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Timing matters: Temporal dynamics of stress effects on memory retrieval

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Abstract Stress may impair memory retrieval. This retrieval impairment has been attributed to the action of the stress hormone cortisol, which is released with a delay of several minutes after a stressful encounter. Hence, most studies tested memory retrieval 20–30 min after stress, when the stress-induced cortisol increase peaks. In the present experiment, we investigated whether retrieval impairments can also be found at later intervals after stress. To this end, participants learned a list of words on day 1. Twenty-four hours later, they were first exposed to a stressor or a nonstressful control manipulation and completed a recognition test for the words either immediately thereafter, 25 min later, or 90 min later. Our findings showed that stress did not impair memory retrieval when memory was tested immediately after the stressor, before cortisol levels were elevated. However, retrieval performance was impaired 25 min after stress, when cortisol levels peaked, as well as 90 min after the stressor, when cortisol levels had already returned to baseline. The retrieval impairment 90 min after stress appeared to be even stronger than the one after 25 min. These findings suggest that the detrimental effects of stress on retrieval performance may last longer than is usually assumed.

Keywords Memory · Retrieval · Stress · Cortisol

It is well known that stress can affect a wide range of cognitive functions, including learning and memory. The nature of stress effects on learning and memory processes, however, is complex and dependent on the timing of the stress experience (for reviews, see Joëls, Pu, Wiegert, Oitzl, & Krugers, 2006; Roozendaal, McEwen, & Chattarji, 2009; Schwabe, Wolf, & Oitzl, 2010). Studies on the influence of stress before learning yielded inconsistent results, with some showing enhanced (Schwabe, Bohringer, Chatterjee, & Schachinger, 2008; Smeets, Giesbrecht, Jelicic, & Merckelbach, 2007) and others impaired (Elzinga, Bakker, & Bremner, 2005; Kirschbaum, Wolf, May, Wippich, & Hellhammer, 1996; Payne et al., 2007) subsequent memory. Stress shortly after learning, however, has been shown to enhance later memory (Cahill, Gorski, & Le, 2003; Smeets, Otgaar, Candel, & Wolf, 2008). Conversely, stress before retention testing appears to impair memory (Buchanan, Tranel, & Adolphs, 2006; De Quervain, Roozendaal, & McGaugh, 1998; Kuhlmann, Piel, & Wolf, 2005; Schwabe & Wolf, 2009; Smeets et al., 2008; but see also Hupbach & Fieman, 2012; Schilling et al., 2013; Schwabe et al., 2009).

How can these opposing influences of stress on memory be explained? It has been proposed that the seemingly conflicting effects of stress on memory processes are owing to the different temporal profiles of action of physiological stress mediators (Diamond, Campbell, Park, Halonen, & Zoladz, 2007; Joëls, Fernandez, & Roozendaal, 2011; Joëls et al., 2006). When a situation is experienced as stressful, adrenaline and noradrenaline are released by the sympathetic nervous system within seconds. In addition, stress activates the hypothalamus–pituitary–adrenal axis, one of the body's major stress response systems, which secretes the stress hormone cortisol with a delay of about 10 min after stressor onset (Joëls & Baram, 2009). Cortisol may then exert rapid non-genomic and slower genomic effects (Joëls, Karst, DeRijk, & De Kloet, 2008). Thus, there are at least three temporal "waves" of the physiological stress response: a first wave starting within seconds that includes noradrenaline and other neurotransmitters; a second wave setting in after several minutes that includes, in addition to noradrenaline, rapid cortisol actions; and a third wave developing after more than an hour that includes mainly slow, gene-mediated actions of cortisol (Joëls &

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Baram, 2009). Importantly, these different waves of the response to stress have been suggested to have opposite effects on brain areas that are critical for memory processes. Rapid stress mediators are thought to enhance the encoding of the stressful experience by facilitating attention and alertness, whereas delayed stress mediators may boost the consolidation of the memory of the stressful encounter by suppressing the encoding or retrieval of unrelated material. Hence, stress is thought to enhance memory when it is part of the learning context and when it occurs around the time of the learning episode, whereas stress out of the learning context should impair memory (Diamond et al., 2007; Joëls et al., 2006). More specifically, it has been suggested that rapid stress effects induce a memory formation mode that promotes the formation of lasting memories of ongoing events. The delayed stress effects, mainly mediated by genomic cortisol actions, however, are thought to initiate a memory storage mode that shields the consolidation of the stressful episode from distraction and competing information processing, thereby suppressing other cognitive processes (Schwabe, Joëls, Roozendaal, Wolf, & Oitzl, 2012).

