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Effects of basal and acute cortisol on cognitive flexibility in an emotional task switching paradigm in men

Angelika Margarete Dierolf [a,*,1], Lea Esther Arlt [a], Karin Roelofs [b], Monika Kölsch [c,2], Mareike Johanna Hülsemann [a], Hartmut Schächinger [c], Ewald Naumann [a]

[a] Department of Psychology, University of Trier, Universitätsring 15, 54286 Trier, Germany
[b] Donders Institute for Brain, Cognition and Behaviour, Centre for Cognitive Neuroimaging, Postbus 9104, 65000 HE Nijmegen, Netherlands
[c] Division of Clinical Psychophysiology, Institute of Psychobiology, University of Trier , Johanniterufer 15, 54290 Trier, Germany

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ABSTRACT

The stress hormone cortisol is assumed to influence cognitive functions. While cortisol-induced alterations of declarative memory in particular are well-investigated, considerably less is known about its influence on executive functions. Moreover, most research has been focused on slow effects, and rapid non-genomic effects have not been studied. The present study sought to investigate the impact of acute cortisol administration as well as basal cortisol levels on cognitive flexibility, a core executive function, within the non-genomic time frame. Thirty-eight healthy male participants were randomly assigned to intravenously receive either cortisol or a placebo before performing a task switching paradigm with happy and angry faces as stimuli. Cortisol levels were measured at six points during the experiment. Additionally, before the experiment, basal cortisol measures for the cortisol awakening response were collected on three consecutive weekdays immediately following awakening and 30, 45, and 60 min after. First and foremost, results showed a pronounced impact of acute and basal cortisol on reaction time switch costs, particularly for angry faces. In the placebo group, low basal cortisol was associated with minimal switch costs, whereas high basal cortisol was related to maximal switch costs. In contrast, after cortisol injection, basal cortisol levels showed no impact. These results show that cognitive flexibility-enhancing effects of acute cortisol administration are only seen in men with high basal cortisol levels. This result supports the context dependency of cortisol administration and shows the relevance of taking basal cortisol levels into account.

Introduction

Non-genomic effects of cortisol and frontal brain functions

When the stress hormone cortisol is secreted into the blood stream, it has at least two ways of affecting peripheral tissues and the brain. Its slow genomic effects evolve from 15 min after secretion at the earliest and operate through the synthesis of proteins (Makara and Haller, 2001). Besides this, a rapid non-genomic pathway influences cellular processes within a time frame of seconds to minutes, independent of genomic mechanisms (Makara and Haller, 2001). Whereas the genomic pathway is mediated for most parts by the cytoplasmic glucocorticoid (GR) and mineralocorticoid receptors (MR) (de Kloet et al., 2005), glucocorticoid membrane receptors, including i.a. membranous MR and GR, are responsible for non-genomic effects (Falkenstein et al., 2000; Groeneweg et al., 2011; Joels et al., 2012; Makara and Haller, 2001). MR and especially GR, which is fully occupied under stress-induced elevated cortisol levels, occur at high density in the hippocampus (Lupien et al., 2007) and prefrontal cortex (PFC) (de Kloet et al., 2005). While the link between cortisol and hippocampal functions has been well established (for a review, see Lupien et al. (2007)), the effect of cortisol on different cognitive functions based on the prefrontal cortex, i.e. executive functions, has only recently been attracting attention (Groeneweg et al., 2011; Miyake et al., 2000), revealing rather inconsistent results (e.g., Elzinga and Roelofs (2005); Plessow et al. (2012); Qin et al. (2009); Schlosser et al. (2013) and Scholz et al. (2009)). Moreover, non-genomic effects in particular have not been considered so far, although they might be opposite to genomic-driven effects and the PFC is known to be affected by rapid corticosteroid mechanisms (Dolcos, 2014; Groeneweg et al., 2011; Makara and Haller, 2001). Hence, the

* Corresponding author.
E-mail addresses: Angelika.Dierolf@ruhr-uni-bochum.de (A.M. Dierolf), s1learlt@uni-trier.de (L.E. Arlt), k.roelofs@fcdonders.ru.nl (K. Roelofs), MonikaKoelsch@web.de (M. Kölsch), s1mahuel@uni-trier.de (M.J. Hülsemann), schaechi@uni-trier.de (H. Schächinger), naumann@uni-trier.de (E. Naumann).
[1] Present address: Department of Cognitive Psychology, Institute of Cognitive Neuroscience, Ruhr University Bochum, 44801 Bochum, Germany.
[2] Present address: Krankenhaus der Barmherzigen Brüder Trier, Nordallee 1, 54292 Trier, Germany.

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present study aimed to investigate non-genomic effects of cortisol on a core executive function, namely cognitive flexibility or mental set shifting, as it is also called (Diamond, 2013; Miyake et al., 2000).

Impact of stress and cortisol on cognitive control

Executive functions, also often referred to as cognitive control, configure the cognitive system for the performance of specific tasks through processes such as perceptual selection, response biasing and on-line maintenance of contextual information (Botvinick et al., 2001). As a core executive function, cognitive flexibility comprises abilities such as the change of perspective or flexible adjustments to new rules, requirements or circumstances (Diamond, 2013) and is typically examined with a task switching paradigm in which subjects are confronted with a set of two or more simple tasks (e.g., Altmann and Gray (2008); Diamond (2013); Meiran et al. (2000) and Monsell (2003)). These tasks require attention to and classification of one specific aspect of the stimuli, with the particular challenge that the performance requirement sometimes changes from one trial to another (switch trials), while at other times it does not (noswitch trials). This leads to the necessity of reconfiguring mental task sets, resulting in extra processing demands (Kiesel et al., 2010; Monsell, 2003). These so-called switch costs become apparent when comparing switch with noswitch trials, namely in larger reaction times and frequently in higher error rates in switch trials (Kiesel et al., 2010; Monsell, 2003).

To our knowledge, so far only a handful of studies have examined the influence of acute cortisol on cognitive flexibility, all operating in the genomic time frame. Wingenfeld et al. (2011) and Vaz et al. (2011) found no effects after oral administration of hydrocortisone, testing cognitive flexibility more than an hour after administration. Using the Trier Social Stress Test to induce stress, Plessow et al. (2012) found larger error-related switch costs after the stressor in the stress group relative to the control group, while the reaction times remained unaltered. The authors used an explicit-cued Task Switch paradigm with digits as target stimuli which had to be categorized either as odd or even or according to their quantity (Plessow et al., 2012). However, there is increasing evidence that the impact of cortisol is greater for emotional compared to neutral material across different cognitive processes (e.g., Buchanan and Lovallo (2001); Putman and Roelofs (2011); Rimmele et al. (2003) and Wolf et al. (2004)). Accordingly, Breitberg et al. (2013) found an infusion of hydrocortisone to alter attention to emotional stimuli, albeit testing shifting over an hour after infusion. As emotional facial expressions are considered as most significant and immediate universal social cues in personal interactions (e.g., Frith (2009) and cited therein), the present study used these as target stimuli. Additionally, since Putman and Roelofs (2011) in their review discuss the implication of task relevance and irrelevance of emotional information in the context of stress, we chose the cues accordingly.

Besides the acute secretion of cortisol in stressful situations, the hormone follows a circadian rhythm with basal levels differing in an interindividual manner (Wüst et al., 2000). Basal cortisol levels have been found to influence cognitive processes in addition to the acute secretion of cortisol (e.g., Beluche et al. (2009); Lupien et al. (1994) and Lupien et al. (1998)). As little is known on the interaction of basal and acute cortisol levels on executive functions, we incorporated trait basal cortisol as a factor in the experimental design.

