 2-back > 2-back	Parietal lobe, inferior parietal lobule (BA[a] 40)	R	47	38	−55	58	4.38	≤.001
	Parietal lobe, superior parietal lobule (BA[a] 7)	L	29	−26	−52	60	4.20	≤.001
	Parietal lobe, precuneus (BA[a] 7)	R	56	9	−52	55	4.13	≤.001
		R	33	18	−60	52	4.11	≤.001
		R	33	26	−57	52	3.74	≤.001
GDT plus 2-back < 2-back	n.s.[b]							

[a] Brodmann area

[b] No significant neural activation differences in the second-level group analysis

In total, the results demonstrated increased brain activation during the dual-task when compared with the single-task performance. However, depending on the single task with which the dual-task performance is compared and depending on the group, different brain areas seem to be involved. Moreover, in the CG there was also a significantly decreased activation in the cuneus during the GDT plus 2-back task compared with the GDT when performed solely. The analysis of the interaction between decision making, executive functions, and stress revealed the following: Stressed participants performing a decision-making task simultaneously with an executive task show an increased activation in the supplementary motor area and the anterior PFC (superior frontal gyrus, BA 10) in comparison with stressed participants performing only the decision-making task.

Correlations between cortisol concentration and brain activity

In order to analyze the relationship between cortisol concentration and brain activity, we calculated correlations between cortisol data and activations in the ROI for each group. We used the results from the second-level analyses shown in Tables 3 and 4. We extracted the parameter estimates (beta values) from each location of the activation pattern resulting from the calculated contrasts for each participant. We also calculated the cortisol increase between baseline and +95-min point of time (directly after the fMRI session) for each participant (cortisol concentration at the +95-min point minus cortisol concentration at baseline). These cortisol data were then correlated with the parameter estimates

Table 4 Comparison between dual-task activation and single-task activation in the stress group

Contrast	Nearest brain region	Laterality	*k*	MNI-coordinates			Peak *t*	*p*
				x	*y*	*z*		
GDT plus 2-back > GDT	Frontal lobe, middle frontal gyrus (BA[a] 9)	L	91	−36	34	42	5.09	≤.001
		L	91	−30	43	40	3.58	≤.001
	Frontal lobe, paracentral lobule (BA[a] 31)	R	67	9	−34	51	4.53	≤.001
	Frontal lobe, precentral gyrus (BA[a] 6)	R	13	59	1	36	3.99	≤.001
	Parietal lobe, superior parietal lobule (BA[a] 7)	R	58	35	−51	63	4.78	≤.001
		R	52	21	−55	64	4.05	≤.001
GDT plus 2-back < GDT	n.s.[b]							
GDT plus 2-back > 2-back	Parietal lobe, postcentral gyrus (BA[a] 2, 5)	R	96	33	−48	63	5.50	≤.001
		R	96	33	−39	69	4.25	≤.001
	Parietal lobe, superior parietal gyrus (BA[a] 7)	R	89	14	−72	55	4.15	≤.001
		R	89	23	−64	58	3.95	≤.001
		L	12	−20	−72	55	3.84	≤.001
	Parietal lobe, inferior parietal lobule (BA[a] 40)	L	17	−38	−43	61	4.39	≤.001
	Frontal lobe, superior frontal gyrus (BA[a] 8)	R	45	20	49	42	4.62	≤.001
GDT plus 2-back < 2-back	n.s.[b]							

[a] Brodmann area

[b] No significant neural activation differences in the second-level group analysis

Table 5 Activation pattern during the dual-task paradigm (comparison: GDT 2-back > GDT and GDT 2-back > 2-back), compared between stress group (SG) and control group (CG)

Contrast	Nearest brain region	Laterality	*k*	MNI-coordinates			Peak *t*	*p*
				x	*y*	*z*		
GDT plus 2-back > GDT								
SG > CG	Frontal lobe, superior frontal gyrus (BA[a] 10)	L	13	−18	47	28	3.92	≤.001
	Frontal lobe/parietal lobe, paracentral lobule (BA[a] 5)	R	55	12	−34	51	4.16	≤.001
SG < CG	n.s.[b]							
GDT plus 2-back > 2-back								
SG > CG	n.s.[b]							
SG < CG	n.s.[b]							

