Neurobiology of Learning and Memory 152 (2018) 32–38

Contents lists available at ScienceDirect

Neurobiology of Learning and Memory

journal homepage: www.elsevier.com/locate/ynlme

Memory retrieval of everyday information under stress

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ARTICLE INFO

Keywords:
Cortisol
Glucocorticoids
Stress hormones
SECPT

ABSTRACT

Psychosocial stress is known to crucially influence learning and memory processes. Several studies have already shown an impairing effect of elevated cortisol concentrations on memory retrieval. These studies mainly used learning material consisting of stimuli with a limited ecological validity. When using material with a social contextual component or with educational relevant material both impairing and enhancing stress effects on memory retrieval could be observed. In line with these latter studies, the present experiment also used material with a higher ecological validity (a coherent text consisting of daily relevant numeric, figural and verbal information). After encoding, retrieval took place 24 h later after exposure to psychosocial stress or a control procedure (20 healthy men per group). The stress group was further subdivided into cortisol responders and non-responders. Results showed a significantly impaired retrieval of everyday information in non-responders compared to responders and controls. Altogether, the present findings indicate the need of an appropriate cortisol response for the successful memory retrieval of everyday information. Thus, the present findings suggest that cortisol increases - contrary to a stressful experience per se – seem to play a protective role for retrieving everyday information. Additionally, it could be speculated that the previously reported impairing stress effects on memory retrieval might depend on the used learning material.

1. Introduction

In our everyday life, we are confronted with various types of information. Sometimes it is necessary to retrieve such information in contexts and states that differ from those during encoding. One conceivable state during retrieval could be stress. When we try to imagine stressful situations, we are typically thinking of exams, speaking in front of an audience or job interviews. In these situations, we are sometimes able to successfully retrieve the relevant information but sometimes we fail. This discrepancy raises the question, which processes and underlying mechanisms are responsible for this memory phenomenon.

Several studies have already demonstrated that stress hormones influence long-term memory processes (Buchanan, Tranel, & Adolphs, 2006; De Quervain, Roozendaal, Nitsch, McGaugh, & Hock, 2000; Kuhlmann, Kirschbaum, & Wolf, 2005; Kuhlmann, Piel, & Wolf, 2005; Schönfeld, Ackermann, & Schwabe, 2014; Tollenaar, Elzinga, Spinhoven, & Everaerd, 2009). Stress operates on brain functions via stress-related neuromodulators such as (nor)epinephrine rapidly released from the adrenal medulla because of the activation of the sympathetic nervous system. The stress-induced activation of the hypothalamus-pituitary-adrenocortical (HPA) axis leads to a slower release of glucocorticoids (GCs) from the adrenal cortex. Due to their lipophilic characteristics, GCs - in particular cortisol in humans - are able to pass the blood-brain-barrier resulting in a crucial modulation of learning and memory processes via the occupation of central nuclear and membrane-bound mineralocorticoid receptors and glucocorticoid receptors (De Kloet, Joëls, & Holsboer, 2005; Joëls, Karst, DeRijk, & De Kloet, 2008; Lupien, Maheu, Tu, Fiocco, & Schramek, 2007).

Exposure to stress or pharmacological cortisol administration prior to retrieval typically impairs memory performance (for reviews see Schwabe, Joëls, Roozendaal, Wolf, & Oitzl, 2012; Shields, Sazma, McCullough, & Yonelinas, 2017; Wolf, 2009, 2017a, 2017b). Impairing stress effects on memory performance were especially detected in cortisol responders after exposure to stress (Buchanan et al., 2006). However, some studies have also failed to find such an effect on memory retrieval (Domes, Heinrichs, Rimmele, Reichwald, & Hautzinger, 2004; Oei, Everaerd, Elzinga, van Well, & Bermond, 2006; Schoofs & Wolf, 2009; Tollenaar, Elzinga, Spinhoven, & Everaerd, 2008; Wolf, Schommer, Hellhammer, Reischies, & Kirschbaum, 2002). These studies differ in the used learning material mainly consisting of stimuli with limited ecological validity (lists of words, pairs of words or series of slides).

Ecological validity refers to the extent to which the learning

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https://doi.org/10.1016/j.nlm.2018.05.008
Received 3 November 2017; Received in revised form 26 April 2018; Accepted 16 May 2018
Available online 19 May 2018
1074-7427/

material reflects the natural conditions of everyday life (Pawlik, 1988). Referring to this definition, it becomes clear that lists of words do not adequately reflect the various kinds and overlapping pieces of information we are confronted with such as when we try to remember names or biographical details of a specific person. Only a few studies used material with a more ecologically valid, socially contextual component reflecting such real life conditions. For example, Takahashi et al. (2004) indicated a retrieval deficit of face-name associations after exposure to stress. In accordance, an impairing stress effect on social memory retrieval was observed when biographical notes were used (photos, telephone numbers, birth dates or part of the life histories of a man and a woman; Merz, Wolf, & Hennig, 2010). For educational relevant material, consisting of a neutral text passage of scientific content, Hupbach and Fieman (2012) could even show a memory enhancing effect of pre-retrieval stress. In accordance, enhanced memory retrieval was found in cortisol responders after stress exposure (Zoladz et al., 2014). This is in line with a previous study proposing a differentiation of stressed participants in cortisol responders and non-responders to detect stress effects on memory retrieval (Buchanan et al., 2006).

