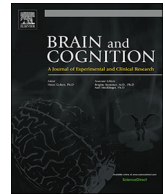




ELSEVIER

Contents lists available at ScienceDirect

## Brain and Cognition

journal homepage: [www.elsevier.com/locate/b&c](http://www.elsevier.com/locate/b&c)

# Pre-encoding stress induced changes in perceived stress, blood pressure and cortisol are differentially associated with recollection and familiarity

Uta S. Wiemers<sup>a</sup>, Tanja C. Hamacher-Dang<sup>a</sup>, Andrew P. Yonelinas<sup>b</sup>, Oliver T. Wolf<sup>a,c,\*</sup>

<sup>a</sup> Department of Cognitive Psychology, Institute of Cognitive Neuroscience, Faculty of Psychology, Ruhr-University Bochum, 44780 Bochum, Germany

<sup>b</sup> University of California, Davis, Department of Psychology, One Shields Avenue, Davis, CA 95616, USA

<sup>c</sup> International Graduate School of Neuroscience, Ruhr-University Bochum, 44780 Bochum, Germany

## ARTICLE INFO

## Keywords:

Stress  
HPA axis  
SNS  
Recognition memory

## ABSTRACT

Stress before encoding is often linked to impaired memory. Further influences of stress on memory are arousal of the to be learned material and memory retrieval type (free recall vs. recognition). In the current study we tested the influence of stress on memory encoding for neutral and negative arousing pictures in healthy young adults. A total of 80 participants (40 men) were subjected either to the socially evaluated cold pressure test or a control condition before encoding of arousing and neutral pictures. One day later participants underwent a recognition test. Results show different relationships between the obtained stress markers and recognition memory. Higher perceived stress ratings predicted poorer overall accuracy for arousing material. Lower perceived stress ratings and larger blood pressure increase predicted higher recollection values for arousing material. In contrast, a larger cortisol increase predicted lower familiarity values for arousing material. Concluding, activity of the sympathetic nervous system (SNS) and a lower feeling of perceived stress predict better recollection. HPA axis activity predicts lower familiarity. Pre-encoding induced changes in the perceived feeling of stress, activity of the SNS, and activity of the HPA axis show specific and distinct relationships to recognition memory.

## 1. Introduction

Stress is the body's reaction to psychological or physical strains, trying to maintain or regain stability (McEwen, 2007). To serve this purpose, two bodily systems react to stressful situations: the sympathetic nervous system (SNS) and the hypothalamus-pituitary-adrenal (HPA) axis (Ulrich-Lai & Herman, 2009). The fast acting SNS activity results in a release of adrenalin and noradrenalin, which are important for the fight-or-flight response (de Kloet, Joëls, & Holsboer, 2005). The HPA axis, reacting slower than the SNS, releases glucocorticoids (cortisol in humans, corticosterones in rodents), which bind to receptors abundant in several brain regions including the hippocampus, amygdala, and prefrontal cortex, all regions responsible for learning and memory processes (de Kloet, Sibug, Helmerhorst, & Schmidt, 2005). An influence of stress on these cognitive processes has been described.

Previous studies revealed that the influence of stressful situations and resulting hormonal and emotional changes on memory is dependent on the timing of the stressor. Stress induced cortisol elevations during memory retrieval lead to impairing effects on memory (de Quervain, Roozendaal, & McGaugh, 1998; de Quervain, Roozendaal, Nitsch, McGaugh, & Hock, 2000; Wolf, 2017). Contrary, elevated levels

of cortisol during memory consolidation usually result in better memory (Cahill, Gorski, & Le, 2003; Sandi, Loscertales, & Guaza, 1997; Shields, Sazma, McCullough, & Yonelinas, 2017). The effect of a stress manipulation before encoding is under debate due to conflicting results. However, a recent meta-analysis identified that a stressor taking place at least 22 min before encoding typically results in a decrease of memory performance, if to be learned material is not directly related to the stressor itself (Shields et al., 2017). Timing however is not the only influencing factor. Memory performance under stressful conditions seems to depend on arousal of the to be learned material, too. Usually, arousing material is remembered better than neutral material (Cahill & McGaugh, 1995; Heuer & Reisberg, 1990) and some studies show an interacting effect of stress and arousal of the learning material on memory (e.g. Buchanan & Lovaglio, 2001; Kuhlmann, Kirschbaum, & Wolf, 2005; Smeets et al., 2009). This interaction, however, is not observed consistently. The aforementioned meta-analysis found out that valence of the learning material was not moderating memory performance if stress was induced before encoding (Shields et al., 2017).

Likewise, the involved memory systems seem to play a role, for example whether participants are required to freely recall material or whether they have to recognize it (recognition memory). Recognition

\* Corresponding author at: Department of Cognitive Psychology, Ruhr-University Bochum, Universitätsstr. 150, 44780 Bochum, Germany.

E-mail addresses: [uta.wiemers@rub.de](mailto:uta.wiemers@rub.de) (U.S. Wiemers), [tanja.hamacher@rub.de](mailto:tanja.hamacher@rub.de) (T.C. Hamacher-Dang), [apyonelinas@ucdavis.edu](mailto:apyonelinas@ucdavis.edu) (A.P. Yonelinas), [oliver.t.wolf@rub.de](mailto:oliver.t.wolf@rub.de) (O.T. Wolf).