[a] Brodmann area

[b] No significant neural activation differences in the second-level group analysis

of the ROI for both groups separately. Results demonstrated a negative correlation between increases in cortisol in the SG and the activation in the left middle frontal gyrus (MNI-coordinate 1: $x = -36$, $y = 34$, $z = 42$; MNI-coordinate 2: $x = -30$, $y = 43$, $z = 49$) for both coordinates (MNI-coordinate 1: $r = -.523$, $p = .038$; MNI-coordinate 2: $r = -.618$, $p = .011$) in the contrast GDT plus 2-back > GDT. This indicates that an increase in cortisol in the SG is accompanied by less activation of parts of the dorsolateral prefrontal area (i.e., BA 9) during the GDT plus 2-back compared with the GDT (see Fig. 4). No other correlations calculated for the SG or CG reached significance.

Discussion

Overall, stress induction was successful. Stressed participants had a higher cortisol concentration after stress induction and throughout the experiment compared with control participants. The main results support the findings of Pabst et al. (2013) that on a behavioral level acute stress in combination with a parallel executive task does not impair decision-making performance. More interestingly, the analyses of the neural correlates revealed significant differences between SG and CG: When stressed participants (compared with non-stressed participants) had to make a decision while simultaneously the working memory was demanded,

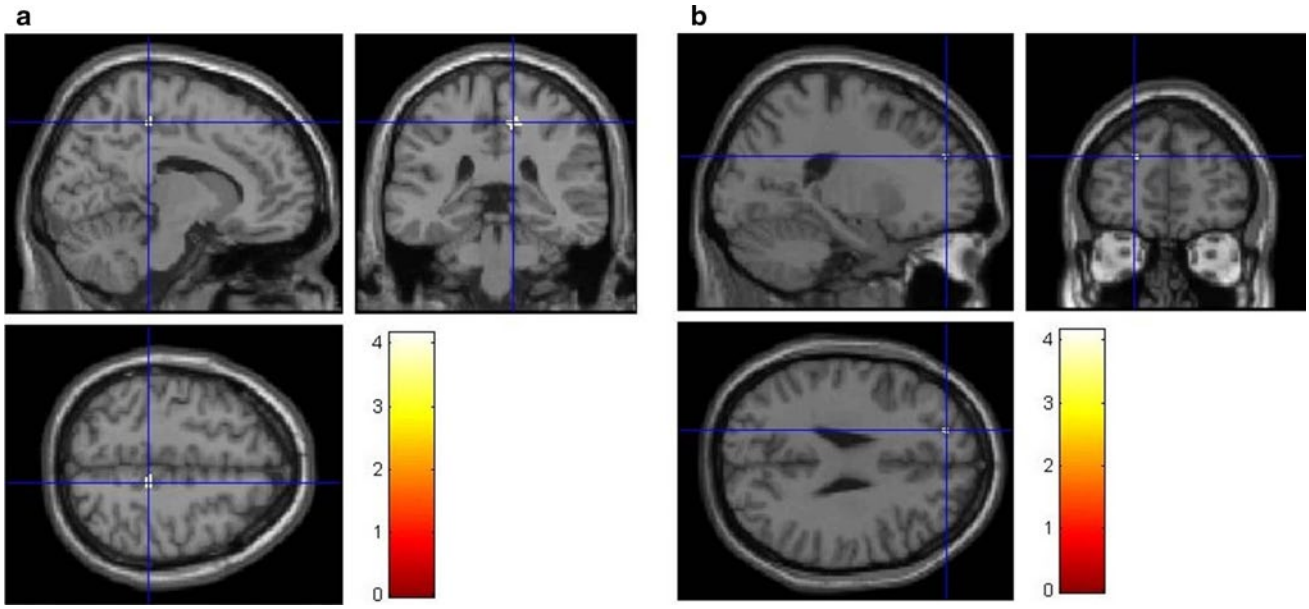

Fig. 3 Results of the dual-task effect (GDT plus 2-back > GDT) in the stress group compared with the control group at a threshold of $p \leq .001$ (uncorrected) and an applied extended threshold of $k \geq 10$ voxel. **a** The supplementary motor area (paracentral lobe) and **b** the superior frontal gyrus were significantly activated (for detailed information see Table 5)