This model can explain the memory-enhancing effects of stress shortly after learning. Moreover, it may also account for at least some of the inconsistent findings on the influence of stress before learning. For example, in a recent study, participants underwent a stressor either shortly before learning or a considerable time before learning (Zoladz et al., 2011). Subsequent memory testing showed that stress enhanced memory when experienced within the context of the learning episode (i.e., shortly before learning), whereas stress impaired memory when experienced out of the learning context. Similarly, stress-induced cortisol elevations correlated positively with memory if participants were stressed shortly before learning but correlated negatively with memory if participants were stressed a longer time before learning (Quadflieg, Schwabe, Meyer, & Smeets, 2013). Further evidence for a dual mode of stress (hormone) effects on memory formation comes from neuroimaging studies, indicating that stress or cortisol rapidly enhances processing in memory-related brain areas, whereas delayed cortisol effects suppress activity in areas critical for memory formation, such as the hippocampus (Henckens et al., 2012; Hermans et al., 2011; Lovallo, Robinson, Glahn, & Fox, 2010).

Although the proposed dual-mode model appears to be able to explain the seemingly discrepant effects of stress on memory formation, its implications for stress effects on memory retrieval are less clear. Most studies tested memory retrieval about 30 min after stressor onset, when peak cortisol concentrations are expected, and found that stress impairs retrieval (Buchanan et al., 2006; Kuhlmann et al., 2005; Smeets et al., 2008). Only recently, a study investigated whether stress effects on retrieval may also be time dependent (Schönfeld, Ackermann, & Schwabe, 2014). In this study, a stressful, exam-like testing situation was created, and retrieval performance under stress was compared with memory 25 min after this stressor. The results showed that stress-induced arousal enhanced retrieval under stress, whereas stress impaired 25-min-delayed retrieval, suggesting that the first wave of the stress response may facilitate retrieval, whereas the second wave disrupts retrieval. How the third wave of the response to stress—that is, gene-mediated cortisol action—affects memory retrieval has not been investigated yet. This, however, is highly important because the role of genomic cortisol actions in memory retrieval determines for how long the retrieval impairment may last after stress.

In the present experiment, we examined the temporal dynamics of stress effects on memory retrieval, with a particular focus on retrieval at shorter and longer delays after stress. To this end, our participants learned a list of words on day 1. Twenty-four hours later, participants underwent a standardized stressor (socially evaluated cold pressor test) or a control manipulation and completed a memory test for the items learned on day 1 either immediately thereafter (before cortisol was elevated; *0-min interval*), 25 min later (when cortisol levels peaked; *25-min interval*), or 90 min later (when cortisol levels returned to baseline but genomic cortisol actions have developed; *90-min interval*). In the 0-min interval condition, we did not expect an effect of stress because, although stress was not part of the retrieval context, cortisol, which is critical for stress-related retrieval impairment (De Quervain et al., 1998; De Quervain, Roozendaal, Nitsch, McGaugh, & Hock, 2000), should not yet be elevated. On the basis of previous studies (Kuhlmann et al., 2005; Smeets et al., 2008) and the assumption of the dual-mode model that, in the memory formation mode, encoding and consolidation processes would be enhanced at the expense of other cognitive processes (Joëls et al., 2006; Schwabe et al., 2012), we predicted that stress 25 min before retrieval would impair memory performance. According to the dual-mode model assumption that delayed cortisol actions would actively suppress cognitive processes unrelated to the stressor (Joëls et al., 2006; Schwabe et al., 2012) and on the basis of findings showing that delayed cortisol effects may indeed reduce activity in brain areas that are critical for retrieval (Henckens et al., 2012), we further predicted that stress may hamper retrieval also after cortisol levels have returned to baseline and that stress effects after 90 min may be even stronger than those observed after 25 min.

Method

Participants

One hundred twenty students of the Ruhr-University Bochum participated in this experiment (60 men, 60

women; age: M = 23.61 years, SEM = 0.28 years). Participation was limited to nonsmokers without current medication intake and without life-time history of any psychiatric or neurological disorders. All participants provided written informed consent for participation before the beginning of the experiment and received a monetary compensation of 10 € per hour. We used a fully crossed between-subjects design with the factors treatment (stress vs. control condition) and treatment–retrieval interval (0 vs. 25 vs. 90 min), thus resulting in six experimental groups. Ten men and 10 women were randomly assigned to each of the six groups.