memory can be broken down into the two processes recollection and familiarity (Baddeley, 2001; Eichenbaum, 2008). Recollection is thought to be an active process during which one is able to actively remember the item and the contextual details of the encountering. Familiarity represents a vague feeling of knowing an item (Skinner & Fernandes, 2007; Wixted & Squire, 2010; Yonelinas, 2002). Studies suggest these two processes to be distinct and to be supported by different brain regions (Kafkas & Montaldi, 2012; Sauvage, Beer, & Eichenbaum, 2010; Sauvage, Fortin, Owens, Yonelinas, & Eichenbaum, 2008; Yonelinas, 2002). Recollection, according to these studies, would be supported by activity of the hippocampus while familiarity would be supported by the perirhinal cortex. However, this view of a dual process model is debated. Other researchers propose these processes to be on a dimensional construct, varying in strength, with familiarity increasing more and more and recollection being at the farthest end with the highest memory strength (Wixted & Squire, 2010; Wixted, 2007). If we accept the dual process model, in which the two processes would be supported by different brain regions, then stress would exert differential effects on recollection and familiarity due to the involvement of different brain regions. Indeed, studies speak in favor of that (McCullough, Ritchey, Ranganath, & Yonelinas, 2015; McCullough & Yonelinas, 2013; Wiemers, Sauvage, Schoofs, Hamacher-Dang, & Wolf, 2013, 2014; Yonelinas, Parks, Koen, Jorgenson, & Mendoza, 2011) and will be reviewed in the next paragraph.

The first study which investigated the effect of a stress manipulation on recollection and familiarity induced stress by skydiving (Yonelinas et al., 2011). Stress shortly after encoding (during consolidation) resulted in an increase of familiarity compared to a no stress control group. This effect was seen only for male participants and neutral pictures. Stress had no effect on recollection. A follow up study with stress induction in the laboratory by the cold pressure test (CPT) showed that stress 20 min after encoding led to an increase in familiarity in males for neutral and negative material. Recollection was not influenced by stress but was higher in general for negative than neutral pictures (McCullough & Yonelinas, 2013). For stimuli (office items) which were present during a stressor (Trier Social Stress Test), we have previously shown that a stress manipulation during encoding led to higher recollection values (Wiemers et al., 2013, 2014). In addition, associations between cortisol and recollection and familiarity have been found in a previous stress study. Cortisol increase in response to a stressful situation induced after encoding and familiarity were positively correlated (McCullough et al., 2015).

To date, no study investigated the effect of pre-encoding stress on recollection and familiarity separately by analyzing ROC curves. Thus, the current study aims at investigating the relationship between a stress manipulation before encoding and memory performance by analyzing several stress measures and their influences on recollection and familiarity. We predicted that stress before encoding leads to an overall decrease in long-term memory performance. We expected that stress exerts differential effects on recollection and familiarity. Last but not least we anticipated that arousing stimulus material would be more influenced by stress than neutral ones.

## 2. Methods

### 2.1. Participants

A total of 80 participants (40 males) were tested. All participants were between 18 and 39 years old (MW = 24.75 years, SD = 4.12) and had a BMI between 19 and 28 kg/m<sup>2</sup> (MW = 23.23 kg/m<sup>2</sup>, SD = 2.32). Participants suffering from somatic or psychiatric disorders, those taking medication influencing the HPA axis, smokers or drug users as well as women taking hormonal contraception were excluded from participation. Participants received a payment of 20€ or course credit for taking part in the experiment. The study was approved by the local ethics committee. Participants were randomly assigned to either the

stress or control group creating one stress group of 40 participants (20 male) and one control group of 40 participants (20 male).

### 2.2. Procedure

Testing took part on two consecutive days in the afternoon between 12 h and 19 h on day 1 and between 13 h and 19:45 h on day 2 to account for circadian rhythm of cortisol secretion. On the first day, participants came to the lab, signed informed consent, filled in some questionnaires, and did a picture-story exercise, the last two are irrelevant for the current study. About 40 min after arrival at the lab, participants provided a baseline measure of blood pressure and a baseline saliva sample (baseline). Afterwards participants were subjected to a stress manipulation of either the Socially Evaluated Cold Pressure Test (SECPT; Schwabe, Haddad, & Schachinger, 2008) or a non-stressful control condition. During both conditions blood pressure was measured. After the SECPT or control condition, participants provided three further saliva samples, one directly after the stress manipulation (+1), one 20 min (+20), and one 32 min (+32) after the end of the stress manipulation, as well as one further sampling of blood pressure 5 min after the end of the stress manipulation. Twenty-two minutes after the stress manipulation (about two minutes after the saliva sample +20), participants were exposed to an incidental encoding task. They saw 120 pictures (60 neutral, 60 arousing) and were supposed to rate the pictures for visual complexity on a 6-point scale as a task to ensure that participants payed attention to the pictures.

On the second testing day, participants completed a surprise recognition test. They were supposed to rate on a 6-point scale how sure they were that they have or have not seen the picture before (Yonelinas & Parks, 2007). On day 2, participants provided two further saliva samples, one before and one after the recognition test.

### 2.3. Material

#### 2.3.1. Hormonal assessment

Participants got the instruction to abstain from eating and drinking anything except water 1 h before testing and from doing excessive sports, drinking alcohol, or taking medication the day before testing. Saliva for hormonal assessment was sampled using Salivettes (Sarstedt, Germany) four times on the first testing day, before (baseline) and one (+1), 20 (+20), and 32 min (+32) after the end of the stress manipulation plus twice on day 2. Cortisol data was analyzed in our laboratory at the Ruhr University Bochum, Germany. Free saliva cortisol concentrations were determined by a commercially available enzyme-linked immunosorbent assays (ELISA; Demeditec, Kiel, Germany) sub served to measure free cortisol concentrations. Inter-assay variations were below 9% and intra-assay variations were below 4%.

#### 2.3.2. Cardiovascular measures

Blood pressure was sampled three times by a Critikon® device (Norderstedt, Germany), the first time directly before the SECPT or control condition (baseline), during the SECPT or control condition (during), and 5 min after the end of the SECPT or control condition (post).