Based on the current state of research discussed above, our study sought to investigate effects of exogenous cortisol on cognitive flexibility, a core executive function, in the non-genomic time frame, using emotional stimuli. Additionally, we included basal cortisol in our analysis in order to look into possible mediating effects of cortisol at trait level. We expected acute cortisol to negatively influence this cognitive control process and thus increase switch costs. Furthermore, we suspected a possible influence of both basal cortisol and the emotion of the facial stimuli.

Methods

Participants

Forty students of the University of Trier, Germany, took part in the study. To our knowledge, sex differences in task switching are rarely reported, if ever (Kray and Lindenberger, 2000; van der Plas et al., 2009), and Shields et al. (2015) in their meta-analysis did not find sex to moderate the impact of acute cortisol administration on various executive functions. With due regard to this and the fact that Plessow et al. (2012) did not find any differences in their study, we decided to include only male subjects. Data from only 38 subjects (mean age = 23.00 years, $SD = 2.89$, range 18–28) are reported as two participants fainted when the intravenous cannula was inserted. All subjects were right-handed, non-smokers, and physically and psychologically healthy. Exclusion criteria were any acute or chronic somatic or psychiatric illnesses, any history of psychiatric, cardiovascular, or stress-related disorders, glaucoma, smoking, increased caffeine consumption or any illicit drug intake within the last six months, or any family history of epilepsy or aneurysms. The experiment was conducted in accordance with the Declaration of Helsinki. The Ethical Committee of the State's Medical Association (Landesärztekammer Rheinland-Pfalz) approved the study. All subjects gave written informed consent and participation was compensated with €50.

Procedure

All subjects were examined individually. Subjects were invited to a preliminary interview in which a medical doctor checked the exclusion criteria, explored their medical and psychiatric history, and informed them about the aim and procedure of the study, i.e., the investigation of the relationship between the steroid hormone cortisol and the perception of and reaction to visual stimuli. The cortisol sampling and experimental procedures were also described. Eligible subjects received sampling devices for the measurement of the basal activity of the hypothalamic–pituitary–adrenal (HPA) axis and a protocol to record sampling times, as well as specific instructions concerning sleep quality, and bed and wake-up times on the night preceding as well as the morning of the sampling. We further emphasized the necessity to adhere to the written instructions and sampling times.

The experiment was conducted between 1:00 pm or approximately 7:00 pm, beginning at 1:00 pm, 3:00 pm, or 5:00 pm, when endogenous cortisol levels are low (Schreiber et al., 2006). One hour prior to the beginning of the Task Switch experiment, subjects were welcomed to the laboratory and gave their first salivary cortisol sample (baseline 1, C_1 − 60 min with reference to the drug injection). After a short medical check, a medical doctor applied the intravenous cannula. Half an hour before the beginning of the experiment, subjects practiced the emotion–gender task switching paradigm and were escorted to the laboratory 15 min later. They were seated in a comfortable chair, 0.80 m away from a computer screen, with a computer keyboard in front of them. After preparation for EEG-measurement[3], the second salivary sample (C_2 − 2 min, baseline 2) was taken. One hour after the insertion of the cannula, the medical doctor intravenously applied either a saline placebo solution (NaCl 0.9%, Braun, Melsungen, Germany) or 4 mg of hydrocortisone (Hydrocortison 100 mg, Rotexmedia, Trittau, Germany) in a double blind procedure, forming the independent variable *Drug*. Two minutes later, the emotion–gender task switching paradigm (242 trials) started, divided into two blocks. In the resting period between these blocks, the third salivary sample was collected (C_3 + 9 min after injection). At the end of the second block,

[3] In a preliminary analysis of the EEG data, previous findings of cue-locked event-related potential within task switching paradigms could not be confirmed. Most likely, this is caused by cue-target-intervals (500 ms) too short for analyses of the P3 or the CNV (contingent negative variation). Therefore, EEG analyses and results are not reported here.

the forth salivary sample was collected (C_4 + 18 min). This was followed by a color-form task switching paradigm which was conducted for exploratory reasons only, and as results from this part can be explained by a simple sequence effect, they will not be reported here. At the end of this experimental session, the fifth salivary sample was gathered (C_5 + 30 min). After the EEG-equipment was removed, subjects filled out several questionnaires and gave their last salivary sample (C_6 + 60 min). Finally, they were informed whether they had received a placebo or cortisol, were completely debriefed, thanked and compensated for their participation.

Emotion–gender task switch

Amongst facial expressions, faces depicting anger and fury should be of particular relevance under stressful conditions, which are linked to a fight-or-flight reaction. Hence, angry faces were used as target stimuli in the present study. Similar to previous studies (e.g., Roelofs et al. (2005); Roelofs et al. (2009) and van Peer et al. (2007)), angry faces were combined with easily distinguishable and happy faces unrelated to a stressful context. Sixty male and female faces each were taken from the normative FACES database described by Ebner et al. (2010), showing each a happy and an angry facial expression, resulting in 240 different faces.

A trial started with the presentation of the cue (visual angle: horizontal 3.58°; vertical 0.5°) in the middle of a 19″ computer screen (Eizo FlexScan 1931). The cue was either the German word "Emotion" (English: emotion) or "Geschlecht" (English: gender), forming the independent variable *Cue*. The words were presented in black color on a gray background. The cue was presented for 500 ms, immediately followed by the target, a happy- or angry-looking male or female face (visual angle: horizontal 9.93°; vertical 12°). The emotion shown by the face constituted the independent variable *Emotion*. By pressing the left or right arrow button on a keyboard, subjects classified the faces according to the cue given either as happy/angry or male/female, with the assignment of happy/angry and male/female to the buttons counterbalanced across subjects. If the trial before the current one had the same cue, the current trial was classified as 'noswitch'; in case of a cue change, the trial was a 'switch' trial, this distinction forming the independent variable *Task Switch*. The next trial started with the presentation of the cue 2.5 s after the last cue.

Subjects performed two blocks of 121 trials each. The first trial of each block always used the same female or male face showing a happy or angry emotion. This was followed by 60 switch and 60 noswitch trials, half of them with an angry facial expression, the other half with a happy facial expression. The sequence of the resulting eight experimental conditions (*Cue* × *Emotion* × *Task Switch*) was randomized with the restriction that three identical conditions appeared in succession at most.

Half an hour before the beginning of the experiment, subjects practiced 32 trials (4 in each experimental condition). The trial structure was identical to the experimental trial described above, with the exception that participants received feedback on the computer screen in case they made an error or the reaction time exceeded 2 s. In the case that they made more than five errors, the training was repeated, otherwise they were given the option of repeating the training session.

Mean reaction times (RTs) for each combination of *Cue* (emotion, gender), *Emotion* (happy, angry) and *Task Switch* (switch, noswitch) were calculated from correct trials only. 3.73% (range: 0,90%–8.30%) of correct trials were excluded due to data trimming: Individual reaction time distributions were trimmed by using only reaction times ±2.5 *SDs* below and above the subject's mean calculated from all correct trials.

An error was defined as an incorrect answer to the emotion or gender classification task. If the previous trial was incorrect, the current trial could not be classified as a switch or noswitch trial. Therefore, these trials (2.61%) were classified as 'ambiguous' and excluded from the analysis. Percent errors were used as an additional dependent variable. Similarly, the first trial of each block was excluded from both RT and error analyses.