Table 6 Comparison of the activation pattern of each task between the stress group (SG) and the control group (CG)

Contrast	Nearest brain region	Laterality	*k*	MNI-coordinates			Peak	*p*
				x	*y*	*z*	*t*	
GDT								
SG > CG	Frontal lobe, superior frontal gyrus (BA[a] 9)	R	23	30	52	33	4.28	≤.001
SG < CG	Parietal lobe, precuneus (BA[a] 7)	R	13	27	−67	36	4.29	≤.001
2-Back								
SG > CG	n.s.[b]							
SG < CG	n.s.[b]							
GDT plus 2-back								
SG > CG	n.s.[b]							
SG < CG	n.s.[b]							

[a] Brodmann area

[b] No significant neural activation differences in the second-level group analysis

a greater activation in BA 10—the more anterior part of the dlPFC, which is also referred to as anterior PFC (Koechlin et al. 1999; Koechlin and Hyafil 2007)—and in a part of the supplementary motor area (paracentral lobe) was revealed in comparison with the activation when no additional demand was given. Additionally, we found that in the SG the increase in cortisol concentration was negatively correlated with the increase in activation in the BA 9 (the more dorsal part of the dlPFC) regarding the contrast *GDT plus 2-back > GDT*. This indicates that in the SG an increase in stress level is associated with a decrease in neural activation in the dorsal part of the dlPFC during the GDT plus 2-back task compared with the GDT. According to Koechlin and Hyafil (2007), the anterior PFC (BA 10) forms with other prefrontal regions the apex of the executive system whereby it is particularly associated with parallel processing of two tasks. In contrast, BA 9 was found to work more serially upon cognitive processes (Dux et al. 2006). Based on their neurocomputational model, Koechlin and Hyafil (2007) suggested that the anterior PFC overcomes such serial constraints by joint consideration of two task sets. Plessow et al. (2012b) and Pabst et al. (2013) assumed that stress may trigger the serial-to-parallel shift by reducing task shielding in order to enable the more resource-efficient parallel processing mode in dual-task situations. The increased activation of the anterior PFC in the stressed and not in non-stressed participants may be associated with such a serial-to-parallel shift. It may be possible that due