The current study aims to broaden this scientific research field by selectively applying ecological valid learning material. We used learning material consisting of verbal, numeric and figural information embedded in a coherent text (invitation to a seminar) as an approximation of everyday confrontation with various kinds of information. After having encoded the relevant material, retrieval took place 24 h later after exposure to psychosocial stress or a control procedure. We expected stress to reduce memory retrieval for everyday information depending on the individual cortisol response (Buchanan et al., 2006). Moreover, cortisol levels should be positively associated with the memory decline.

2. Materials and methods

2.1. Participants

Forty healthy, male students were recruited via mailing announcements or flyers at the University of Trier, Germany. Inclusion criteria consisted of an age between 18 and 35 years and a BMI ranging from 18 to 27 kg/m^2. Exclusion criteria comprised regular medication intake, previous participation at the same stress procedure (see Section 2.2), acute and chronic somatic diseases, especially diseases known to influence endogenous hormone levels (e.g. asthma, hyper-/hypothyroidism), any history of psychiatric treatment or a current mental disorder, regular drug, alcohol or nicotine use (five cigarettes per month were allowed). We explicitly instruct participants to refrain from alcohol consumption the evening before the testing sessions. Moreover, they should refrain from smoking, drinking caffeine, acute physical stress, eating and drinking anything but water 1.5 h before testing sessions started.

The study protocol was approved by the ethics committee of the University of Trier. Each participant provided a written informed consent prior to the first testing session. They received either partial course credit or 20,-€ for compensation.

2.2. Study design and procedure

Participants were tested on two subsequent days in a randomized between-subject design (stress vs. control group). Both testing sessions were conducted between 1 and 5 p.m. in different rooms. After arrival on the first day, participants were asked to answer some questionnaires concerning demographic data and exclusion criteria. Then, participants were instructed to read a provided text for intentional encoding (see Section 2.3). Encoding was limited to a period of four minutes in total.

After arrival on the second day, participants were randomly assigned either to the stress or to the control group. The stress procedure consisted of the *socially evaluated cold-pressor test* (SECPT; Schwabe, Haddad, & Schächinger, 2008). Participants of the stress group were informed that they have to immerse their dominant hand and forearm in ice-cold (0–3 °C) water while they were videotaped and watched by an unknown and neutral woman entering the room after this instruction. In the control condition, participants had to immerse their dominant hand and forearm in a repository with warm water (36–37 °C), while no additional person was watching and no videotaping was taking place. After three minutes, participants were told to take their arm out of the repository. If participants could not tolerate to keep their arms in the ice water, they were told to hold their arms above the respiratory for the remaining period (only two participants took their hands and forearms out of the cold water after about 2:50 min).

During the subsequent waiting period, participants were asked to respond to the SANB (Skala Angst vor negativer Bewertung; Vormbrock & Neuser, 1983), the German version of the *Fear of Negative Evaluation Scale* (FNE; Watson & Friend, 1969). This trait questionnaire measures the cognitive part of social anxiety symptomatology, especially fear of negative evaluation. On 20 items, participants should choose the respective answer option out of four (1 = almost never applies, 4 = almost always applies), which generally applies to them. The scores of each item are added up to a sum score. Reliability as well as validity of this questionnaire were reported as high and satisfying (Cronbach's $\alpha = .94$; Vormbrock & Neuser, 1983). After 20 min relative to stress onset, retrieval of the details of the encoded material took place for a maximum time of five minutes. At the end of the testing session, participants were debriefed and received their compensation.

2.3. Memory assessment

Memory performance was assessed by using the memory subtask from the German version of the Wilde-Intelligence-Test 2 (WIT-2; Kersting, Althoff, & Jäger, 2008). This subtask measures memory performance with a satisfying internal consistency of $\alpha = .78$ and a retest-reliability of $r = .67$. It consists of a two-sided text with verbal (e.g. 'The seminar was organized by the chief officer Mrs. Hornstein.'), numeric (e.g. 'The advanced training will take place in the context of a seminar form the 25th to the 28th of June.'), and figural (symbols on a city map e.g. a sign of a train station) information about the schedule of a seminar. During encoding, participants were instructed to read the text as a whole to get a general idea and subsequently to memorize all details of the text. To ensure that the participants were able to address themselves unhurriedly to the task, they were told that the time limit of four minutes would be sufficient for a good retrieval performance.