#### 2.3.3. Stress induction

Stress was induced using the SECPT as described elsewhere (Schwabe, Bohringer, Chatterjee, & Schachinger, 2008). In short, participants had to hold their hand including the wrist into ice-cold water (0–3 °C) for up to three minutes while being videotaped and watched by a neutral and reserved acting examiner. In the non-stressful control condition, participants immersed their hand including the wrist into warm water (36–37 °C) without being watched and videotaped.

Directly after the stress induction or control condition, participants had to answer four questions about the procedure. They had to rate on a scale from 0 to 100 how hard it was to hold the hand in the water, how

unpleasant the situation was, how stressed they felt during the situation, and how painful it was to hold the hand in the water.

#### 2.3.4. Pictures

The picture stimuli have been used before in research about stress and recognition memory (Yonelinas et al. 2011) and consisted in total of 240 pictures, primarily from the International Affective Picture Scale (IAPS). Half of the pictures were neutral, half arousing (aversive). Two picture sets of each 120 pictures (half neutral) were created and counterbalanced across participants so that half of the participants saw the first, the other half the second set for encoding on day 1. On day two, each participant saw both sets so that 120 pictures have been seen the day before and 120 have not been seen the day before.

### 2.4. Statistical analyses

#### 2.4.1. Stress measures

For some of the analyses, we calculated Delta Increase of cortisol and blood pressure (mean arterial pressure; MAP) by subtracting the baseline value from the peak value (+20 value for cortisol, during-measure for blood pressure) in order to obtain a measure of increase in cortisol concentration or blood pressure due to the stress- or control condition. Cortisol and blood pressure were analyzed with repeated measures analyses of variance (ANOVA) with TIME of measurement as within-subject factor (baseline, +1, +20, +32 for cortisol analyses and baseline, during, post for blood pressure analyses) and STRESS (stress vs. control) and SEX (male vs. female) as between-subject factors. Greenhouse Geisser corrections were applied where sphericity was violated. Perceived stress ratings were analyzed with independent samples *t*-test with corrected values for unequal variances where necessary.

#### 2.4.2. Memory data

In order to analyze overall performance of memory data, answers of the memory recognition task were dichotomized into “seen the picture before” (“yes”) and “not seen the picture before” (“no”). Hit rates (HR; number of correctly recognizing old pictures as old divided by total number of old pictures) and false alarm rates (number of falsely recognizing new pictures as old divided by total number new pictures) were calculated. In order to analyze accuracy (Pr) we subtracted false alarm rates from hit rates according to the Two-High Threshold Model (Corwin, 1994; Snodgrass and Corwin, 1988) for neutral and emotional pictures separately. Accuracy was tested by a mixed model ANOVA with AROUSAL (arousing vs. neutral) as within-subject factor and STRESS (stress vs. control) and SEX (male vs. female) as between-subject factors. Greenhouse Geisser corrections were applied where sphericity was violated.

#### 2.4.3. ROC analyses

In order to assess the influence of stress on recollection (R) and familiarity ( $d'$ ), ROC analyses were performed on the recognition task (Yonelinas, 1994). The probability of hits was plotted against the probability of false alarms across five cumulated bias levels (Yonelinas & Parks, 2007) to create the curves. A curve for each participant was generated by an excel solver using the method of least-squares (Yonelinas, 1997). Afterwards, individual curves were examined for a bad spread and to check whether answer level was at chance level, both constituting curves which do not allow for an analysis of recollection and familiarity. Thus, these curves were excluded. A measure for recollection (R) is reflected by the height of the *y*-intercept of the ROC curves (asymmetry, the higher the *y*-intercept, the stronger recollection is present). A measure for familiarity ( $d'$ ) as the memory strength is derived from the distances between the means of the old and the new

item distributions (curvilinearity, the more curvilinear a ROC curve, the more familiarity is present; Yonelinas, 1997). Typically, recognition memory for single items is comprised of both recollection, expressed by a ROC curve with a *y*-intercept significantly higher than 0, and familiarity processes, expressed by a curvilinearity higher than 0 (Yonelinas, 1997). In order to analyze directly whether stress had a differential effect on recollection and familiarity,  $d'$  can be converted from the distance measure into a probability estimate of familiarity (F).

In order to analyze differential effects of stress on recollection and familiarity, a mixed model ANOVA with RECOGNITION MEMORY (R vs. F) and AROUSAL (arousing vs. neutral) as within-subject factors and STRESS (stress vs. control) and SEX (male vs. female) as between-subject factors was conducted. Greenhouse Geisser corrections were applied where sphericity was violated.

#### 2.4.4. Regression analyses

In order to analyze whether a regression model containing group membership (stress or control group), cortisol increase, blood pressure increase, perceived stress after the SECPT/control, and sex could predict memory, we calculated regression models for arousing and neutral accuracy separately. We used the forward method to evaluate the model with the best fit.  $\text{Memory} = \beta_0 + \beta_1 * \text{Group} + \beta_2 * \text{DeltaCort} + \beta_3 * \text{DeltaMAP} + \beta_4 * \text{perceived stress} + \beta_5 * \text{sex}$

## 3. Results

### 3.1. Participants

Four participants (4 male; 3 from the control group) either had a negative ROC curve or only used 1–2 response keys and thus produced 1-point ROCs. Thus, we excluded these participants from all analyses (Yonelinas & Parks, 2007).

### 3.2. Stress measures

#### 3.2.1. Cortisol response

Cortisol response to the stress manipulation was analyzed with log transformed data due to a violation of normality. Since Mauchly's Test revealed a violation of sphericity ( $\chi^2(5) = 241.90, p < .001$ ), Greenhouse Geisser corrected *p*-values ( $\epsilon = .39$ ) are reported. Cortisol increased over time in the stress but not in the control condition as reflected in a significant TIME  $\times$  STRESS interaction effect ( $F(1.17, 84.45) = 11.97, p < .001$ ). There was no effect of stress and sex, neither main, nor interaction effect. Planned comparisons revealed no differences between the stress and control group at baseline and at time point +1, but significant differences 23 min ( $t(74) = -3.04, p = .003$ ) and 32 min ( $t(71.19) = -2.66, p = .010$ ) after the stress manipulation. Stressed participants showed higher salivary cortisol concentrations than control participants (Fig. 1, raw data for better visualization). There were no group differences in cortisol concentration on the second day ( $p > .05$ ).