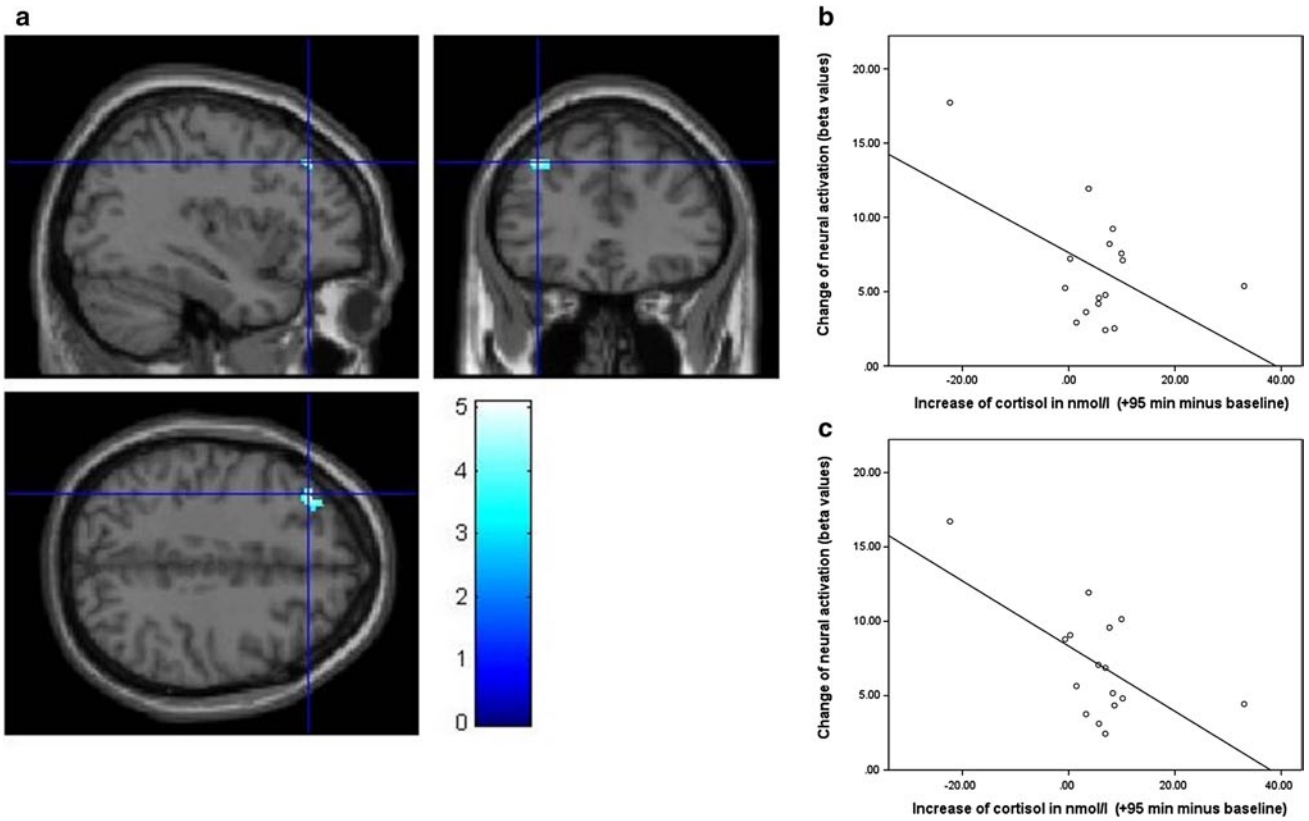

Fig. 4 **a** Increasing cortisol concentration in the stress group is associated with a deactivation in the middle frontal gyrus during the GDT plus 2-back when compared with the GDT. The fixing cross was set at MNI-coordinate 1 ($x = -36$, $y = 34$, $z = 42$). The plot of the negative correlation between increase in cortisol in the stress group (from baseline to time point +95 min) and brain activation **b** at the MNI-coordinate 1 and **c** at the MNI-coordinate 2 ($x = -30$, $y = 43$, $z = 40$)

to reduced task shielding, the anterior PFC maintains previously selected task sets in a pending state for automatic retrieval and implementation upon the process of the ongoing task as described by Koechlin and Hyafil (2007). Even though we did not find a deactivation in serially working brain areas (e.g., BA 9; Dux et al. 2006) in the SG when compared with the CG, the negative relationship within the SG between brain activation in BA 9 and cortisol concentration may point in the same direction: In decision-making situations with a simultaneous executive task, stress seems to lead to reduced activation of serial processing brain areas (dorsal part of the dlPFC, BA 9) while simultaneously to an increased activation of brain areas associated with parallel processing (anterior PFC, BA 10). This may have led to a reduced task shielding of the decision-making task as well as the executive task, resulting in good behavioral performance in both tasks. The finding of the increased activation in the supplementary motor area may be most likely due to the fact that performing a single task involved one hand and the participants had to give their answers only every 4 s. In contrast, when performing both tasks (GDT plus 2-back) simultaneously, participants had to use their second hand and give an answer at least every 2,750 ms. This might have led to a greater motor and sensory response. However, it has to be mentioned that this increased activity was only found in the SG and not in the CG. Therefore, we assume that this increase may also be due to the serial-to-parallel switch in the SG: Performing two tasks serially is probably accompanied by less motor response because only one hand at a time needs to be used. In contrast, performing two tasks simultaneously involves both hands, probably leading to an increased motor response.