Basal and acute HPA axis activity

Just as in a previous study by our group (Böhnke et al., 2010), the cortisol awakening response was assessed on three consecutive weekdays prior to the experiment according to the protocol of Hellhammer et al. (2007) to obtain a reliable trait measure of HPA axis activity. Subjects collected samples of native saliva at home each day at awakening and 30, 45, and 60 min later. Awakening time was arranged between 6:00 and 8:00 am and held constant intraindividually over the three days for all subjects, since awakening time has been shown to influence the cortisol awakening response (Kudielka and Kirschbaum, 2003). During the sampling period, subjects drank nothing but water and refrained from brushing their teeth, eating, and exercising. The subjects stored all samples in the refrigerator or freezer until returning them to our laboratory on the day of the experiment.

The area under the curve with respect to ground (AUCG) of the cortisol awakening response (nmol/l) was calculated as a trait measure of HPA axis activity (Hellhammer et al., 2007) with the formula reported in Pruessner et al. (2003), representing the entire area under the cortisol awakening response with respect to ground. The AUCG was calculated for each subject and day and then averaged over all days to form one reliable indicator of basal HPA axis activity for each subject. All but two subjects complied with the measurement protocol. Compliance was defined as a deviation of no more than 10 min from the targeted time for the first and 7 min for the other samples (Kudielka and Kirschbaum, 2003). The AUCGs of the two subjects (one from each *Drug* group) were averaged across only two days due to non-compliance on the third day. Their data was retained since the reliability of the AUCG when averaged over two days is still acceptable (Hellhammer et al., 2007).

Based on the average AUCG values, subjects were divided by a median split into a 'low' (AUCG low: $M = 529.85$; $SD = 155.63$) and 'high' (AUCG high: $M = 946.70$; $SD = 179.04$) basal cortisol group. This constitutes the independent variable *Basal Cortisol*. This results in the following group sizes: Placebo/AUCG low = 10, Placebo/AUCG high = 9, Cortisol/AUCG low = 9, Cortisol/AUCG high = 10.

During the experiment, six salivary cortisol samples were collected at the time points reported above. Subjects provided native saliva in 2 ml reaction tubes (Sarstedt, Nümbrecht, Germany). Collection tubes were positioned on the table in front of the subject and sampling instructions were given via computer. Immediately following the experiment, samples were frozen for biochemical analysis. Salivary cortisol was analyzed with a time-resolved immunoassay with fluorescence detection as described in detail elsewhere (Dressendörfer et al., 1992). Intra- and interassay variability was <10 and 12%, respectively.

Statistical analyses

For the manipulation check, the values of salivary cortisol (nmol/l) during the experimental session were submitted to a *Drug* (cortisol, placebo) by *Basal Cortisol* (low, high) by *Time* (6) ANOVA with repeated measurement on the last factor. Similarly, a *Drug* (cortisol, placebo) by *Basal Cortisol* (AUCG low, AUCG high) ANOVA was calculated for basal HPA axis activity (AUCG).

All dependent variables (reaction times, error percentage) were submitted to a *Drug* (cortisol, placebo) by *Basal Cortisol* (AUCG low, AUCG high) by *Cue* (emotion, gender) by *Emotion* (happy, angry) by *Task Switch* (switch, noswitch) ANOVA, with repeated measurement on the last three factors. Significant interactions were followed by Dunn's multiple comparison procedure (Kirk, 1995), which is basically a Bonferroni-corrected t-Test for specified a priori contrasts. For each Dunn's test, the critical difference ψ_{krit} ($\alpha = 0.05$) and number of

comparisons c are specified. Additionally, we report the empirical effect size Ω^2 for all significant (significance level 0.05) ANOVA effects (Cohen, 1988). In case the assumption of sphericity was violated, the degrees of freedom for all ANOVAs were Huynh–Feldt-corrected (Huynh and Feldt, 1976).

Given the current discussion on the a priori power of statistical tests (see Button et al. (2013)), we report the power values for the relevant statistical tests. The basic hypothesis assumes a *Drug* by *Task Switch* interaction, possibly moderated by *Basal Cortisol*. Given our sample size of 38 subjects and a significance level of 0.05, the two- and three-way interactions can detect a relatively small effect of $\Omega^2 \geq 0.05$ with a probability of $1\text{-}\beta > 0.99$[4]. This calculation assumes a plausible population correlation for reaction time measures of $\rho = 0.90$, which is supported by our empirical data. Should these interactions be further qualified by *Cue* and/or *Emotion*, power even increases as the number of observations increases by including these repeated measured independent variables. All power calculations were done with G*POWER3 (Faul et al., 2007).

Results

Manipulation checks

The *Drug* by *Basal Cortisol* by *Time* ANOVA for cortisol taken during the experimental session showed the expected interaction between *Drug* and *Time* ($F(5,170) = 15.52$; $p < 0.001$; $\omega^2 = 0.24$), depicted in Fig. 1. Post-hoc analyses ($\psi_{krit} = 3.72$; $c = 6$) revealed significantly elevated cortisol levels for the cortisol group relative to the placebo group at time points C3 to C6; at C1 and C2, before the injection, no significant difference in cortisol levels could be found. No effects including the independent variable *Basal Cortisol* were observed (all $Fs < 2.01$; all $ps > 0.10$).

Regarding basal HPA axis activity, the statistical analysis revealed no significant results besides the expected main effect of *Basal Cortisol* ($F(1,34) = 56.80$; $p < 0.001$; $\omega^2 = 0.60$).

Errors

On average, accuracy was very high, with a mean error rate of 2.70% ($SD = 1.85\%$), indicating limited validity of this analysis (Shadish et al., 2002). Still, for the sake of completeness, results are reported in brief (for further information, see Supplement).

The ANOVA *Drug* by *Basal Cortisol* by *Cue* by *Emotion* by *Task Switch* with repeated measurements on the last three factors revealed a main effect of *Task Switch* ($F(1,34) = 13.22$; $p < 0.001$; $\omega^2 = 0.14$), with more errors in the switch ($M = 3.36$; $SD = 2.56$) relative to the noswitch condition ($M = 2.03$; $SD = 1.69$).

Moreover, the analysis revealed a significant interaction *Cue* by *Emotion* by *Task Switch* ($F(1.34) = 4.84$; $p < 0.05$; $\omega^2 = 0.01$) which was qualified by the quadruple interaction *Drug* by *Cue* by *Emotion* by *Task Switch* ($F(1,34) = 5.96$; $p < 0.05$, $\omega^2 = 0.02$). The follow-up test for the comparison of error switch costs, i.e. the difference between switch vs. noswitch errors, between the placebo and the cortisol group at each combined level of cue and emotion ($\psi_{krit} = 2.10$; $c = 4$) revealed higher error switch costs for the cortisol group relative to the placebo group for angry faces with the preceding cue emotion (see Fig. A1, Supplement).

Furthermore, the ANOVA revealed a significant interaction *Basal Cortisol* by *Emotion* ($F(1.34) = 5.10$; $p < 0.05$; $\omega^2 = 0.05$) which was further qualified by the interaction of *Basal Cortisol* by *Emotion* by *Task Switch* ($F(1,34) = 9.43$; $p < 0.01$, $\omega^2 = 0.05$). Comparing error switch costs between the low and the high basal cortisol groups for each facial expression, the Dunn's Multiple Comparison Procedure revealed higher error switch costs for the low relative to the high basal cortisol group for angry faces, but the reversed pattern for happy faces ($\psi_{krit} = 1.12$; $c = 2$, see Fig. A2, Supplement).

Finally, the interaction *Drug* by *Basal Cortisol* by *Cue* by *Task Switch* ($F(1,34) = 5.61$; $p < 0.05$, $\omega^2 = 0.03$) was significant. For the post-hoc analysis, error switch costs were calculated and compared between the AUCG groups as well as the drug groups ($\psi_{krit} = 2.94$; $c = 8$). Within the low basal cortisol group, error switch costs in the placebo and the cortisol group did not differ. In contrast, within the high basal cortisol group, the cortisol group showed higher error switch costs compared to the placebo group when the cue was gender (see Fig. A3, Supplement). Within each drug group, no difference was found between the low and the high basal cortisol groups.