#### 3.2.2. Mean arterial pressure

Mean arterial pressure (MAP) was analyzed with log transformed data due to a violation of normality. We found a TIME  $\times$  STRESS interaction ( $F(2, 144) = 43.40, p < .001$ ), a main effect of TIME ( $F(2, 144) = 35.05, p < .001$ ), a main effect of STRESS ( $F(1, 72) = 18.27, p < .001$ ), and a main effect of SEX ( $F(1, 72) = 37.81, p < .001$ ). At baseline there were no stress group differences, but between the manipulation ( $t(74) = -6.48, p < .001$ ) and post manipulation ( $t(74) = -2.12, p = .04$ ) stressed participants showed higher MAP than control participants. In general, males show higher MAP than females (Table 1).

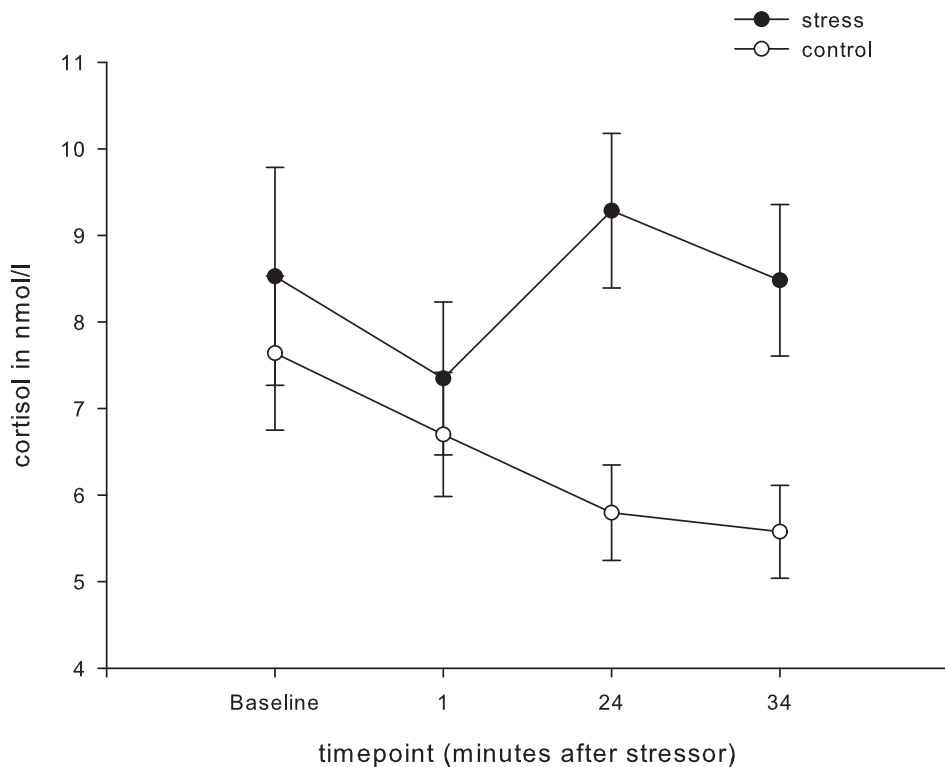


Fig. 1. Mean values of salivary cortisol concentrations in nmol/l before (baseline), as well as 1, 24, and 34 min after the SECPT or control condition of the stress and control group.

3.2.3. Perceived stress ratings

Perceived stress ratings were log transformed due to violation of normality. Results of independent sample t-tests showed that stressed participants rated the SECPT as harder ( $t(56.04) = -13.68, p < .001$ ), more unpleasant ( $t(74) = -12.05, p < .001$ ), more stressful ( $t(63.77) = -8.11, p < .001$ ), and more painful ( $t(68.09) = -17.67,$

$p < .001$ ) than the control participants rated the warm water task (Table 1).

Table 1

raw mean values of stress and memory measures, \* marks significant ( $p < .05$ ) post hoc test differences between the stress and the control group.

	Stress mean (SE)	Control mean (SE)	Significance
<i>Mean arterial pressure (mmHg)</i>			
Baseline	83.65 (1.77)	80.29 (1.61)	
During	94.92 (2.02)	78.99 (1.46)	*
Post	83.44 (1.61)	78.73 (1.37)	*
<i>Perceived stress measures</i>			
Hardness	51.28 (4.95)	0.81 (0.46)	*
Unpleasantness	52.56 (4.97)	3.51 (1.46)	*
Stressfulness	39.23 (4.77)	2.16 (0.69)	*
Painfulness	55.67 (4.77)	1.35 (1.11)	*
<i>Memory accuracy (Pr)</i>			
Arousing	0.53 (0.03)	0.58 (0.02)	
Neutral	0.47 (0.03)	0.54 (0.02)	
<i>Hit rate</i>			
Arousing	0.74 (0.02)	0.74 (0.02)	
Neutral	0.62 (0.02)	0.65 (0.02)	
<i>False alarm rate</i>			
Arousing	0.21 (0.03)	0.16 (0.02)	
Neutral	0.15 (0.03)	0.11 (0.01)	
<i>Recognition memory</i>			
R arousing	0.30 (0.04)	0.37 (0.04)	
F arousing	0.40 (0.03)	0.39 (0.03)	
R neutral	0.31 (0.03)	0.38 (0.03)	
F neutral	0.40 (0.03)	0.38 (0.03)	

3.3. Memory results

3.3.1. Accuracy

Memory accuracy (Pr, see Table 1 for raw data) was analyzed after log-transformation due to violation of normality. Results showed that emotional pictures were recognized more accurately than neutral pictures (significant main effect of AROUSAL:  $F(1, 72) = 14.41, p < .001$ ; Table 1). Descriptively stressed participants showed worse memory accuracy but this effect was not significant ( $F(1, 72) = 2.96, p = .09$ ). There were no additional effects of stress (all  $p > .05$ ).