Twenty-four hours later, retrieval took place approximately 20 min after stress onset. Therefore, the experimenter submitted 21 questions – seven per information type - to the participants with six answer options each. They were instructed to mark the correct answer on an enclosed sheet with a cross. For each information type (verbal, numeric, figural), the number of correct answers was added up. The sum of all correct answers reflects the global memory score.

2.4. Measurement and analysis of the stress response

The activation of the sympathetic nervous system was assessed by the measurement of systolic and diastolic blood pressure using an automatic upper arm blood pressure monitor (Bosch + Sohn, Jungingen, Germany). The blood pressure cuff was attached to the upper arm of the non-dominant hand's side. The measurements took place before stress onset (baseline), during the three minutes of the stressor (peak) and eight minutes after stress onset (post). To reduce measurement errors, participants were instructed not to move or to talk during the measurements and the assessment of blood pressure was conducted three times consecutively within a time window of three minutes per measurement period. We calculated the mean values of systolic and diastolic blood pressure out of the three values per period.

In order to verify the activation of the HPA axis, salivary samples

were collected on the first day before and after encoding, on the second day before (baseline), immediately (+3 min), 20 and 30 min after stress onset by using Salivette collection devices (Sarstedt, Nümbrecht, Germany). The samples were stored at −20 °C until cortisol was assayed. Saliva cortisol was determined by use of a Dissociation-Enhanced Lanthanide Fluorescent Immunoassay (DELFIA; Dressendörfer, Kirschbaum, Rohde, Stahl, & Strasburger, 1992). Intra- and inter-assay coefficients of variance were below 6.7% and 9.0%, respectively.

In order to assess the subjective experience of stress, participants should indicate how stressful, painful and unpleasant they experienced the corresponding procedure immediately after the offset of the respective procedure. The rating scale ranged from 0 ('not at all') to 100 ('very much') and was adapted from Schwabe et al. (2008).

2.5. Statistical analyses

All data were analyzed with SPSS 22.0 software (SPSS Inc., Chicago, USA). We calculated independent *t*-tests (stress vs. control group) for the demographic data as well as the psychometric measurements.

Cortisol values were transformed by using the Box-Cox Power Transformation (Osborne, 2010) to provide normally distributed values. We conducted several repeated measures analyses of variance (ANOVA) to investigate changes in physiological parameters concerning blood pressure and cortisol concentrations. Therefore, the repeated measurement factor 'time' consisted of the several times of measurement (*systolic* as well as *diastolic blood pressure*: baseline, peak, post; *cortisol* first day: before and after encoding; *cortisol* second day: baseline; +3, +20, +30 min) and the between-group factor 'group' (stress vs. control).

As Buchanan et al. (2006) suggested a differentiation of the stress group in responders and non-responders to detect stress effects on memory retrieval, we also performed a cortisol responder analysis using the criterion previously reported (Miller, Plessow, Kirschbaum, & Stalder, 2013). According to this criterion, responders had to exert a stress-induced cortisol increase of 1.5 nmol/l relative to baseline levels. As cortisol peaks 20 min after stress onset, this value was used for determining the increase from baseline.

For memory performance, we calculated an ANOVA with the three information types as repeated measurement factor ('scale': numeric vs. figural vs. verbal) and with the between-group factor 'group' (stress vs. control). As outlined above, we subdivided the stress group in cortisol responders and non-responders according to the recommendation of Buchanan et al. (2006) and recalculated stress effects on memory performance by conducting the same analyses with the between-group factor 'cortisol response' (responders vs. non-responders vs. controls). Furthermore, Pearson's product-moment correlations were performed to determine whether the physiological stress response was associated with memory performance. Increases in the respective parameters were defined as the difference of the peak and the baseline value (Δ RR_{sys}, Δ RR_{dia}, Δ cortisol).

We corrected all results by the Greenhouse-Geisser degrees of freedom adjustment, where appropriate and effect sizes (η_p^2) are reported accordingly.

3. Results

3.1. Demographic data and questionnaires

The male participants were on average 24.45 ± 3.31 (*M* ± *SD*) years old and had a mean BMI of 22.89 ± 1.86 kg/m^2. There were no significant differences between the stress and control group concerning age ($t_{(37.2)} = 1.764$, $p > .05$) or BMI ($t_{(37.5)} = 0.582$, $p > .05$). In addition, no between-group differences emerged within an univariate ANOVA with the factor 'cortisol response' (see Section 3.2), neither concerning age ($F_{(2,35)} = 1.719$, $p > .05$) nor concerning BMI ($F_{(2,35)} = 0.561$, $p > .05$). In Table 1, mean age and BMI are shown for responders, non-responders and controls.