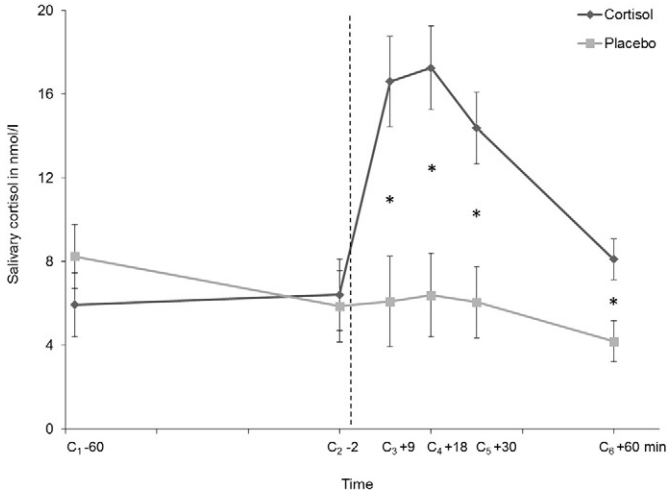

Fig. 1. Cortisol during the experimental session. Salivary cortisol in nmol/l at the six different time points C_1 to C_6 as a function of time (minutes, with reference to the drug injection (dotted line)) for the cortisol group and the placebo group. Error bars indicate standard errors of the mean. *: $p < 0.05$.

Reaction times

Table 1 contains mean reaction times (RTs in ms) and standard deviations (*SD*) for the different experimental groups and the conditions *Emotion* and *Task Switch*. When comparing switch and noswitch trials, it became apparent that RTs in noswitch trials were generally shorter than in switch trials. Additionally, the difference between switch and noswitch trials (i.e., switch costs) was descriptively larger when a reaction toward an angry face was required.

Upon analyzing the RTs via a *Drug* by *Basal Cortisol* by *Cue* by *Emotion* by *Task Switch* ANOVA, the main effect of *Task Switch* ($F(1,34) = 73.69$; $p < 0.001$; $\omega^2 = 0.49$) as well as the main effects of *Cue* ($F(1,34) = 40.40$; $p < 0.001$; $\omega^2 = 0.34$) and *Emotion* ($F(1,34) = 6.34$; $p < 0.05$; $\omega^2 = 0.07$) were significant. As expected, RTs (ms) in noswitch trials ($M = 870.28$; $SD = 164.64$) were significantly faster than in switch trials ($M = 939.32$; $SD = 196.57$). Furthermore, RTs following the cue emotion ($M = 941.93$; $SD = 193.73$) exceeded RTs following the cue gender ($M = 867.67$; $SD = 170.52$), and overall, happy faces ($M = 895.11$; $SD = 181.01$) were met with a faster reaction than angry faces ($M = 914.49$; $SD = 180.41$).

Besides this, the analysis revealed a significant interaction of *Task Switch* and *Emotion* ($F(1,34) = 4.36$; $p < 0.05$; $\omega^2 = 0.02$). Comparing switch and noswitch mean RTs within each emotion condition, the Dunn's Multiple Comparison Procedure revealed significant switch costs for both emotions, but larger costs for angry (switch: $M = 955.48$; $SD = 205.93$; noswitch: $M = 873.51$; $SD = 160.83$) than for happy (switch: $M = 923.16$; $SD = 193.57$; noswitch: $M = 867.05$; $SD = 165.60$) faces ($\psi_{krit} = 26.50$; $c = 2$).

[4] $1\text{-}\beta$ = power: probability to detect a given effect, if it really exists; β = error of falsely accepting the null hypothesis.

Table 1
Mean RTs in milliseconds (ms) and standard deviations (*SD*) in the noswitch and switch conditions, as well as the switch costs for the cortisol and the placebo groups with high or low basal cortisol (AUCG) in the different experimental conditions of *Emotion* averaged over *Cue*.

RTs (ms)		Noswitch		Switch		Switch costs (switch–noswitch)	
Emotion	AUCG	Placebo	Cortisol	Placebo	Cortisol	Placebo	Cortisol
Angry	Low	819 (119)	885 (148)	844 (139)	975 (174)	25	90
	High	914 (229)	877 (145)	1070 (283)	933 (171)	156	56
Happy	Low	794 (131)	864 (128)	834 (182)	914 (141)	50	50
	High	931 (252)	879 (155)	1008 (251)	927 (182)	77	48

Most interestingly, however, the statistical analysis revealed a significant effect of cortisol administration on the reaction times in noswitch and switch trials, albeit as a function of *Basal Cortisol* ($F(1,34) = 8.96$, $p < 0.01$, $\omega^2 = 0.10$, see Fig. 2). For the post-hoc analysis, switch costs of the mean RTs were calculated and compared between the AUCG groups as well as the drug groups. Within the AUCG high group, the results showed significantly higher switch costs in the placebo group (switch costs: 116.66) compared to the cortisol group (switch costs: 52.50), while the opposite pattern was observed within the AUCG low group, with lower switch costs in the placebo group (switch costs: 37.44) relative to the cortisol group (switch costs: 69.54). However, the latter contrast of switch costs just missed significance. Comparing high and low basal HPA axis activity, the post-hoc analysis revealed significantly higher switch costs in the AUCG high versus the AUCG low group within the placebo group, while no difference was found within the cortisol group ($\psi_{krit} = 42.72$; $c = 4$).

The aforementioned interactions were further qualified by a four-way interaction of the factors *Task Switch*, *Emotion*, *Basal Cortisol* and *Drug* ($F(1,34) = 7.32$, $p < 0.05$, $\omega^2 = 0.04$). Comparing the switch costs between the four groups (*Drug* × *Basal Cortisol*) within each facial expression, the post-hoc analysis revealed a very similar structure to the one found in the triple interaction described above for the angry faces, albeit more pronounced ($\psi_{krit} = 51.42$; $c = 8$; see Fig. 3, left graph, Table 1).

Again, within the AUCG high group, the placebo group showed significantly higher switch costs compared to the cortisol group. The opposite pattern, with lower switch costs in the placebo group relative to the cortisol group, was found in the AUCG low group, reaching significance this time. Moreover, high basal cortisol caused higher switch costs in the placebo group, whereas the groups AUCG low and AUCG high showed similar switch costs within the cortisol group. For happy faces, the switch costs did not differ between the groups (see Fig. 3, right graph). No further main effects or interactions reached significance (all $Fs < 3.74$, $ps > 0.10$).

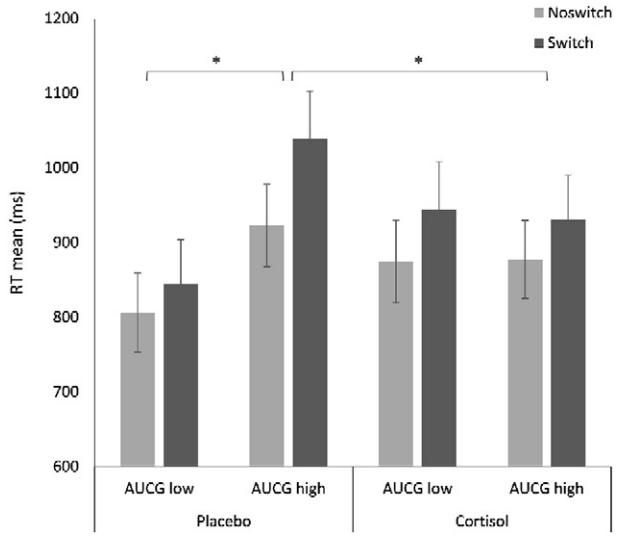

Fig. 2. Impact of basal and acute cortisol on RT switch costs. Mean reaction times (RTs in ms) for noswitch and switch trials for the drug groups (placebo; cortisol) with low and high basal cortisol (AUCG low; AUCG high). Error bars indicate standard errors of the mean. Square brackets indicate significant differences between switch costs, i.e., the difference between the switch and the noswitch condition. $p < 0.05$.