Studies investigating reactivity of stress in the brain found that stress increases the release of catecholamine, in particular dopamine (Abercrombie et al. 1989; Hutson et al. 2004; Morrow et al. 2000). Since the prefrontal cortex provides a high density of D1 receptors, the influence of stress leads to a high activity in this area (Thierry et al. 1976; Williams and Castner 2006). However, most studies found that an increase in dopamine is followed by an impairment of cognitive functions (Arnsten 2009; Arnsten and Goldman-Rakic 1998), which was not found in the current study. Here, stressed participants performed all tasks as well as the CG in both executive associated tasks. Regarding the

GDT plus 2-back task performance, the current finding seems to be in line with a recent study also demonstrating that stress does not impair dual-tasking performance (Beste et al. 2013) and may be due to a shift to a less demanding processing mode (c.f. Pabst et al. 2013; Plessow et al. 2012a). Still, this cannot explain the missing differences in the single-task conditions. In particular, decision-making performance as well as working memory performance was found to be reduced by stress (e.g., Lupien et al. 1999; Porcelli and Delgado 2009; Putman et al. 2010; Schoofs et al. 2008; Starcke et al. 2008). Possible explanations why we did not find any differences in task performance are briefly discussed in the "Limitation" section.

Regarding the single-task performance, the analyses of the neural correlates revealed again significant differences between the SG and the CG, but only during the GDT: Stressed participants showed increased activation in the dorsal part of the superior frontal gyrus (dlPFC) and decreased activation in the precuneus. Both areas are known to be involved in decision making under risk (Labudda et al. 2008; Lighthall et al. 2012): the dorsal superior frontal gyrus is part of the dlPFC and therefore involved in executive functioning (Alvarez and Emory 2006; Lie et al. 2006), while the precuneus is especially associated with mental arithmetic (Dehaene et al. 1999; Stanescu-Cosson et al. 2000). Both regions are highly relevant for GDT performance (Labudda et al. 2008). However, the current findings may suggest that under stress, brain areas associated with executive functions seem to be more involved than areas associated with mental arithmetic. This may be because executive functions are involved in task shielding, which is known to be increased in demanding single-task situations in order to perform well on the task (Plessow et al. 2011).

All other comparisons of the neural correlates between SG and CG (GDT plus 2-back solely, 2-back solely, and GDT plus 2-back > 2-back) revealed no significant differences. Concerning the 2-back task solely, the results are in contrast to those reported by Cousijn et al. (2012) and Qin et al. (2009) who found decreased activation in different brain areas due to acute stress while performing an n-back working memory task. However, it has to be mentioned that the areas that were deactivated in those studies are different: While Cousijn et al. (2012) found a decrease in activation in the medial temporal lobe in male participants, Qin et al. (2009) found a deactivation in the dlPFC in female participants. Thus, the findings reveal no homogeneous picture. Additionally, the stressor in the current study (TSST) differed completely from the one used in the other two studies (aversive movie clips). This may have led to differential stress reactions resulting in the heterogeneous findings. It may be advisable to engage in further research in order to get a clearer picture of the activation pattern when performing a 2-back task under the influence of acute stress (e.g., using similar stressors or directly comparing the differential stress reactions due to different stressors).

So far and to our best knowledge, this is the first study that investigated the underlying neural correlates of the GDT plus 2-back task. Therefore, we additionally compared the activation patterns of the dual task with the decision-making task (GDT plus 2-back > GDT) within the CG only. This revealed an increased activity in the cingulate gyrus as well as in the medial frontal gyrus. These areas were also found to be activated in studies investigating neural correlates during working memory (for a review see Owen et al. 2005). While the activation in the medial frontal gyrus is additionally associated with executive functioning (Talati and Hirsch 2005), the activation in the anterior part of the cingulate gyrus emphasizes the increased complexity and effort in the dual task (Callicott et al. 1999). The resulting activation pattern when comparing the dual task with the 2-back task (GDT plus 2-back > 2-back) is in line with the study of Labudda et al. (2008), which investigated the neural correlates of decision making using a paradigm similar to the GDT. The activated brain areas are associated with number processing, exact calculation (inferior parietal lobe; Dehaene et al. 2004; Pesenti et al. 2000) and mathematical approximation functions (precuneus, superior parietal lobe; Dehaene et al. 1999; Stanescu-Cosson et al. 2000), which are involved in the GDT performance. Those comparisons reveal that the manipulation of the dual task as well as each single task was successful and support the validity of our findings discussed above.