Table 1
Mean (± SEM) age, body-mass-index as well as day 2 blood pressure data and stress ratings in responders, non-responders and controls.

	Responders	Non-responders	Controls
Demographics			
Age	23.11 ± 0.56	23.91 ± 1.14	25.44 ± 0.83
Body-mass-index	22.70 ± 0.76	22.73 ± 0.55	23.35 ± 0.38
Systolic blood pressure (mmHg)			
Baseline (pre-stress/control)	120.72 ± 4.09	119.73 ± 3.97	117.01 ± 3.06
During hand immersion	142.93 ± 4.30**	138.62 ± 4.17**	120.34 ± 3.21
Post (stress/control)	118.20 ± 3.24	120.21 ± 3.15	114.69 ± 2.42
Diastolic blood pressure (mmHg)			
Baseline (pre-stress/control)	69.55 ± 3.01	72.71 ± 2.92	70.95 ± 2.25
During hand immersion	95.85 ± 2.93**	89.67 ± 2.84**	73.00 ± 2.19
Post (stress/control)	68.94 ± 2.62	74.58 ± 2.54	70.64 ± 1.96
Ratings after stress/control condition			
Stressful	58.36 ± 5.68**	21.81 ± 5.51	8.60 ± 4.24
Painful	68.26 ± 4.18**	43.88 ± 4.06**	2.95 ± 3.12
Unpleasant	65.32 ± 6.77**	38.40 ± 6.57**	8.32 ± 5.06

** $p < .001$ compared to controls (there were no significant differences between responders and non-responders).

The stress group reported higher fear of negative evaluation in the SANB compared to the control group ($t_{(38)} = 2.967$, $p = .005$, $\eta_p^2 = 0.189$). Further analysis including an univariate ANOVA with the factor 'cortisol response' (see Section 3.2) revealed a significant between-group difference ($F_{(2,35)} = 4.813$, $p = .014$, $\eta_p^2 = 0.216$) with higher reported fear in non-responders compared to controls ($p = .004$). There were no significant differences between either responders and non-responders ($p > .05$) or responders and controls ($p > .05$). Because of this significant difference, the SANB mean score was included as covariate in all further analyses.

3.2. Stress response

As described above, we included the SANB score as a covariate in the ANCOVA concerning cortisol concentrations in addition to the repeated measurement factor 'time' and the between-groups factor 'group'. For both days, a significant time x group interaction emerged (first day: $F_{(1,37)} = 7.723$, $p = .009$, $\eta_p^2 = 0.173$; second day: $F_{(1.5,56.6)} = 25.618$, $p < .001$, $\eta_p^2 = 0.409$) as well as a significant main effect of 'group' on day 2 ($F_{(1,37)} = 8.543$, $p = .006$, $\eta_p^2 = 0.188$). On the first day, follow-up analyses revealed no significant between-group differences, neither for the first ($F_{(1,37)} = 0.072$, $p = .79$, $\eta_p^2 = 0.02$) nor for the second measurement ($F_{(1,37)} = 1.401$, $p = 0.244$, $\eta_p^2 = 0.036$). On the second day, stressed participants showed higher concentrations compared to controls 20 min ($F_{(1,37)} = 30.729$, $p < .001$, $\eta_p^2 = 0.454$) as well as 30 min after stress onset ($F_{(1,37)} = 14.03$, $p = .001$, $\eta_p^2 = 0.275$). Since we were particularly interested in the effects of cortisol increases on memory performance based on the prior literature, we performed a cortisol responder analysis using the criterion previously reported by Miller et al. (2013). Nine responders, eleven non-responders and 18 participants in the control group were identified (two controls showed a cortisol increase above 1.5 nmol/l and were excluded from further analyses including 'cortisol response' as between-groups factor).

The ANCOVA with the repeated measurement factor 'time', the between-groups factor 'cortisol response' (responders vs. non-responders vs. control group) and the covariate 'SANB' revealed a significant time x cortisol response interaction ($F_{(3.1,53.2)} = 29.983$, $p < .001$, $\eta_p^2 = 0.638$). The follow-up univariate ANCOVA affirmed significant between-group differences 20 min ($F_{(2,34)} = 38.658$, $p < .001$, $\eta_p^2 = 0.695$) as well as 30 min ($F_{(2,34)} = 16.137$, $p < .001$,