Materials

Two lists of German nouns, each consisting of 30 neutral and 30 negative nouns, were used as stimuli. Neutral and negative nouns were taken from a German word database (Hager & Hasselhorn, 1993), on the basis of their emotional valence and arousal scores. Furthermore, neutral and negative nouns, as well as the nouns of the two word lists, were matched for imagery, frequency, and word length. In order to ensure that neutral and negative words were indeed experienced as neutral and negative, respectively, participants rated all words with respect to valence and arousal on a scale from 0 (*very negative*/*not at all arousing*) to 100 (*very positive*/*very arousing*) at the end of the experiment. In retrospect, these ratings confirmed the classification of words as neutral and negative, respectively: neutral words were rated as neutral (M = 49.69, SEM = 0.87) and not arousing (M = 12.83, SEM = 1.28), whereas negative words were rated as rather negative (M = 30.49, SEM = 1.01) and moderately arousing (M = 44.49, SEM = 1.73; neutral vs. negative words: both ps < .0001).

Procedure

Participants were tested in two sessions on consecutive days. In order to control for the diurnal rhythm of the stress hormone cortisol, all testing took place in the afternoon between 1 p.m. and 6 p.m.

On day 1, participants saw neutral and negative nouns on a computer screen and were instructed to memorize these words. Words were presented one at a time for 2 s, in randomized order. Each word was presented twice. Whether word list 1 or 2 (see above) was used at study was counterbalanced across participants and groups. At the end of the first experimental day, participants completed a free recall test in which they wrote all words they could remember on a sheet of paper.

Twenty-four hours later, on day 2, participants underwent the socially evaluated cold pressor test (SECPT) or a warm water control test, depending on the experimental group. The SECPT is a standardized laboratory stressor that has been described in detail elsewhere (Schwabe, Haddad, & Schachinger, 2008). Briefly, participants immersed their right hand up to and including the wrist for up to 3 min (or until they could no longer tolerate it) into ice water (0°–2 °C). They were monitored by an unfamiliar person and videotaped during hand immersion, because social evaluation is critical for stress induction (Dickerson & Kemeny, 2004). Participants in the control condition submerged their right hand up to and including the wrist for 3 min into warm water (35°–37 °C); they were neither monitored nor videotaped.

In order to assess the successful stress induction by the SECPT, we took subjective ratings, blood pressure measurements, and saliva samples at several time points across the experiment. Immediately after the treatment, participants rated on a scale from 0 (*not at all*) to 100 (*very*) how stressful, painful, and unpleasant they had experienced the previous situation. In addition, we measured participants' blood pressure, an indicator of sympathetic activity, using a Dinamap system (Critikon, Florida) immediately before, during, and immediately after the treatment. Saliva samples were collected using Salivette collection devices (Sarstedt, Germany) before as well as immediately and 25 min after the treatment; participants in the 90-min-interval conditions gave another saliva sample before their retention test. From saliva, we analyzed cortisol concentrations using an immunoassay (IBL, Germany).

After the stress or control manipulation, participants completed a recognition test. They were presented 120 words, including the 60 words they had seen the day before and 60 new words (30 neutral, 30 negative), one after another on a computer screen and were asked to indicate for each word by buttonpress whether they had seen the word on day 1 or not. Memory performance in this recognition test was expressed by the sensitivity index d', computed as z [p(hit)] − z [p(false alarm)] (see Wickens, 2002). A perfect hit rate of 100 % for neutral or negative words was corrected and set to 98.3 % (30 "old" neutral or negative words: 29/30 + 1/30 × 0.5 = 0.983), as suggested by Wickens (2002). Accordingly, if a participant made no error of commission, the false alarm rate was set to 1.66 %. Critically, the recognition test took place either immediately after the treatment, 25 min after the treatment, or 90 min after the treatment. Participants' in the 25-min- and 90-min-interval groups were allowed to read in the break between the treatment and the recognition test. Following the recognition test, participants rated the valence and arousal of all words that were used in this experiment (see above).