Limitations

There are some limitations to our study, which have to be mentioned. First, the fMRI version of the GDT was most likely easier to perform than the original version, since participants only had to choose among four instead of 14 alternatives. This could be the reason why we did not find significant differences on a behavioral level. Secondly, the experimental conditions (GDT, 2-back, and GDT plus 2-back) and the high-level control task were all similar in design and visual input. Therefore, it may be possible that even though the participants were advised to perform one of the single tasks (GDT or 2-back), they still paid attention to the second task on the screen, even though it was frozen and not executable. This circumstance was not controlled, and given that we had a within-subject design with respect to the different activation conditions (GDT solely, 2-back solely, and GDT plus 2-back), this may have reduced the power for the comparison between the SG and CG in the second-level analyses. In future studies, it would be helpful to use the activation conditions as a between-factor, as well. Thirdly, the time interval after the TSST until the end of the

behavioral tasks, in which we investigated the influence of stress, was around 60 min. However, it is known that the peak cortisol response is about 21–40 min after the onset of a stressor (Dickerson and Kemeny 2004) and should return to baseline 41–60 min after cessation of the stressor (Kirschbaum and Hellhammer 1994). Nevertheless, the data demonstrated that the SG compared with the CG had a higher cortisol concentration after the TSST as well as at the end of the study. Fourthly, the fMRI investigation itself was an unfamiliar situation for the participants, in which they were confronted with loud noises from the scanner and other unfamiliar conditions that could have created stress in the participants (c.f. Eatough et al. 2009; Tessner et al. 2006). This could have had a reducing effect on the positive affect in all participants, and therefore, group differences in the PANAS might have been diminished, resulting in a non-significant group effect on the subjective stress response. Still, as mentioned before, the physiological data (cortisol concentration) demonstrated that the neuroendocrine stress level differed between groups: The SG had a higher cortisol concentration than the CG. Therefore, we concluded that the stress induction was successful. However, in future studies it might be helpful to further reduce the subjective stress level in the CG and to increase the stress level in the experimental group to have stronger effects on both behavioral and neural level. At least it has to be pointed out that the assumptions regarding the serial-to-parallel shift need to be treated with caution. Due to the fact that the contrast GDT plus 2-back > 2-back did not reveal any significant results, it may be possible that the current findings regarding the contrast GDT plus 2-back > GDT are task specific. Additionally, the activation found in this contrast is of very small cluster size ($k = 13$).

Conclusion

Despite these limitations, we conclude that the findings reported here support the results of Pabst et al. (2013) that acute psychological stress in combination with a parallel executive task seems to preserve decision-making performance from decreasing. Moreover, the current study reveals that making advantageous decisions in a stressful situation, while simultaneously the working memory is demanded otherwise, is accompanied by an increased activation in the anterior PFC (BA 10). Thus, this region may be included in the process that maintains good decision-making performance. Pabst et al. (2013) assumed that such underlying mechanism may be a shift from sophisticated serial processing mode to a less demanding parallel processing mode (Plessow et al. 2012b). It may be possible that the anterior PFC is involved in this mechanism, because it was found that this region overcomes the serial constraint of two tasks by joint consideration of those, resulting in a parallel processing mode (Koechlin and Hyafil 2007). Future studies should investigate the possible role of the anterior PFC in the serial-to-parallel shift in more detail. Several studies demonstrated that patients with executive dysfunctions have problems performing two tasks simultaneously (Baddeley et al. 1997; Dalrymple-Alford et al. 1994; Greene et al. 1995). Understanding the neural and cognitive mechanisms in dual tasking in more detail may give us the opportunity to further investigate how it may be possible to train or compensate those functions so that in case of executive dysfunctions or in demanding situations, the handling of two task simultaneously will still be manageable.

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