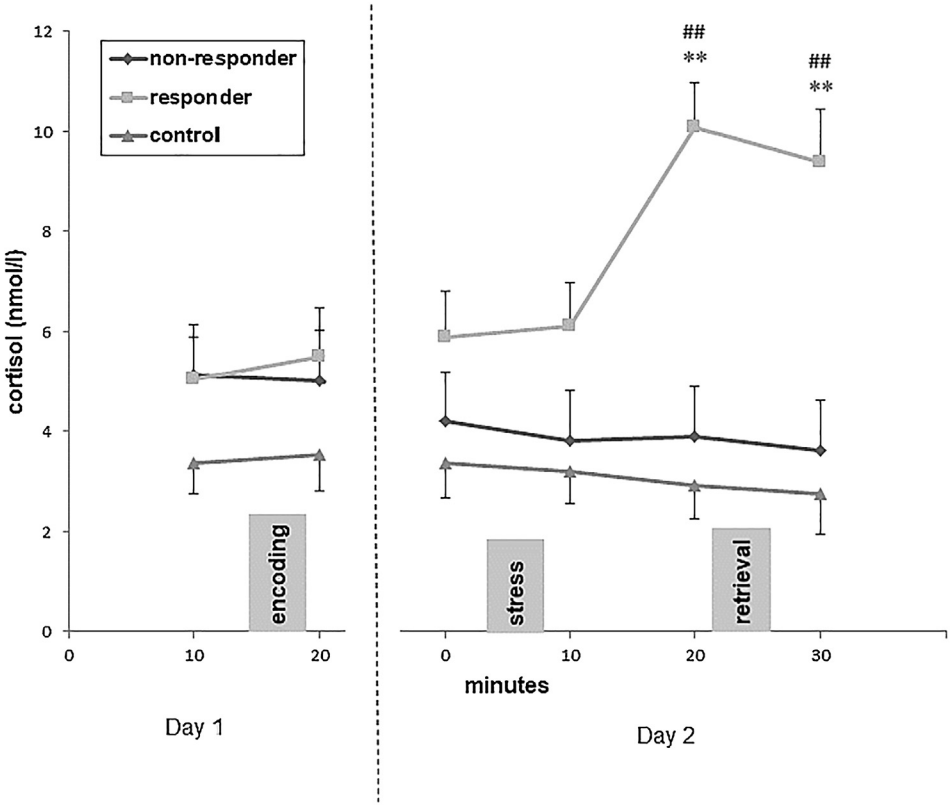

Fig. 1. Display of the experimental timeline and mean cortisol concentrations (± SEM). Note that raw data are depicted in this figure, whereas statistical analyses were conducted with transformed data (cf. Section 2.5). On day 1, before and after encoding of the relevant material cortisol concentrations were determined. On day 2, stress induction took place after a baseline measurement of cortisol and blood pressure. Blood pressure was also determined during the stress/control procedure as well as five minutes afterwards. Saliva samples were collected immediately after the stress or control procedure, +20 as well as +30 min relative to stress onset. Cortisol concentrations were significantly higher in responders +20 as well as +30 min after stress onset compared to controls ($^{**}p < .001$) and non-responders ($^{\#\#}p < .001$).

$\eta_p^2 = 0.487$) after stress-onset, with higher concentrations in responders relative to controls (both $p < .001$) and relative to non-responders (both $p < .001$; cf. Fig. 1). Pairwise comparisons additionally revealed significant higher cortisol concentrations in non-responders compared to controls 20 min ($p = .003$) as well as 30 min after stress-onset ($p = .046$). Neither significant differences concerning baseline levels on the second day ($F_{(2,34)} = 0.038$, $p = .963$) nor immediately after stress exposure were observed ($F_{(2,34)} = 1.286$, $p = .289$). The corresponding analyses without the SANB score as covariate are described in the supplemental information.

The ANCOVA for the cortisol measurements on the first day revealed a significant time x cortisol response interaction ($F_{(2,34)} = 4.493$, $p = .019$, $\eta_p^2 = 0.209$). However, follow-up univariate ANCOVA showed no significant between-group differences before ($F_{(2,34)} = 0.062$, $p > .05$) or after encoding ($F_{(2,34)} = 0.824$, $p > .05$).