Using the forward method for multiple regression models for accuracy data showed that for **arousing stimuli** the best fitting model was the one including perceived stress as predictor ( $F(1,75) = 5.98, p = .017$ ) with an  $R^2 = .075$ . The predictor was negatively associated to overall accuracy. Thus, higher perceived stress ( $\beta = -.287, p = .011$ ) was related to worse memory performance for arousing stimuli. Applying multiple regression using the forward method for accuracy of **neutral stimuli** resulted in no significant model ( $p > .05$ ).

3.3.2. ROC

ROC data analyzed by a mixed model ANOVA revealed no interaction or main effects for the factors STRESS, AROUSAL, and SEX (all  $p > .1$ , Table 1).

**Regression models for ROC data** were analyzed to find out whether stress measures predict recollection and familiarity with the same regression models for recollection and familiarity as well as arousing and neutral stimuli separately, as described above.

3.3.2.1. *Arousing stimuli.* For **recollection** of the **arousing stimuli** the best fitting model was the one including perceived stress and DeltaMAP with  $F(2, 75) = 7.15, p = .001$  with an  $R^2 = .164$ . Stronger increase in

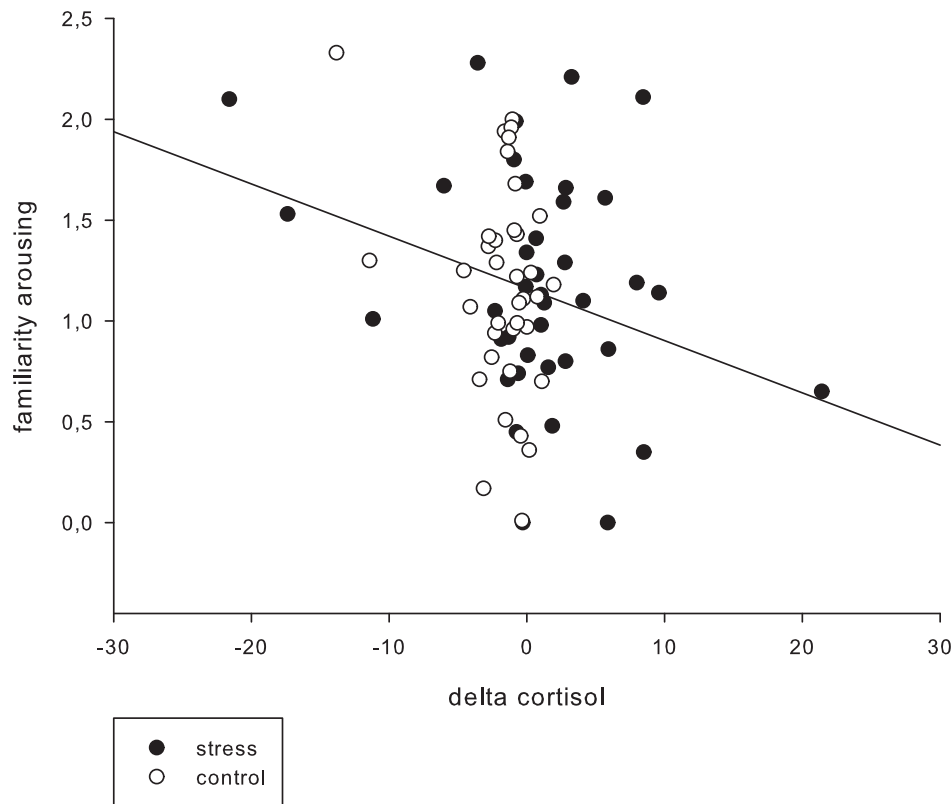


Fig. 2. Scatterplot of the association between raw values of delta cortisol (x-axis) and familiarity values (y-axis).

blood pressure ( $\beta = .268$ ,  $p = .021$ ) and lower perceived stress ( $\beta = -.404$ ,  $p = .001$ ) predicted better recollection.

For **familiarity** of the **arousing stimuli** the best fitting model included DeltaCort as predictor ( $F(1, 75) = 6.19$ ,  $p = .015$  with an  $R^2 = .077$ ). A larger cortisol increase predicted lower familiarity ( $\beta = -.278$ ,  $p = .015$ ). This association is depicted in Fig. 2 (see below).

**3.3.2.2. Neutral stimuli.** For **recollection** of the **neutral stimuli** no model was significant ( $p > .05$ ). Similarly for **familiarity** of the **neutral stimuli**, also no model was significant ( $p > .05$ ).

#### 4. Discussion

The current study investigated the effect of a stressful situation and resulting bodily and emotional changes induced before encoding on recognition memory, using the framework of the dual process model. Overall the stress group and the control group did not differ substantially in their recognition memory performance. However regression analyses revealed interesting relationships between obtained stress measures and memory only for arousing pictures.