Discussion

The present study sought to investigate non-genomic effects of exogenous cortisol on the core executive function of cognitive flexibility in healthy male subjects.

The cortisol manipulation was successful; the injection of 4 mg led to a significant increase of cortisol, similar to that was found in other studies using either a similar dose or stress inductions such as the socially evaluated cold pressor stress test or the Trier Social Stress Test (Plessow et al., 2012; Schwabe et al., 2008, Fig.1a; Schilling et al., 2013). Moreover, the task switching paradigm showed the expected switch costs (Monsell, 2003), with less accuracy and slower reaction times in switch compared to noswitch trials.

Partly in accordance with our hypothesis, exogenous cortisol administration resulted in altered switch costs in our male sample, both in error rates and reaction times (RTs). However, regarding accuracy, error rates were very low in general. Cortisol injection led to slightly more error switch costs, albeit depending on the cue, the emotion of the target stimuli and basal cortisol levels, respectively. More importantly, drug administration altered RT switch costs as a function of basal HPA axis activity and, in addition, of target emotion, but independently of the cue. After placebo administration, switch costs of RTs were larger in case of high but not of low basal HPA axis activity. In case of cortisol administration, however, trait basal HPA activity had no additional impact and switch costs were reduced relative to the placebo group, especially for angry faces.

More precisely, in our male sample, RTs were particularly fast in the Placebo group with low basal HPA axis activity. This group showed the smallest switch costs effects, indicating the most effective cognitive control. Thus, without further cortisol treatment, low basal cortisol levels led to quick and flexible reactions in situations in which task goals changed. In contrast, in the placebo group, high basal cortisol was associated with the slowest reactions and largest switch costs. This difference between participants with high vs. low basal trait levels of cortisol, as assessed by CAR, in the placebo group is in line with the well-established negative effects of chronically high cortisol. Hypercortisolism, apparent in illnesses such as Cushing's disease, has been shown to change affect and cognition, even leading to a so-called 'steroid psychosis' (Lupien et al., 2007). Likewise, Schlosser et al. (2011) in their review reported an association of chronically elevated cortisol levels with cognitive impairments in patients with major depression. Even though the high basal cortisol group did not reach pathological levels of cortisol, our findings point in similar directions. However, so far, there is little knowledge about the influence of trait basal HPA axis activity on cognitive performance in healthy subjects, and the protocol for valid trait measurements of basal cortisol as specified by Hellhammer et al. (2007) is rarely, if ever, used.

When acute cortisol was applied, both the low and the high basal cortisol groups in our male sample showed RTs in the medium range. The tendency of acute cortisol effects to overlay basal HPA axis activity

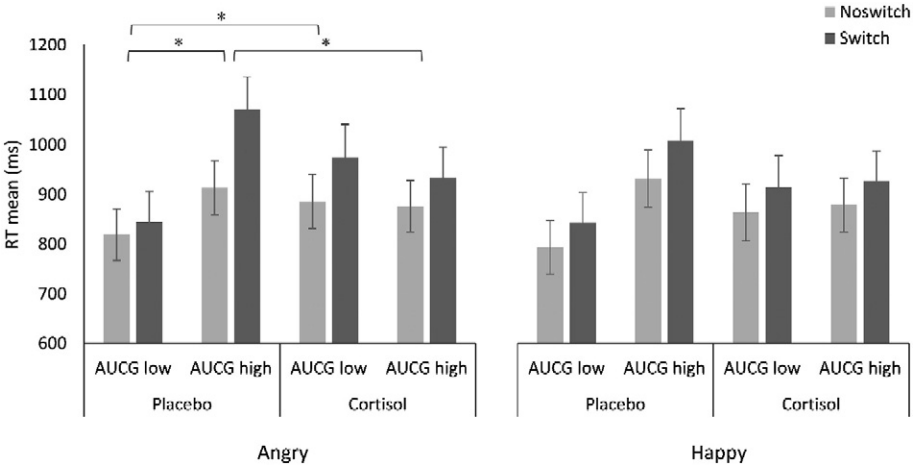

Fig. 3. Impact of basal and acute cortisol on RT switch costs for angry and happy faces. Mean reaction times (RTs in ms) for noswitch and switch trials for the drug groups (placebo; cortisol) with low and high basal cortisol (AUCG low; AUCG high), separately for the target stimuli: angry (left graph) and happy faces (right graph). Error bars indicate standard errors of the mean. Square brackets indicate significant differences between switch costs, i.e., the difference between the switch and the noswitch condition. $p < 0.05$.

is also apparent in the relationship between cortisol and aggression, in which basal cortisol effects were not significant after cortisol administration (Böhnke et al., 2010). Furthermore, Haller et al. (2004) found a similar effect in rats, in that chronically low basal cortisol was not followed by abnormal aggression when corticosterone was injected prior to a conflict. Although these results come from aggression research, they support our finding that acute cortisol influences behavior (i.e., RTs) independent of basal levels. When no acute stress is present and thus situational demands govern behavior, basal cortisol does have an impact.

Upon closer inspection, the equalizing effect of intravenous cortisol administration had opposite effects on the performance depending on the basal cortisol levels. Whereas the cortisol injection in men with high basal cortisol levels led to an improved performance, i.e., faster reactions and reduced switch costs, the cortisol injection diminished the benefit in men with low basal levels, causing switch costs almost twice those of the placebo group with low basal cortisol, reaching significance in case of angry faces. Considering the HPA axis hormonal cascade with the end product cortisol, an additional injection of cortisol might cause a further decline of adrenocorticotropic hormone (ACTH) levels due to the negative feedback loop (Joels et al., 2012) of already low basal ACTH levels, a consequence of low basal cortisol in healthy subjects. In case of high basal cortisol and thus high basal ACTH levels, however, an acute administration of cortisol reduces ACTH levels to a "normal" level. Currently, there is very little knowledge about the impact of ACTH or other HPA axis players other than cortisol on cognitive functions. However, Wolkowitz (1994) in his review reported that an administration of corticosteroids caused reduced ACTH levels which were associated with cognitive impairment.

Alternatively, the interaction of basal and acute cortisol might be explained by a different receptor density in individuals with high and low basal cortisol levels and the consequential occupation of only high or both high and low cortisol-affine receptor types (with more excitatory or inhibitory effects, respectively) in the case of exogenous cortisol administration. However, this is speculative so far and further research is needed to explain the underlying biological mechanism of the interplay between basal and acute cortisol. Nevertheless, the pattern showing a reversed effect of acute cortisol depending on basal cortisol concentrations might explain why the impact of acute cortisol on performance is often rather weak without the consideration of basal HPA axis activity, highlighting its relevance in stress research. Evidently, the effect observed in our study would not have been detected without the differentiation of basal HPA axis activity, and some previous studies on the topic which did not consider this aspect (e.g., Plessow et al. (2012); Steinhauser et al. (2007); Vaz et al. (2011) and Wingenfeld et al. (2011)) failed to find effects of stress and cortisol on RT switch costs.