Statistical analysis

Memory data on day 1 were analyzed by a group (six experimental groups) × emotionality (neutral vs. negative words) ANOVA. In order to test for potential interaction effects of

experimental treatment and the treatment–retrieval interval, memory performance on day 2 was subjected to a treatment (control vs. stress condition) × treatment–retrieval interval (0 vs. 25 vs. 90 min) × emotionality ANOVA. To assess potential sex differences in stress effects on memory, we included in explorative analyses participants' sex as an additional factor. The subjective stress ratings were analyzed by means of a treatment × treatment–retrieval interval ANOVA, and the physiological stress responses by means of a treatment × treatment–retrieval interval × time point of measurement ANOVA. Significant main or interaction effects were pursued by simple effects analyses. All reported *p*-values are two-tailed.

Results

Day 1: Immediate free recall

In the immediate free recall test on day 1, participants recalled significantly more negative (M = 8.36, SEM = 0.27) than neutral (M = 6.27, SEM = 0.28) words, $F(1, 112) = 45.56$, $p < .001$, $\eta^2 = .29$. However, there was no difference between the six groups in immediate free recall performance, neither overall, $F(5, 112) = 0.71$, $p = .61$, $\eta^2 = .03$, nor depending on the emotionality of the words, $F(5, 112) = 0.90$, $p = .49$, $\eta^2 = .04$, indicating that initial memory encoding was comparable in the experimental groups. Women recalled more items than did men, $F(1, 108) = 6.43$, $p = .01$, $\eta^2 = .06$, irrespective of the experimental group and the emotionality of the words, all Fs < 2.37, all ps > .12, all η^2s < .03. Overall, it is to be noted that the immediate free recall test performance was rather moderate, which might be due to the learning material used and the type of memory test.

Day 2: Subjective and physiological stress responses

Participants' subjective assessments and significant changes in blood pressure and salivary cortisol confirmed the successful stress induction by the SECPT.

Subjective ratings

As was, expected, participants who underwent the SECPT rated the treatment as significantly more stressful, painful, and unpleasant than did participants who underwent the warm water control manipulation, all Fs(1, 112) > 116, all $ps < .001$, all η^2s > .51 (Table 1). The subjective experience of the SECPT was similar in the three treatment–retrieval interval conditions [treatment × treatment–retrieval interval interactions, all Fs(2, 112) < 1.55, all ps > .20, all η^2s < .03].

Blood pressure

Systolic and diastolic blood pressure increased in response to the SECPT, but not in response to the control manipulation [treatment × time point of measurement interactions, both Fs(2, 224) > 36, both ps < .001, both η^2s > .24]. As is shown in Table 1, blood pressure was significantly elevated during the SECPT and returned to baseline shortly after the exposure to the SECPT. The stressor-induced increases in blood pressure did not differ between the three treatment–retrieval interval conditions [treatment × time point of measurement × treatment–retrieval interval interactions, both Fs(4, 224) < 0.87, both ps > .48, both η^2s < .02].

Salivary cortisol

The exposure to the SECPT led also to a significant increase in cortisol [treatment × time point of measurement interaction, $F(2, 224) = 28.99$, $p < .001$, $\eta^2 = .21$; see Fig. 1]. Whereas groups did not differ before or immediately after the treatment, both ts(118) < 0.20, both ps > .84, participants who underwent the SECPT had significantly elevated cortisol concentrations, relative to the control groups, 25 min after the treatment, $t(118) = 4.57$, $p < .001$, when the memory test began in the 25-min-interval groups. In the 90-min treatment–retrieval interval groups, however, cortisol concentrations had already returned to baseline before retention testing started (i.e., 90 min after the treatment), $t(38) = 0.89$, $p = .38$. Overall, the stressor-induced cortisol increases were similar in the three treatment–retrieval interval conditions [treatment × time point of measurement × treatment-retrieval interval interaction, $F(2, 224) = 0.89$, $p = .47$, $\eta^2 = .02$].