We observed a relationship between different stress markers and memory only for emotionally arousing pictures. Typically, emotional items are remembered better than neutral items (Cahill & McGaugh, 1995; Heuer & Reisberg, 1990). We also found this effect in the current study. Furthermore, the influence of stress on emotional material is often stronger than the effect on neutral material (Shields et al., 2017). However, studies show conflicting results. Stress manipulations administered before encoding of neutral and emotional stories enhance memory for an emotional story but impair memory for a neutral story (Payne, et al., 2007). Additionally, a stress manipulation taking place before encoding enhances memory for negative arousing material (Wolf, 2012). However, an enhancing effect of a pre-encoding stress manipulation on memory for neutral words has been reported as well

(Schwabe, et al., 2008). Others observed an impairing effect of a pre-encoding stress manipulation on recognition memory of neutral information only (Zoladz et al., 2013) or a negative association of blood pressure and cortisol increase with free recall of negative words (Zoladz, et al., 2011). A recent meta-analysis concluded that valence was no significant moderator of pre-encoding stress on memory performance (Shields et al., 2017), reflecting the inconsistent results of previous studies mentioned above. Our results, however, support the notion, that memory for emotional arousing material is especially influenced by stress.

Fitting to the hypothesis that memory performance would be impaired by pre-encoding stress, we found that higher perceived stress ratings were related to a poorer overall recognition performance. However, this was not evident for the physiological stress measures cortisol or MAP. On this level, only perceived stress predicted memory performance. Studies investigating the effects of perceived stress on memory are rare, often perceived stress is used as a manipulation check only. A review assessing the associations between perceived and objective stress measures found results to be rather weak, both concerning consistency across studies as well as strength of correlations (Campbell & Ehlert, 2012). Keeping in mind the weak associations between perceived and physiological stress measures, more research is needed to find out mechanisms behind perceived stress ratings and memory performance. A possible link could be that memory is dependent on other cognitive processes which are influenced by the feeling of stress. A study found that emotion (here: anxiety) influenced cognitive processes (here: working memory). Anxiety negatively predicted working memory performance during stress (Hood, Pulvers, Spady, Kliebenstein, & Bachand, 2015). Also, rumination has been discussed as being an impairing factor for working memory (Koster, de Lissnyder, & de Raedt, 2013). Thus, future studies should assess whether the perceived feeling of stress influences memory encoding through other cognitive processes, as for example working memory.

When we analyzed the effect of pre-encoding stress on recollection



and familiarity separately, we again found relationships between the obtained stress measures and memory only for negatively arousing pictures. Recollection was best predicted by a model including blood pressure (positive relationship) and perceived stress (negative relationship). Results fit with studies showing that an activation of the SNS enhances encoding and consolidation (Cahill & McGaugh, 1998; van Stegeren, 2008).

We also found associations of pre-encoding stress and familiarity. The higher the increase of cortisol due to the stress manipulation, the lower was familiarity. An influence of cortisol on familiarity has been found in previous studies. The direction of these effects are probably again depending on the timing of the stressor. Stress manipulations taking place during consolidation enhanced familiarity (McCullough et al., 2015; McCullough & Yonelinas, 2013; Yonelinas et al., 2011). In the current study we induced stress 22 min before encoding, exactly the time frame during which the meta-analysis by Shields et al. (2017) found stress exerting a detrimental effect on memory. Here, the effect was visible in a negative relationship of cortisol on familiarity. Thus, our results are in line with previous studies and models of an impairing effect of elevated cortisol concentrations on memory encoding (see Joëls, Fernandez, & Roozendaal, 2011; Kirschbaum, Wolf, May, Wippisch, Hellhammer, 1996).

According to the dual process model, the hippocampus is involved in recollection and the perirhinal cortex is involved in familiarity (Kafkas & Montaldi, 2012; Sauvage et al., 2010; Sauvage et al. 2008; Yonelinas, 2002). One would expect stress exerting its influences more on recollection processes (Wiemers et al., 2013) due to a high density of cortisol receptors in this area (Ulrich-Lai & Herman, 2009). That may be true, if stress is present during encoding and the to be learned material is relevant to the stressor (Shields et al., 2017; Wiemers et al., 2013). Here and in former studies, where stress was induced shortly before or after learning and learning material was not relevant to the stressor, cortisol was found to have a selective influence on memory strength (familiarity). It has been suggested that stress does not facilitate storage in the hippocampus only but rather the storage of information in a broader cortical network (Yonelinas et al. 2011). Additionally, it has been found that patients suffering from prefrontal damage show deficits in familiarity but not recollection (Aly, Yonelinas, Kishiyama, & Knight, 2011). Since there is a high density of cortisol receptors in the prefrontal cortex, this might be one possible additional brain region where stress could exert its influences.

Throughout our analyses we did not find an influence of or an association with sex. Some studies found a blunted cortisol response to a stressor of women taking hormonal contraceptives compared to men (e.g. Kirschbaum, Kudielka, Gaab, Schommer, & Hellhammer, 1999) but not free cycling women compared to men (e.g. Merz, 2017). Thus, we only included free cycling women in order to induce a similar cortisol response in men and women.

Some studies found that the impact of pre-encoding stress on memory differs between men and women (e.g. Zoladz et al., 2013). Moreover in women stress effects might be further modulated by the menstrual cycle (Andreano, Arjomandi & Cahill, 2008, Zoladz et al., 2015). We did not assess menstrual cycle phase of our participants in the present study, which could be considered a limitation. Moreover our study might have been underpowered in order to detect potentially subtle sex differences. A recent review on the topic is provided by Merz and Wolf (2017).

In the study we found a moderate increase of cortisol in response to the SECPT which is in line with previous work from our group. Since we were interested in relating individual measures of subjective stress, blood pressure and cortisol to recognition memory performance we included the entire sample into the regression analyses instead of creating sub-groups based on a responder criterion. Since all participants of the stress group passed through the stress procedure we think it is valid to include all of them into one analysis which aims at integrating different stress markers.