In general, switch costs in RTs are considered to reflect the cognitive control processes activated when switching between different competing tasks is required (Monsell, 2003; Wylie and Allport, 2000). However, higher error rates are also frequently found in switch trials compared to noswitch trials (Monsell, 2003). In the present study, acute cortisol had opposite effects on errors and RTs. The enhanced switch costs in the cortisol group are in line with the findings reported by Plessow et al. (2012) (see above). However, similar to our results, accuracy was very high in general and even in the stress group error rates did not exceed 8%, just as in the present study. Thus, these results might be caused by floor effects, which entail reduced reliability due to a high probability for random results (Cramer and Howitt, 2004; Shadish et al., 2002). Moreover, respective effect sizes in the present study as well as in the study by Plessow et al. (2012) are rather small ($\omega^2 \leq 0.05$). Therefore, these results should be interpreted with caution until conceptual replications with paradigms producing higher error rates are available. However, the stress effects reported by Plessow et al. (2012) were only found in the error rates, whereas no significant interactions including the factor stress could be revealed in the RTs. The authors explain this as a change of strategy in order to keep reactions fast under stress, while error rates go up (Plessow et al., 2012). This assumption is in accordance with the cognitive-energetical framework postulated by Hockey (1997) which states that regulatory processes required for coping with stress allocate resources at the expense of performance. Thus, the reduced RT switch costs due to cortisol injection in the present study with healthy men might be caused by the adoption of a performance-protection strategy demanding less capacity (Hockey, 1997, p. 78). These compensatory control mechanisms allowed our male sample to maintain manifest performance, but probably imply so-called "latent performance decrements" (Hockey, 1997, p. 82), which might be reflected in the slight increase of errors.

On the other hand, others found mere positive effects of hydrocortisone administration on inhibitory performance (emotional distracter interference in working memory: Oei et al. (2009), emotional Go Nogo task in healthy control participants: Schlosser et al. (2013)). Hence, contrary to our hypothesis, cortisol can have improving effects on executive functions. As hydrocortisone was administered orally in both of the studies mentioned, the positive effect of exogenous cortisol is probably not solely restricted to non-genomic mechanisms. But it is noteworthy

that these studies used emotional material, just as the present study, which might fortify more adaptive reactions in case of elevated cortisol levels.

Regarding the emotion of the target stimuli, the above-described effect of acute and basal cortisol on RT switch costs was particularly pronounced for angry faces. Since low basal cortisol levels have been associated with aggressive behavior (Böhnke et al., 2010 and cited therein), it seems plausible that angry faces are processed preferentially and with enhanced cognitive flexibility by the placebo group with low basal cortisol, indicated by minimal switch costs and very fast reactions (see Fig. 3 and Table 1). Less is known about the impact of high basal cortisol levels on emotional processing. However, van Honk et al. (1998) reported enhanced avoidance of angry faces in participants with high baseline cortisol. Our results point in a similar direction, with slow reaction times and the largest switch costs in the placebo group with high basal levels of cortisol, suggesting less cognitive control in this case, probably due to the attention captured by these stimuli. Regarding the impact of acute exogenous cortisol on the processing of emotional threat-related material, previous studies have fairly consistently shown alterations, albeit with inconsistent results concerning the direction of this impact (for a review, see Putman and Roelofs (2011)). The present study might shed light on these divergence based on our results regarding basal cortisol. Depending on the level of basal cortisol in the placebo group, the comparison with the equalizing effect of acute cortisol resulted in either an enhancement or a reduction of cognitive flexibility as measured by switch costs, when responding to angry faces. This is supported by the finding that cortisol administration led to increased avoidance of angry faces in highly anxious males (van Peer et al., 2007), who show higher cortisol awakening responses (Vreeburg et al., 2010). Nevertheless, three things should be noted. First, in the present study, the reactions to happy faces showed the same pattern, albeit without reaching significance. Hence, the influence of acute and basal cortisol is not entirely exclusive to threat-related stimuli. Second, in contrast to the effect of cortisol on affective behavior reviewed by Putman and Roelofs (2011), task-relevance of the emotional faces as manipulated by the cue did not influence this effect. Third, the three-way interaction of basal HPA axis activity and acute cortisol administration on switch costs showed a rather high impact, explaining about 10% of effect variance, whereas the higher order interaction with emotion explained only 4% of effect variance. Therefore, we consider the impact of the target's emotion to be rather weak in comparison to the emotion-independent effect on cognitive control.

The present study was the first to investigate combined effects of trait basal HPA axis activity and acute exogenous cortisol manipulation on a core executive function, namely cognitive flexibility, in healthy men within the non-genomic timeframe. Still, some limitations should be mentioned. For one thing, the use of an exogenous hydrocortisone injection allowed a precise timing of peak plasma levels, essential for the investigation of non-genomic effects. However, hydrocortisone artificially raises cortisol levels, thus lacking the quality of a real-life stressor, while a psychological stressor leads to an activation of both the HPA axis and the sympathetic nervous system. Since acute sympathetic activation has been found to alter effects of cortisol on executive functions (Elzinga and Roelofs, 2005), the immediate, acute impact of a naturalistic stressor on cognitive flexibility might differ from the present findings.

Moreover, the study only included healthy young men for which reason the present results cannot be readily generalized to women. Although the meta-analysis on effects of acute cortisol administration on executive functions by Shields et al. (2015) did not reveal sex as a moderating variable, Breitberg et al. (2013) did find dose- and sex-depended genomic impacts of a cortisol injection in an affective Go Nogo task. Thus, further research is needed to clarify possible sex effects in the context of cognitive control and especially with regard to the impact of basal cortisol in this context.

Taken together, the present study provides evidence for the non-genomic impact of acute exogenous cortisol as well as basal HPA axis activity on cognitive flexibility in healthy men, operationalized with an emotional task switching paradigm. In our male sample, low basal HPA axis activity was associated with minimal switch costs regarding reaction times, whereas high basal HPA axis activity notably impaired cognitive flexibility. An acute administration of cortisol, however, abolished this effect at the expense of high accuracy, the latter impact on errors being independent of basal cortisol but dependent on the cue and the emotion of the target. These results highlight the relevance of rapid effects of cortisol on executive functions. At the same time our results underline the relevance of considering trait basal HPA axis activity in healthy subjects, indicating a possible moderator beyond drug dosage and time delay between cortisol manipulation and testing (Shields et al., 2015). Furthermore, threat-related emotions seem to play an essential role under the influence of cortisol, as the described effect is more pronounced toward angry faces and has not been found in studies using neutral stimuli. To clarify the specificity of non-genomic relative to genomic effects, the present study should be replicated in a within-subjects design, including the comparison of neutral to different emotional stimuli and extending it to both males and females.

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Conflict of interest

None declared.

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References

Altmann, E.M., Gray, W.D., 2008. An integrated model of cognitive control in task switching. Psychol. Rev. 115 (3), 602–639. http://dx.doi.org/10.1037/0033-295X.115.3.602.

Beluche, I., Chaudieu, I., Norton, J., Carrière, I., et al., 2009. Persistence of abnormal cortisol levels in elderly persons after recovery from major depression. J. Psychiatry Res. 43 (8), 777–783. http://dx.doi.org/10.1016/j.jpsychires.2008.10.011.

Böhnke, R., Bertsch, K., Kruk, M.R., Naumann, E., 2010. The relationship between basal and acute HPA axis activity and aggressive behavior in adults. J. Neural Transm. 117 (5), 629–637. http://dx.doi.org/10.1007/s00702-010-0391-x.

Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D., 2001. Conflict monitoring and cognitive control. Psychol. Rev. 108 (3), 624–652. http://dx.doi.org/10.1037/0033-295X.108.3.624.

Breitberg, A., Drevets, W.C., Wood, S.E., Mah, L., et al., 2013. Hydrocortisone infusion exerts dose- and sex-dependent effects on attention to emotional stimuli. Brain Cogn. 81 (2), 247–255. http://dx.doi.org/10.1016/j.bandc.2012.10.010.

Buchanan, T.W., Lovallo, W.R., 2001. Enhanced memory for emotional material following stress-level cortisol treatment in humans. Psychoneuroendocrinology 26, 307–317. http://dx.doi.org/10.1016/S0306-4530(00)00058-5.

Button, K.S., Ioannidis, J.P.A., Mokrysz, C., Nosek, B.A., et al., 2013. Empirical evidence for low reproducibility indicates low pre-study odds. Nat. Rev. Neurosci. 14 (12), 877. http://dx.doi.org/10.1038/nrn3475-c6.

Cohen, J., 1988. Statistical power analysis for the behavioral sciences. second ed. xxi. L. Erlbaum Associates, Hillsdale, N.J, p. 567.

Cramer, D., Howitt, D., 2004. The sage dictionary of statistics: a practical resource for students in the social sciences. Sage Pub. [S.l.], 272 pp.