Day 2: Memory performance

Participants' memory performance in the recognition test is displayed in Fig. 2. A 2 (treatment: control, stress) × 3 (treatment–retrieval interval: 0, 25, 90 min) × 2 (emotionality of the words: neutral, negative) ANOVA yielded, in addition to main effects of treatment, $F(1, 112) = 8.04$, $p = .005$, $\eta^2 = .07$, and treatment–retrieval interval, $F(2, 112) = 5.10$, $p = .008$, $\eta^2 = .08$, a significant treatment × treatment–retrieval interval interaction, $F(2, 112) = 3.86$, $p = .024$, $\eta^2 = .07$. In order to pursue this interaction effect, we compared the performance of the stress and control groups in the three treatment–retrieval interval conditions, separately. If memory was tested immediately after the treatment, stress did not affect memory performance, $F(1, 38) = 0.14$, $p = .71$, $\eta^2 < .01$. However, if memory was tested 25 min after the treatment, when cortisol levels peak, stress resulted in a (marginally significant) memory impairment, $F(1, 38) = 3.90$, $p = .056$, $\eta^2 = .10$. This memory impairment was even more pronounced if memory was assessed 90 min after stressor exposure, $F(1, 38) = 9.44$, $p = .004$, $\eta^2 = .20$.

Table 1 Mean (*SEM*) subjective and blood pressure responses to the stressor

	0-Min Interval		25-Min Interval		90-Min Interval	
	Control	Stress	Control	Stress	Control	Stress
Subjective rating						
Stressfulness	2.50 (1.43)	47.00 (5.94)*	2.00 (1.38)	53.16 (7.65)*	2.11 (1.64)	41.00 (6.57)*
Painfulness	0.50 (0.50)	56.50 (5.39)*	0.00 (0.00)	64.74 (6.68)*	1.58 (1.15)	66.00 (6.22)*
Unpleasantness	4.50 (1.35)	59.00 (6.28)*	2.50 (1.43)	62.11 (6.51)*	3.68 (1.91)	62.00 (6.63)*
Systolic blood pressure						
Before treatment	115.38 (2.53)	125.13 (2.48)*	123.15 (3.77)	118.71 (3.22)	125.74 (4.15)	112.30 (6.34)
During treatment	117.33 (4.76)	**142.80 (3.22)***	120.83 (3.78)	**138.34 (4.88)***	122.66 (3.71)	**132.25 (3.36)***
After treatment	110.85 (2.55)	123.62 (2.47)*	119.55 (3.57)	118.26 (2.78)	119.66 (3.94)	115.95 (3.46)
Diastolic blood pressure						
Before treatment	67.15 (1.27)	69.40 (1.37)	69.00 (1.99)	67.39 (1.97)	71.11 (2.04)	65.40 (1.73)
During treatment	68.14 (1.29)	**87.22 (2.22)***	70.50 (2.00)	**86.16 (3.29)***	71.71 (1.69)	**82.13 (2.93)***
After treatment	64.43 (1.46)	68.98 (1.63)	69.43 (1.79)	68.95 (2.04)	69.53 (1.87)	65.55 (2.01)

Boldface: significant increase relative to baseline ($p < .05$)

*Significant difference between the stress and control groups ($p < .05$)

Indeed, when memory performance was compared directly between the stress groups of the 25- and 90-min-interval conditions, recognition performance was worse in participants that were stressed 90 min before memory testing, $F(1, 38) = 5.13$, $p = .029$, $\eta^2 = .12$. In order to assess the role of cortisol in these time-dependent effects of stress, we performed correlational analyses between memory performance for neutral and negative stimuli and both the peak cortisol concentrations and the cortisol increase relative to baseline. These analyses, however, yielded no significant correlations, all rs < .26, all ps > .12, which might at least partly be due to a lack of statistical power.

Although recognition memory was generally better for negative than for neutral words, $F(1,112) = 9.24$, $p = .003$, $\eta^2 = .08$, the emotionality of the words did not modulate the effects of the treatment or treatment–retrieval interval [interactions including the factor emotionality, all Fs < 2.12, all ps > .12, all η^2s < .04]. Moreover, when hit and false alarm rates were analyzed separately, we did not find significant effects of treatment and treatment–retrieval interval, both Fs (2, 112) < 2.43, both ps > .10, both η^2s ≤ .04. Men and women did not differ in their memory performance on day 2, and there were no sex differences in the influence of stress on memory performance, all Fs < 2.36, all ps > .10, all η^2s ≤ .04.