Analyses of blood pressure fortified the finding of a successful stress induction (*systolic blood pressure:* time x cortisol response interaction, $F_{(3.6,61.1)} = 5.837$, $p = .001$, $\eta_p^2 = 0.256$; main effect cortisol response, $F_{(2,34)} = 3.22$, $p = .052$, $\eta_p^2 = 0.181$; *diastolic blood pressure:* time x cortisol response interaction: $F_{(3.8,64.5)} = 23.563$, $p < .001$, $\eta_p^2 = 0.581$, main effect time, $F_{(1.9,64.5)} = 8.09$, $p = .001$, $\eta_p^2 = 0.192$; main effect cortisol response, $F_{(2,34)} = 3.399$, $p = .045$, $\eta_p^2 = 0.167$). Follow-up analysis revealed significant higher blood pressure during the stressor (*systolic blood pressure:* $F_{(2,34)} = 10.175$, $p < .001$, $\eta_p^2 = 0.374$; *diastolic blood pressure:* $F_{(2,34)} = 21.232$, $p < .001$, $\eta_p^2 = 0.555$) in responders and non-responders relative to controls (all $p < .002$). No significant differences emerged for blood pressure measured during the baseline (all $F_{(2,34)} < 0.291$, all $p > .05$) or post hand immersion (all $F_{(2,34)} = 0.291$, $p > .05$; cf. Table 1). Furthermore, responders and non-responders (all $p < .001$) reported significantly higher subjective stress (stressful vs. painful vs. unpleasant) compared to controls (subjective stress x cortisol response: $F_{(3.5,58.9)} = 4.14$, $p = .007$, $\eta_p^2 = 0.196$). Both groups rated the hand immersion into water as significantly more painful ($F_{(2,34)} = 80.718$, $p < .001$, $\eta_p^2 = 0.826$) and unpleasant ($F_{(2,34)} = 22.641$, $p < .001$, $\eta_p^2 = 0.571$) in comparison to the control group (all $p < 0.05$). With respect to the rating of stressfulness ($F_{(2,34)} = 24.961$, $p < .001$, $\eta_p^2 = 0.595$), only the responders showed significant higher ratings relative to controls ($p < .001$). Over all subscales, responders reported significant higher subjective stress compared to non-responders (all $p < .001$; cf. Table 1).

3.3. Stress effects on memory retrieval of everyday information

First, we conducted an ANCOVA with the three information types as repeated measurement factor ('scale': numeric vs. figural vs. verbal) and the between-group factor 'group' (stress vs. control). Second, we replaced the between-group factor 'group' with the between-group factor 'cortisol response' (responders vs. non-responders vs. controls). We included the SANB score as a covariate in these analyses because of the significant between-group differences in this measure (cf. Section 3.1). The equivalent analyses without this covariate are presented in the supplemental information.

Analyses including the factor 'group' revealed neither significant main effects ('scale': $F_{(2,69.5)} = 0.001$, $p > .05$; 'group': $F_{(1,35)} = 2.468$, $p > .05$) nor a significant interaction scale x group ($F_{(2,69.5)} = 0.726$, $p > .05$). However, when subdividing the stress group into cortisol responders and non-responders and by excluding two control participants showing a cortisol response from the analysis, a significant between-group difference was observed ($F_{(2,34)} = 3.851$, $p = .031$, $\eta_p^2 = 0.185$), with an impaired memory performance over all types of information in non-responders compared to responders ($p = .014$) and controls ($p = .029$; cf. Fig. 2). Responders and controls did not significantly differ in their memory performance ($p > .05$). Neither a significant main effect of scale ($F_{(2,67.6)} = 0.005$, $p > .05$) nor a significant scale x cortisol response interaction ($F_{(4,67.6)} = 0.484$, $p > .05$) emerged. Correlation analyses revealed a marginally significant trend within all stressed participants: a higher increase from baseline to peak was associated with an improved memory retrieval performance concerning the global memory score ($r = .404$, $p = .077$; cf. Fig. 3).

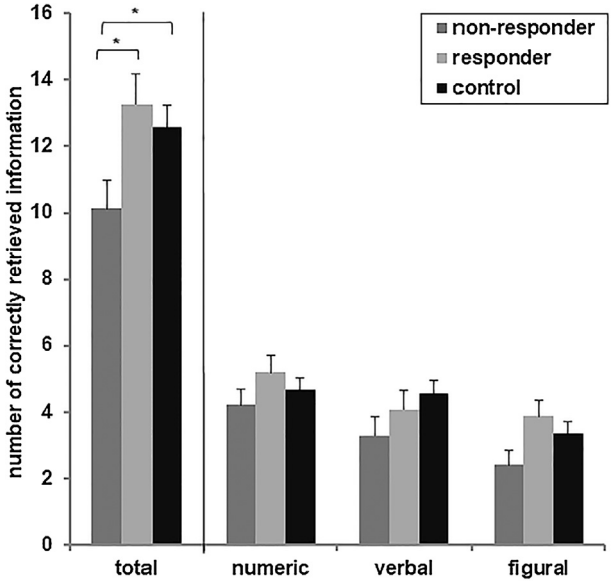

Fig. 2. Mean (± SEM) of correctly retrieved information for the three information types (numeric, figural, verbal) as well as the global memory score of the WIT-2 (total; depicting the sum of the three single information types' values). Analyses revealed a significant between-group difference with impaired memory retrieval in non-responders compared to responders and controls. $^{*}p < .05$.