Concluding, the current study replicated findings that negative arousing pictures are remembered better than neutral pictures. Perceived feeling of being stressed was related to worse overall memory performance and worse recollection memory. In contrast, blood pressure was related positively to recollection. Finally, the cortisol increase negatively predicted familiarity. Our results support the notion that increased SNS activity is beneficial for memory encoding while increased cortisol concentrations exert negative effects (Joëls et al., 2011). In addition the findings highlight the need for a multimodal assessment of perceived and physiological stress markers in order to further disentangle the complex association between stress and recognition memory.

## Acknowledgement

We thank Dagmar Bienek and Sarah Tebrügge for help with the recruitment and testing of the participants.

## Funding

This work was funded by the German Research Foundation (DFG) project B4 of Collaborative Research Center (SFB) 874 “Integration and Representation of Sensory Processes”.

## References

- Aly, M., Yonelinas, A. P., Kishiyama, M. M., & Knight, R. P. (2011). Damage to the lateral prefrontal cortex impairs familiarity but not recollection. *Behavioural Brain Research*, *225*, 297–304.
- Andreano, J. M., Arjomandi, H., & Cahill, L. (2008). Menstrual cycle modulation of the relationship between cortisol and long-term memory. *Psychoneuroendocrinology*, *33*, 874–882.
- Baddeley, A. (2001). The concept of episodic memory. *Philosophical Transactions of the Royal Society of London. Series B*, *356*, 1345–1350.
- Buchanan, T. W., & Lovallo, W. R. (2001). Enhanced memory for emotional material following stress-level cortisol treatment in humans. *Psychoneuroendocrinology*, *26*, 307–317.
- Cahill, L., Gorski, L., & Le, K. (2003). Enhanced human memory consolidation with post-learning stress: Interaction with the degree of arousal at encoding. *Learning & Memory*, *10*, 270–274.
- Cahill, L., & McGaugh, J. L. (1995). A novel demonstration of enhanced memory associated with emotional arousal. *Consciousness and Cognition*, *4*, 410–421.
- Cahill, L., & McGaugh, J. L. (1998). Mechanisms of emotional arousal and lasting declarative memory. *Trends in Neurosciences*, *21*, 294–299.
- Campbell, J., & Ehler, U. (2012). Acute psychosocial stress: Does the emotional stress response correspond with physiological responses? *Psychoneuroendocrinology*, *37*, 1111–1134.
- Corwin, J. (1994). On measuring discrimination and response bias: Unequal numbers of targets and distractors and two classes of distractors. *Neuropsychology*, *8*, 110–117.
- de Kloet, E. R., Joëls, M., & Holsboer, F. (2005a). Stress and the brain: From adaptation to disease. *Nature Reviews Neuroscience*, *6*, 463–475.
- de Kloet, E. R., Sibug, R. M., Helmerhorst, F. M., & Schmidt, M. (2005b). Stress, genes and the mechanism of programming the brain for later life. *Neuroscience & Biobehavioral Reviews*, *29*, 271–281.
- de Quervain, D. J., Roozendaal, B., & McGaugh, J. L. (1998). Stress and glucocorticoids impair retrieval of long-term spatial memory. *Nature*, *394*, 787–790.
- de Quervain, D. J., Roozendaal, B., Nitsch, R. M., McGaugh, J. L., & Hock, C. (2000). Acute cortisone administration impairs retrieval of long-term declarative memory in humans. *Nature Neuroscience*, *3*, 313–314.
- Eichenbaum, H. (2008). *Learning and memory*. New York: W.W. Norton & Company.
- Heuer, F., & Reisberg, D. (1990). Vivid memories of emotional events: The accuracy of remembered minutiae. *Memory & Cognition*, *18*, 496–506.
- Hood, A., Pulvers, K., Spady, T. J., Kliebenstein, A., & Bachand, J. (2015). Anxiety mediates the effect of acute stress on working memory performance when cortisol levels are high: A moderated mediation analysis. *Anxiety, Stress, & Coping*, *28*, 545–562.
- Joëls, M., Fernandez, G., & Roozendaal, B. (2011). Stress and emotional memory: A matter of timing. *Trends in Cognitive Sciences*, *15*, 280–288.
- Kafkas, A., & Montaldi, D. (2012). Familiarity and recollection produce distinct eye movement, pupil and medial temporal lobe responses when memory strength is matched. *Neuropsychologia*, *50*, 3080–3093.
- Kirschbaum, C., Wolf, O. T., May, M., Wippisch, W., & Hellhammer, D. H. (1996). Stress- and treatment-induced elevations of cortisol levels associated with impaired declarative memory in healthy adults. *Life Sciences*, *58*, 1475–1483.
- Kirschbaum, C., Kudielka, B. M., Gaab, J., Schommer, N. C., & Hellhammer, D. C. (1999). Impact of gender, menstrual cycle phase, and oral contraceptives on the activity of the hypothalamus-pituitary-adrenal axis. *Psychosomatic Medicine*, *61*, 154–162.
- Koster, E. H., de Lissnyder, E., & de Raedt, R. (2013). Rumination is characterized by