Discussion

It is commonly assumed that stress interferes with memory retrieval (Roozendaal et al., 2009; Schwabe et al., 2012). This view is mainly based on the findings of studies that tested the retrieval of previously learned material about 30 min after stress, when stress-induced cortisol levels peak (Buchanan et al., 2006; Kuhlmann et al., 2005; Smeets et al., 2008). However, it remained unclear whether stress does indeed universally impair memory retrieval, irrespective of the timing of the stress exposure, and for how long after stress the

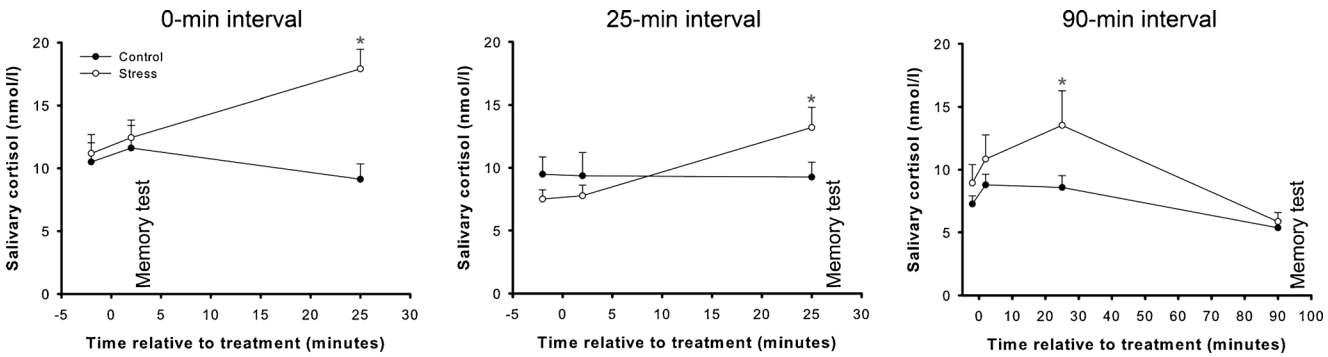

Fig. 1 Salivary cortisol concentrations of the stress and control groups for each of the three treatment–retrieval interval conditions. In all treatment–retrieval interval conditions, cortisol concentrations increased significantly in the stress group, but not in the control group. * Significant difference between the stress and control groups ($p < .05$). Error bars represent standard errors of the means

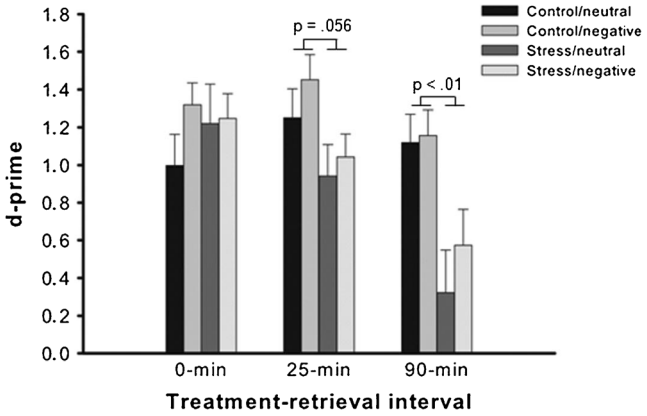

Fig. 2 Recognition memory performance expressed as *d'*, depending on the experimental treatment (control vs. stress) and the treatment–retrieval interval. Memory performance remained unaffected when memory was tested immediately after the stressor exposure. However, if memory was tested 25 min or, in particular, 90 min after the stress experience, memory was significantly impaired. Error bars represent standard errors of the means

retrieval impairment may last. Specifically, it remained unclear whether the retrieval impairment may outlast the stress-induced cortisol increase. The present study provides answers to these questions. We exposed participants to a stressor immediately before, 25 min before, or 90 min before a memory test for previously learned material. Our results showed that stress impaired 25-min-delayed and, in particular, 90-min-delayed retrieval, but not retrieval performance immediately after stress. These data suggest that stress does not hinder memory retrieval as long as cortisol is not yet elevated. Once cortisol levels are increased in response to stress, retrieval is impaired, and this impairment may persist after cortisol levels returned to baseline.