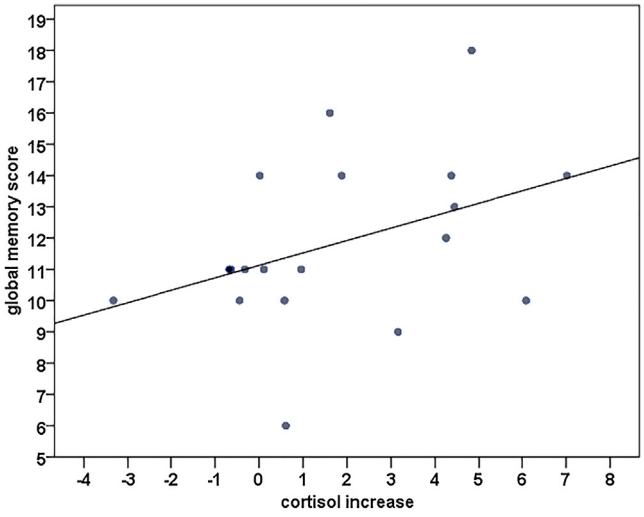

Fig. 3. Scatterplot of the correlation between cortisol increased from baseline to peak and the global memory score within the stressed participants. Note that one point represents three participants who reached the same value concerning the global memory score (11) and showed nearly the same cortisol increase (−0.61 nmol/l).

4. Discussion

The aim of the present experiment was to further examine the influence of stress on memory retrieval by using everyday information. We intended to apply more ecologically valid material using a text with various kinds of information, namely numeric, figural and verbal information taken from the memory subtask of the WIT-2 (Kersting et al., 2008). Stress reduced memory retrieval only in cortisol non-responders, who significantly differed from cortisol responders and controls. Additionally, a higher cortisol increase from baseline to peak was associated by trend with a memory improvement in all stressed participants.

The current results are in contrast to the majority of findings that have postulated impaired memory retrieval after acute stress (e.g. De Quervain et al., 2000; Kuhlmann, Kirschbaum, & Wolf, 2005; Schönfeld et al., 2014; Tollenaar et al., 2009; for reviews: Schwabe et al., 2012; Shields et al., 2017; Wolf, 2009), especially in cortisol responders (Buchanan et al., 2006). One possible explanation for the discrepant results might concern the used learning material. In previous studies, this mainly consisted of lists of words (Kuhlmann, Kirschbaum, & Wolf, 2005; Kuhlmann, Piel, & Wolf, 2005; Rohleder, Wolf, Kirschbaum, & Wolf, 2009; Smeets, Otgaar, Candel, & Wolf, 2008; Wolf et al., 2001), pairs of words (Tollenaar et al., 2008) or series of slides (Schönfeld et al., 2014) demonstrating the impairing stress effect especially for emotional material (Kuhlmann, Kirschbaum, & Wolf, 2005; Kuhlmann, Piel, & Wolf, 2005; Schönfeld et al., 2014; Smeets et al., 2008; Shields et al., 2017). Roozendaal, Hahn, Nathan, De Quervain, and McGaugh (2004) suggested that the interaction between the hippocampus and the basolateral amygdala is responsible for this effect of emotionality. The present material did not include any emotional component triggering amygdala activity potentially explaining this discrepancy of our results with previous findings.

Moreover, our learning material consisted of different information types containing ecologically valid and everyday components within one framework such as names of persons, time of day and signs on a city map. In line with a previous investigation demonstrating stress to enhance retrieval performance of educationally relevant information in men (Hupbach & Fieman, 2012), we could find improved memory retrieval in male cortisol responders relative to non-responders. Therefore, the memory retrieval of material with higher ecological validity might be divergently influenced by pre-retrieval stress compared to previously used material. This assumption is supported by meta-analytical evidence demonstrating 'words' as a potential moderator of the stress effect on memory retrieval (Shields et al., 2017). Moreover, this possibility of a moderating effect can also be found at least on the descriptive level in our results (see Fig. 2): cortisol responders showed a better memory performance for the global memory score as well as for the numeric and figural information compared to controls. A different picture emerged concerning verbal information, which corresponds to the postulated impaired memory after stress underlining the moderating role of verbal material on this effect. Importantly, future studies systematically manipulating the ecological validity of the learning material are clearly needed to explicitly test our assumption of the moderating role of ecological validity on stress effects on memory retrieval.