de Kloet, E.R., Joëls, M., Holsboer, F., 2005. Stress and the brain: from adaptation to disease. Nat. Rev. Neurosci. 6 (6), 463–475. http://dx.doi.org/10.1038/nrn1683.
Diamond, A., 2013. Executive functions. Annu. Rev. Psychol. 64, 135–168. http://dx.doi.org/10.1146/annurev-psych-113011-143750.
Dolcos, F., 2014. The fast and the slow sides of cortisol's effects on emotional interference and sustained attention. Front Neurosci. 8 http://dx.doi.org/10.3389/fnins.2014.00268.
Dressendörfer, R., Kirschbaum, C., Rohde, W., Stahl, F., Strasburger, C., 1992. Synthesis of a cortisol-biotin conjugate and evaluation as a tracer in an immunoassay for salivary cortisol measurement. J. Steroid Biochem. Mol. Biol. 43 (7), 683–692. http://dx.doi.org/10.1016/0960-0760(92)90294-S.
Ebner, N.C., Riediger, M., Lindenberger, U., 2010. FACES—a database of facial expressions in young, middle-aged, and older women and men: development and validation. Behav. Res. Methods 42 (1), 351–362. http://dx.doi.org/10.3758/BRM.42.1.351.
Elzinga, B.M., Roelofs, K., 2005. Cortisol-induced impairments of working memory require acute sympathetic activation. Behav. Neurosci. 119 (1), 98–103. http://dx.doi.org/10.1037/0735-7044.119.1.98.
Falkenstein, E., Tillmann, H.C., Christ, M., Feuring, M., Wehling, M., 2000. Multiple actions of steroid hormones—a focus on rapid, nongenomic effects. Pharmacol. Rev. 52 (4), 513–556 PMID:11121509.
Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39 (2), 175–191. http://dx.doi.org/10.3758/BF03193146.
Frith, C., 2009. Role of facial expressions in social interactions. Philos. Trans. R. Soc. B 364 (1535), 3453–3458. http://dx.doi.org/10.1098/rstb.2009.0142.
Groeneweg, F.L., Karst, H., de Kloet, E.R., Joels, M., 2011. Rapid non-genomic effects of corticosteroids and their role in the central stress response. J. Endocrinol. 209 (2), 153–167. http://dx.doi.org/10.1530/JOE-10-0472.
Haller, J., Halasz, J., Mikics, E., Kruk, M.R., 2004. Chronic glucocorticoid deficiency-induced abnormal aggression, autonomic hypoarousal, and social deficit in rats. J. Neuroendocrinol. 16 (6), 550–557. http://dx.doi.org/10.1111/j.1365-2826.2004.01201.x.
Hellhammer, J., Fries, E., Schweisthal, O., Schlotz, W., et al., 2007. Several daily measurements are necessary to reliably assess the cortisol rise after awakening: state- and trait components. Psychoneuroendocrinology 32 (1), 80–86. http://dx.doi.org/10.1016/j.psyneuen.2006.10.005.
Hockey, G.R.J., 1997. Compensatory control in the regulation of human performance under stress and high workload; a cognitive-energetical framework. Biol. Psychol. 45 (1–3), 73–93. http://dx.doi.org/10.1016/S0301-0511(96)05223-4.
Huynh, H., Feldt, L.S., 1976. Estimation of the Box correction for degrees of freedom from sample data in randomized block and split-plot designs. J. Educ. Behav. Stat. 1 (1), 69–82. http://dx.doi.org/10.3102/10769986001001069.
Joels, M., Sarabdjitsingh, R.A., Karst, H., 2012. Unraveling the time domains of corticosteroid hormone influences on brain activity: rapid, slow, and chronic modes. Pharmacol. Rev. 64 (4), 901–938. http://dx.doi.org/10.1124/pr.112.005892.
Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., et al., 2010. Control and interference in task switching—a review. Psychol. Bull. 136 (5), 849–874. http://dx.doi.org/10.1037/a0019842.
Kirk, R.E., 1995. Experimental design: procedures for the behavioral sciences. third ed. xiv. Brooks/Cole, Pacific Grove, Calif, p. 921.
Kray, J., Lindenberger, U., 2000. Adult age differences in task switching. Psychol. Aging 15 (1), 126–147. http://dx.doi.org/10.1037/0882-7974.15.1.126.
Kudielka, B., Kirschbaum, C., 2003. Awakening cortisol responses are influenced by health status and awakening time but not by menstrual cycle phase. Psychoneuroendocrinology 28 (1), 35–47. http://dx.doi.org/10.1016/S0306-4530(02)00008-2.
Lupien, S., Lecours, A.R., Lussier, I., Schwartz, G., et al., 1994. Basal cortisol levels and cognitive deficits in human aging. J. Neurosci. 14 (5 Pt 1), 2893–2903 PMID: 8182446.
Lupien, S.J., de Leon, M., de Santi, S., Convit, A., et al., 1998. Cortisol levels during human aging predict hippocampal atrophy and memory deficits. Nat. Neurosci. 1 (1), 69–73. http://dx.doi.org/10.1038/271.
Lupien, S.J., Maheu, F., Tu, M., Fiocco, A., Schramek, T.E., 2007. The effects of stress and stress hormones on human cognition: Implications for the field of brain and cognition. Brain Cogn. 65 (3), 209–237. http://dx.doi.org/10.1016/j.bandc.2007.02.007.
Makara, G.B., Haller, J., 2001. Non-genomic effects of glucocorticoids in the neural system. Evidence, mechanisms and implications. Prog. Neurobiol. 65 (4), 367–390. http://dx.doi.org/10.1016/S0301-0082(01)00012-0.
Meiran, N., Chorev, Z., Sapir, A., 2000. Component processes in task switching. Cogn. Psychol. 41 (3), 211–253. http://dx.doi.org/10.1006/cogp.2000.0736.
Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., et al., 2000. The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. Cogn. Psychol. 41 (1), 49–100. http://dx.doi.org/10.1006/cogp.1999.0734.
Monsell, S., 2003. Task switching. Trends Cogn. Sci. 7 (3), 134–140. http://dx.doi.org/10.1016/S1364-6613(03)00028-7.
Oei, N.Y., Tollenaar, M.S., Spinhoven, P., Elzinga, B.M., 2009. Hydrocortisone reduces emotional distracter interference in working memory. Psychoneuroendocrinology 34 (9), 1284–1293. http://dx.doi.org/10.1016/j.psyneuen.2009.03.015.
Plessow, F., Kiesel, A., Kirschbaum, C., 2012. The stressed prefrontal cortex and goal-directed behaviour: acute psychosocial stress impairs the flexible implementation of task goals. Exp. Brain Res. 216 (3), 397–408. http://dx.doi.org/10.1007/s00221-011-2943-1.
Pruessner, J.C., Kirschbaum, C., Meinlschmid, G., Hellhammer, D.H., 2003. Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. Psychoneuroendocrinology 28 (7), 916–931. http://dx.doi.org/10.1016/S0306-4530(02)00108-7.
Putman, P., Roelofs, K., 2011. Effects of single cortisol administrations on human affect reviewed: coping with stress through adaptive regulation of automatic cognitive processing. Psychoneuroendocrinology 36 (4), 439–448. http://dx.doi.org/10.1016/j.psyneuen.2010.12.001.
Qin, S., Hermans, E.J., van Marle, H.J.F., Luo, J., Fernández, G., 2009. Acute psychological stress reduces working memory-related activity in the dorsolateral prefrontal cortex. Biol. Psychiatry 66 (1), 25–32. http://dx.doi.org/10.1016/j.biopsych.2009.03.006.
Rimmele, U., Domes, G., Mathiak, K., Hautzinger, M., 2003. Cortisol has different effects on human memory for emotional and neutral stimuli. Neuroreport 14 (18), 2485–2488. http://dx.doi.org/10.1097/00001756-200312190-00038.
Roelofs, K., Elzinga, B.M., Rotteveel, M., 2005. The effects of stress-induced cortisol responses on approach-avoidance behavior. Psychoneuroendocrinology 30 (7), 665–677. http://dx.doi.org/10.1016/j.psyneuen.2005.02.008.
Roelofs, K., van Peer, J., Berretty, E., Jong, P.d., et al., 2009. Hypothalamus–pituitary-adrenal axis hyperresponsiveness is associated with increased social avoidance behavior in social phobia. Biol. Psychiatry 65 (4), 336–343. http://dx.doi.org/10.1016/j.biopsych.2008.08.022.
Schilling, T.M., Kölsch, M., Larra, M.F., Zech, C.M., et al., 2013. For whom the bell (curve) tolls: cortisol rapidly affects memory retrieval by an inverted U-shaped dose–response relationship. Psychoneuroendocrinology 38 (9), 1565–1572. http://dx.doi.org/10.1016/j.psyneuen.2013.01.001.
Schlosser, N., Wolf, O.T., Wingenfeld, K., 2011. Cognitive correlates of hypothalamic–pituitary–adrenal axis in major depression. Expert. Rev. Endocrinol. Metab. 6 (1), 109–126. http://dx.doi.org/10.1586/eem.10.79.
Schlosser, N., Wolf, O.T., Fernando, S.C., Terfehr, K., et al., 2013. Effects of acute cortisol administration on response inhibition in patients with major depression and healthy controls. Psychiatry Res. http://dx.doi.org/10.1016/j.psychres.2012.12.019.
Scholz, U., La Marca, R., Nater, U.M., Aberle, I., et al., 2009. Go no-go performance under psychosocial stress: beneficial effects of implementation intentions. Neurobiol. Learn. Mem. 91 (1), 89–92. http://dx.doi.org/10.1016/j.nlm.2008.09.002.
Schreiber, J., Shirtcliff, E., Hulle, C., Lemerychalfant, K., et al., 2006. Environmental influences on family similarity in afternoon cortisol levels: twin and parent–offspring designs. Psychoneuroendocrinology 31 (9), 1131–1137. http://dx.doi.org/10.1016/j.psyneuen.2006.07.005.
Schwabe, L., Haddad, L., Schachinger, H., 2008. HPA axis activation by a socially evaluated cold-pressor test. Psychoneuroendocrinology 33 (6), 890–895. http://dx.doi.org/10.1016/j.psyneuen.2008.03.001.
Shadish, W.R., Cook, T.D., Campbell, D.T., 2002. Experimental and quasi-experimental designs for generalized causal inference. Wadsworth Cengage Learning, Belmont, CA, p. 623.
Shields, G.S., Bonner, J.C., Moons, W.G., 2015. Does cortisol influence core executive functions? A meta-analysis of acute cortisol administration effects on working memory, inhibition, and set-shifting. Psychoneuroendocrinology 58, 91–103. http://dx.doi.org/10.1016/j.psyneuen.2015.04.017.
Steinhauser, M., Maier, M., Hubner, R., 2007. Cognitive control under stress: How stress affects strategies of task-set reconfiguration. Psychol. Sci. 18 (6), 540–545. http://dx.doi.org/10.1111/j.1467-9280.2007.01935.x.
van der Plas, E.A., Crone, E.A., van den Wildenberg, W.P., Tranel, D., Bechara, A., 2009. Executive control deficits in substance-dependent individuals: a comparison of alcohol, cocaine, and methamphetamine and of men and women. J. Clin. Exp. Neuropsychol. 31 (6), 706–719. http://dx.doi.org/10.1080/13803390802484797.
van Honk, J., Tuiten, A., van den Hout, M., Koppeschaar, H., et al., 1998. Baseline salivary cortisol levels and preconscious selective attention for threat. A pilot study. Psychoneuroendocrinology 23 (7), 741–747. http://dx.doi.org/10.1016/S0306-4530(98)00047-X.
van Peer, J.M., Roelofs, K., Rotteveel, M., van Dijk, J.G., et al., 2007. The effects of cortisol administration on approach-avoidance behavior: an event-related potential study. Biol. Psychol. 76 (3), 135–146. http://dx.doi.org/10.1016/j.biopsycho.2007.07.003.
Vaz, L.J., Pradella-Hallinan, M., Bueno, O.F.A., Pompéia, S., 2011. Acute glucocorticoid effects on the multicomponent model of working memory. Humanist. Psychol. 26 (7), 477–487. http://dx.doi.org/10.1002/hup.1230.
Vreeburg, S.A., Zitman, F.G., van Pelt, J., Derijk, R.H., et al., 2010. Salivary cortisol levels in persons with and without different anxiety disorders. Psychosom. Med. 72 (4), 340–347. http://dx.doi.org/10.1097/PSY.0b013e3181d2f0c8.
Wingenfeld, K., Wolf, S., Krieg, J.-C., Lautenbacher, S., 2011. Working memory performance and cognitive flexibility after dexamethasone or hydrocortisone administration in healthy volunteers. Psychopharmacology 217 (3), 323–329. http://dx.doi.org/10.1007/s00213-011-2286-4.
Wolf, O.T., Kuhlmann, S., Buss, C., Hellhammer, D.H., Kirschbaum, C., 2004. Cortisol and memory retrieval in humans: influence of emotional valence. Ann. N. Y. Acad. Sci. 1032 (1), 195–197. http://dx.doi.org/10.1196/annals.1314.019.
Wolkowitz, O., 1994. Prospective controlled studies of the behavioral and biological effects of exogenous corticosteroids. Psychoneuroendocrinology 19 (3), 233–255. http://dx.doi.org/10.1016/0306-4530(94)90064-7.
Wüst, S., Wolf, J., Hellhammer, D.H., Federenko, I., et al., 2000. The cortisol awakening response — normal values and confounds. Noise Health 2 (7), 79–88 PMID: 12689474.
Wylie, G., Allport, A., 2000. Task switching and the measurement of "switch costs". Psychol. Res. 63 (3–4), 212–233. http://dx.doi.org/10.1007/s004269900003.