- valence-specific impairments in switching of attention. *Acta Psychologica*, *144*, 563–570.
- Kuhlmann, S., Kirschbaum, C., & Wolf, O. T. (2005). Effects of oral cortisol treatment in healthy young women on memory retrieval of negative and neutral words. *Neurobiology of Learning and Memory*, *83*, 158–162.
- McCullough, A. M., Ritchey, M., Ranganath, C., & Yonelinas, A. (2015). Differential effects of stress-induced cortisol responses on recollection and familiarity-based recognition memory. *Neurobiology of Learning and Memory*, *123*, 1–10.
- McCullough, A. M., & Yonelinas, A. P. (2013). Cold-pressor stress after learning enhances familiarity-based recognition memory in men. *Neurobiology of Learning and Memory*, *106*, 11–17.
- McEwen, B. S. (2007). Physiology and neurobiology of stress and adaptation: Central role of the brain. *Physiological Reviews*, *87*, 873–904.
- Merz, C. J. (2017). Contribution of stress and sex hormones on memory encoding. *Psychoneuroendocrinology*, *82*, 51–58.
- Merz, C. J., & Wolf, O. T. (2017). Sex differences in stress effects on emotional learning. *Journal of Neuroscience Research*, *95*, 93–105.
- Payne, J. D., Jackson, E. D., Hoscheidt, S., Ryan, L., Jacobs, W. J., & Nadel, L. (2007). Stress administered prior to encoding impairs neutral but enhances emotional long-term episodic memories. *Learning & Memory*, *14*, 861–868.
- Sandi, C., Loscertales, M., & Guaza, C. (1997). Experience-dependent facilitating effect of corticosterone on spatial memory formation in the water maze. *European Journal of Neuroscience*, *9*, 637–642.
- Sauvage, M. M., Beer, Z., & Eichenbaum, H. (2010). Recognition memory: Adding a response deadline eliminates recollection but spares familiarity. *Learning & Memory*, *17*, 104–108.
- Sauvage, M. M., Fortin, N. J., Owens, C. B., Yonelinas, A. P., & Eichenbaum, H. (2008). Recognition memory: Opposite effects of hippocampal damage on recollection and familiarity. *Nature Neuroscience*, *11*, 16–18.
- Schwabe, L., Bohringer, A., Chatterjee, M., & Schachinger, H. (2008). Effects of pre-learning stress on memory for neutral, positive and negative words: Different roles of cortisol and autonomic arousal. *Neurobiology of Learning and Memory*, *90*, 44–53.
- Schwabe, L., Haddad, L., & Schachinger, H. (2008). HPA axis activation by a socially evaluated cold-pressor test. *Psychoneuroendocrinology*, *33*, 890–895.
- Shields, G. S., Sazma, M. A., McCullough, A. M., & Yonelinas, A. P. (2017). The effects of acute stress on episodic memory: A meta analysis and integrative review. *Psychological Bulletin*, *143*, 636–675.
- Skinner, E. L., & Fernandes, M. A. (2007). Neural correlates of recollection and familiarity: A review of neuroimaging and patient data. *Neuropsychologia*, *45*, 2163–2179.
- Smeets, T., Wolf, O. T., Giesbrecht, T., Sijstermans, K., Telgen, S., & Joels, M. (2009). Stress selectively and lastingly promotes learning of context-related high arousing information. *Psychoneuroendocrinology*, *34*, 1152–1161.
- Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology: General*, *117*, 34–50.
- Ulrich-Lai, Y. M., & Herman, J. P. (2009). Neural regulation of endocrine and autonomic stress responses. *Nature Reviews Neuroscience*, *10*, 397–409.
- van Stegeren, A. H. (2008). The role of the noradrenergic system in emotional memory. *Acta Psychologica*, *127*, 532–541.
- Wiemers, U. S., Sauvage, M. M., Schoofs, D., Hamacher-Dang, T. C., & Wolf, O. T. (2013). What we remember from a stressful episode. *Psychoneuroendocrinology*, *38*, 2268–2277.
- Wiemers, U. S., Sauvage, M. M., & Wolf, O. T. (2014). Odors as effective retrieval cues for stressful episodes. *Neurobiology of Learning and Memory*, *112*, 230–236.
- Wixted, J. T., & Squire, L. R. (2010). The role of the human hippocampus in familiarity-based and recollection-based recognition of memory. *Behavioural Brain Research*, *215*, 197–208.
- Wixted, J. T. (2007). Dual-process theory and signal-detection theory of recognition memory. *Psychological Review*, *114*, 152–176.
- Wolf, O. T. (2017). Stress and memory retrieval: Mechanisms and consequences. *Current Opinion in Behavioral Science*, *14*, 40–46.
- Wolf, O. T. (2012). Immediate recall influences the effects of pre-encoding stress on emotional episodic long-term memory consolidation in healthy young men. *Stress*, *15*, 272–280.
- Yonelinas, A. P. (1994). Receiver-operating characteristics in recognition memory: Evidence for a dual-process model. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*, 1341–1354.
- Yonelinas, A. P. (1997). Recognition memory ROCs for item and associative information: The contribution of recollection and familiarity. *Memory & Cognition*, *25*, 747–763.
- Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language*, *46*, 441–517.
- Yonelinas, A. P., & Parks, C. M. (2007). Receiver operating characteristics (ROCs) in recognition memory: A review. *Psychological Bulletin*, *133*, 800–832.
- Yonelinas, A. P., Parks, C. M., Koen, J. D., Jorgenson, J., & Mendoza, S. P. (2011). The effects of post-encoding stress on recognition memory: Examining the impact of skydiving in young men and women. *Stress*, *14*, 136–144.
- Zoladz, P. R., Clark, B., Warnecke, A., Smith, L., Tabar, J., & Talbot, J. N. (2011). Pre-learning stress differentially affects long-term memory for emotional words, depending on temporal proximity to the learning experience. *Physiology & Behavior*, *103*, 467–476.
- Zoladz, P. R., Peters, D. M., Cadle, C. E., Kalchik, A. E., Aufdenkampe, R. L., Dailey, A. M., ... Rorabaugh, B. R. (2015). Post-learning stress enhances long-term memory and differentially influences memory in females depending on menstrual stage. *Acta Psychologica (Amsterdam)*, *160*, 127–133.
- Zoladz, P. R., Warnecke, A. J., Woelke, S. A., Burke, H. M., Frigo, R. M., Pisansky, J. M., ... Talbot, J. N. (2013). Pre-learning stress that is temporally removed from acquisition exerts sex-specific effects on long-term memory. *Neurobiology of Learning and Memory*, *100*, 77–87.