Furthermore, our data provide evidence for the assumption of an inverted U-shaped relationship between cortisol levels and memory performance (Lupien & McEwen, 1997): increasing cortisol concentrations should enhance memory performance until an optimum level is reached. With more intense cortisol increases, memory performance should decline again. In terms of this inverted U-shaped curve, on the one hand, cortisol responders may be associated with enhanced memory performance. On the other hand, non-responders were not able to show such an enhanced output because their cortisol levels did not increase and therefore they seem to remain near the foot of the inverted U-shaped curve. To further verify this assumption, further studies might use different dosages of cortisol given to the participants before retrieval (e.g. 1 mg vs. 2 mg vs. 5 mg vs. 20 mg) instead of the application of a stressor as realized before in humans (Lupien et al., 2007; Schilling et al., 2013). Additionally, the proposed curvilinearity could be observed with tests of quadratic trends in a larger sample of participants, possibly in combination with addition of more stressful components to the SECPT to ensure that cortisol levels will considerably increase. These cortisol levels exceeding the optimum should be associated with impaired memory retrieval similar to that of non-responders.

The SECPT represents a common and standardized procedure in stress research, which can provoke a reliable HPA axis activation resulting in moderate increases of cortisol concentrations (Schwade et al., 2008), most likely reflecting everyday stressful encounters. Furthermore, only the combination of social evaluation and ice-cold water, not

social evaluation or ice-cold water alone, has been shown to reliably activate the HPA axis (Schwade et al., 2008). Since social evaluation is a central part of the SECPT, the SANB was given to the participants to assess their fear of negative evaluation. As results indicated, groups unexpectedly differed in this trait measure leading to the question whether the SECPT could have led to a bias in responding to the SANB (which was given after the SECPT). Therefore, the SANB score was included as a covariate in all analyses. Nevertheless, future studies should account for the possible person x situation interaction and optimally hand out trait measures at baseline. Main advantages of the SECPT in comparison to other psychosocial stress procedures like the 'Trier Social Stress Test' (TSST; Kirschbaum, Pirke, and Hellhammer 1993) include the economy in case of time and persons as well as the control procedure (which is generally used in only one version compared to a variety of control procedures applied for the TSST). Due to the higher potency of the TSST to activate the HPA axis (Giles, Mahoney, Brunyé, Taylor, & Kanarek, 2014; Skoluda et al., 2015), future studies should also apply this procedure to see if the reported stress effects on memory retrieval of everyday information can also be observed with this method.

Since only male participants were tested, the observed stress effects on memory retrieval cannot be transferred to women in different menstrual cycle phases or taking oral contraceptives (OCs; for a review: Merz & Wolf, 2017). For example, Kuhlmann and Wolf (2005) showed a significantly impaired memory performance after cortisol administration occurring in free-cycling women, but not in OC women. In contrast, Schoofs and Wolf (2009) were not able to find such an effect in free-cycling women, although they demonstrated the stress-impairing effect in men with the identical design (Kuhlmann, Piel, & Wolf, 2005). Future studies should precisely address the role of sex hormones to affirm these sex-specific effects and extend them to everyday information.

Moreover, our sample encompassed only 20 participants per group, even smaller sample sizes were given after subdividing the stress group into cortisol responders and non-responders. Therefore, we performed a post-hoc power analysis (G*Power 3, Faul, Erdfelder, Lang, & Buchner, 2007), which showed an unsatisfying power of 25.5%. To achieve 80% power for the repeated measurement ANOVA with three groups, future studies should use a sample size of n = 69 with 23 participants per group. Nevertheless, power was sufficient (99.3%) to detect the significant main effect of cortisol response. Please note that our sample size calculation was not based on expected null effects and that the meaningfulness of post-hoc power analyses is somewhat limited.

Lastly, a curious point arose in the control group: two participants responded with a marked cortisol increase even though they only immersed their hand in warm water and were not observed. Unexpectedly, one participant reported higher subjective stress (but no increase in blood pressure was observed) compared to all other controls, which might have resulted in the unusual cortisol increase. This participant and the second participant did not differ from the other controls in terms of all obtained data (including demographic and subjective data, blood pressure, stress ratings or coefficients of variation of single cortisol levels). Thus, it can only be speculated why the second man responded to the warm water procedure.

5. Conclusion

In sum, our results suggest that the earlier reported stress effects on memory retrieval might, at least partly, depend on the used learning material. Assumedly, the use of less ecologically valid material, especially when involving an emotional component, results in the commonly mentioned impairing stress effects, whereas the implementation of stimulus material consisting of ecologically valid and neutral information can lead to the opposite picture. Future research should vary these two factors (ecologically validity and emotionality) independently. For our daily life, in confrontation with various kinds of information, not all containing emotional components, we might conclude that relatively high cortisol levels might be advantageous for retrieval processes.

Acknowledgements

We gratefully acknowledge the help of Lisa Glänzer and Shu Zhang during recruitment and stressing of participants. Additionally, we thank the members of the biochemical laboratory of the Department of Biological and Clinical Psychology (University of Trier) for saliva analyses.

Role of the funding source

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no conflict of interest.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.nlm.2018.05.008.

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