Together with recent findings showing that stress-induced arousal may even enhance memory retrieval if stress is an integral part of the retrieval situation and if cortisol concentrations are not yet elevated (Schönfeld et al., 2014), the present data suggest that stress effects on memory retrieval are time dependent. Stress shortly before or during memory retrieval may be beneficial for retrieval if stress and retrieval are closely related; otherwise, stress shortly before retention testing appears to have no effect on retrieval. Stress during retrieval might also act as a distractor and, hence, reduce performance; such effects, however, are probably due to the well-known dual-task interference effects (Pashler, 1994), rather than to specific stress effects. As time after a stressor proceeds, allowing cortisol to increase, memory retrieval is impaired, owing to rapid, nongenomic actions of cortisol, most likely in interaction with noradrenaline (Joëls et al., 2011; Roozendaal, Hahn, Nathan, de Quervain, & McGaugh, 2004). This stress-induced retrieval impairment remains or is even amplified when slower, genomic cortisol actions set in. Thus, the temporal dynamics of stress effects on memory retrieval appear to be mainly related to the action of the stress hormone cortisol, which is in line with evidence from human and rodent studies in which cortisol (or corticosterone in rodents) levels were manipulated pharmacologically before retrieval (De Quervain, Aerni, & Roozendaal, 2007; De Quervain et al., 1998; De Quervain et al., 2000).

According to the dual-mode model of stress effects on memory (Joëls et al., 2006; Schwabe et al., 2012), the retrieval impairments 25 and 90 min after stress are due to different processes. During the proposed memory formation mode that is induced by noradrenaline and rapid cortisol actions, cognitive functions are focused on the processing and encoding of the ongoing stressful experience, which leaves less capacity for other cognitive processes, such as the retrieval of stressor-unrelated material. In that sense, the retrieval impairment that is observed about 30 min after stress may be considered a by-product or side effect of the stress-induced enhancement of memory formation. During the subsequent memory storage mode, however, genomic cortisol actions are thought to suppress information processing, in order to shield the consolidation of the stressful event. Given that genomic cortisol actions may suppress the activity of brain areas relevant to memory retrieval (Henckens et al., 2012), we predicted that the retrieval impairment would be even more pronounced during the proposed memory storage mode than during the memory formation mode. Indeed, the retrieval impairment appeared to be stronger 90 min after the stressor than 25 min after the stressor.

If memory is still impaired after cortisol levels have returned to baseline, the question arises for how long these disruptive effects of stress may last. Human data on this issue are missing. Findings from rodents, however, indicate that the detrimental influence of stress on retrieval is gone about 4 h after the stressor (De Quervain et al., 1998). Another important question is whether the stress-induced retrieval impairment is temporary or lasting. Does stress transiently reduce the accessibility of the stored information, or does stress before retrieval permanently alter the memory trace? Although some data suggest that stress effects on retrieval are transient (Tollenaar, Elzinga, Spinhoven, & Everaerd, 2008), others indicate that the influence of stress or cortisol on retrieval can persist for at least up to 6 months (Tollenaar et al., 2008; Tollenaar, Elzinga, Spinhoven, & Everaerd, 2009). Accumulating evidence suggests that memories reenter a labile state when they are reactivated during retrieval and that a process of reconsolidation is needed to stabilize them anew (Hardt, Einarsson, & Nader, 2010). During reconsolidation, memories can be modified. Thus, stress-induced cortisol elevations around the time of retrieval may interact with memory reactivation to alter the retrieved memories. In line with this idea, there is some evidence that stress or cortisol after memory retrieval may change memories (Cai, Blundell, Han, Greene, & Powell, 2006; Maroun & Akirav, 2008; Schwabe & Wolf, 2010). Finally, it is important to note that we

examined here the influence of stress on the retrieval of stressor-unrelated material. Future studies are required to test whether stress impairs indeed the retrieval of all memory traces or whether the retrieval of material associated with the stressor might even be enhanced.

Impairments of memory retrieval after stress have important practical implications. In educational contexts, for instance, the stress-induced retrieval impairment may affect performance in exams and result in "blackouts." Moreover, stress effects on memory retrieval may have important clinical implications because several mental disorders, including phobia or posttraumatic stress disorder (PTSD), are characterized by abnormal memory processes (American Psychiatric Association, 2013). It has been argued that if abnormal memories are a hallmark of these disorders and if stress or stress hormones impair memory retrieval, the stress or cortisol effects may be employed to hamper the retrieval of dysfunctional memories (De Quervain & Margraf, 2008). Indeed, there are early promising data suggesting that patients with PTSD or phobia might benefit from cortisol treatment (Aerni et al., 2004; Soravia et al., 2006). The present findings underline that stress may impair memory retrieval, depending on the presence of cortisol. In particular, our findings demonstrate that the detrimental effects of stress on memory retrieval may last longer than usually expected.

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