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Acute stress affects prospective memory functions via associative memory processes

Ágnes Szőllősi[a,*], Péter Pajkossy[a,b], Gyula Demeter[a,b], Szabolcs Kéri[a,c], Mihály Racsmány[a,b]

[a] Department of Cognitive Science, Budapest University of Technology and Economics, Budapest, Hungary
[b] Research Group on Frontostriatal Disorders, Hungarian Academy of Sciences, Budapest, Hungary
[c] National Institute of Psychiatry and Addictions, Nyírő Gyula Hospital, Budapest, Hungary

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ABSTRACT

Recent findings suggest that acute stress can improve the execution of delayed intentions (prospective memory, PM). However, it is unclear whether this improvement can be explained by altered executive control processes or by altered associative memory functioning. To investigate this issue, we used physical-psychosocial stressors to induce acute stress in laboratory settings. Then participants completed event- and time-based PM tasks requiring the different contribution of control processes and a control task (letter fluency) frequently used to measure executive functions. According to our results, acute stress had no impact on ongoing task performance, time-based PM, and verbal fluency, whereas it enhanced event-based PM as measured by response speed for the prospective cues. Our findings indicate that, here, acute stress did not affect executive control processes. We suggest that stress affected event-based PM via associative memory processes.

1. Introduction

Effective functioning in everyday life relies heavily on the ability of performing intended actions. Moreover, adaptive behaviour frequently requires the delayed execution of such intentions, i.e., prospective memory (PM) – see Meacham (1982). The execution of a delayed intention (the PM response) can be triggered by specific external PM cues (event-based PM), or in other cases, the intended action has to be executed at a specific time in the future (time-based PM) – see Einstein and McDaniel (1990, 2005).

1.1. *The role of executive control in prospective remembering*

The term "executive functions" refers to a set of processes that are necessary when automatic responses are not enough for optimal behaviour and the attention-demanding control of behaviour is needed (see e.g., Engle, 2002; Miyake et al., 2000; Norman & Shallice, 1986; Smith & Jonides, 1999). PM involves various executive control processes, such as planning and maintaining information in working memory (Kliegel, Martin, McDaniel, & Einstein, 2002), cognitive flexibility to switch attention to the PM cue and the inhibition of ongoing behaviour (Bisiacchi, Schiff, Ciccola, & Kliegel, 2009; Kliegel, Mackinlay, & Jäger, 2008) as well as monitoring for the PM cue (Einstein & McDaniel, 1990; Smith & Bayen, 2004). Event- and time-based PM differ in several aspects (see e.g., Guynn, 2008; Kvavilashvili & Ellis, 1996; Marsh, Hicks, & Cook, 2008; McDaniel & Einstein, 2000; Smith, Bayen, & Martin, 2010) and one important distinction is related to executive functions.

In time-based PM situations, successful intention execution always depends on executive control processes, because responses are triggered by internal cues and are driven by self-initiated retrieval processes (see Einstein & McDaniel, 1990; Sellen, Louie, Harris, & Wilkins, 1997). Most of the dominant theories highlight the important role of executive control in event-based PM as well (McDaniel & Einstein, 2000; McDaniel, Guynn, Einstein, & Breneiser, 2004; Smith, 2003; Smith & Bayen, 2004). However, the multiprocess model proposes that the retrieval of an event-based PM response could be triggered automatically and spontaneously by environmental cues and the involvement of executive control depends on various factors, e.g., on the focality of the PM cue (McDaniel et al., 2004; McDaniel & Einstein, 2000). Specifically, in focal PM situations there is an overlap between the processing of the PM stimuli and the processing of the PM cue, whereas in non-focal PM tasks there is no overlap between them. Therefore, performing a non-focal PM task requires attention demanding executive control processes, rather than when one performs a focal PM task. The multiprocess model also highlights that there is a tendency to minimize the

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* Corresponding author at: Department of Cognitive Science, Budapest University of Technology and Economics, 1111-Budapest, Egry Jozsef utca 1, Hungary.
E-mail addresses: aszollosi@cogsci.bme.hu (Á. Szőllősi), ppajkossy@cogsci.bme.hu (P. Pajkossy), gdemeter@cogsci.bme.hu (G. Demeter), szkeri@cogsci.bme.hu (S. Kéri), racsmany@cogsci.bme.hu (M. Racsmány).

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requirement of executive control in event-based PM situations, and individuals prefer to use more automatic retrieval strategies whenever circumstances allow this (Einstein et al., 2005; Einstein & McDaniel, 2005; McDaniel & Einstein, 2007). Moreover, it seems that performance is better when the execution of PM responses involves automatic memory processes rather than executive control (Einstein et al., 2005). In these situations, PM responses are driven by associative memory (McDaniel & Einstein, 2007; see also Moscovitch, 1994). That is, individuals form associations between the anticipated PM cue and the intended action. Later, when the cue is encountered, PM retrieval does not require effortful searching processes (i.e., executive control), instead, a reflexive-associative memory system triggers retrieval and brings the intended action to consciousness (see also Einstein & McDaniel, 1996; McDaniel & Einstein, 2000).

Event-based PM is usually tested in dual-task situations where individuals perform a simple ongoing task while they have to maintain and execute delayed intentions. A reliable index of executive control requirement is the so-called ongoing cost of remembering (Smith, 2003; for a review, see e.g., Cohen & Gollwitzer, 2008). That is, if capacity-demanding attentional resources are needed for optimal performance in PM situations, individuals tend to show reduced performance (i.e., slower response speed) on the primary ongoing task when they have to maintain delayed intentions. However, the exact nature of the relationship between the ongoing cost and PM performance is still under debate (Einstein et al., 2005; Heathcote, Loft, & Remington, 2015; Scullin, McDaniel, & Einstein, 2010; Smith, 2003). According to some previous studies, in addition to executive control involvement (as indicated by the ongoing cost), associative memory processes can contribute to prospective remembering (e.g., Scullin et al., 2010).

1.2. Effects of stress on executive functions and prospective memory

Experiencing stressful situations triggers the activation of the hypothalamic-pituitary-adrenal (HPA) axis and the secretion of stress hormones, such as glucocorticoids (GCs) – in humans: cortisol (see e.g., Charmandari, Tsigos, & Chrousos, 2005; O'Connor, O'Halloran, & Shanahan, 2000). It is widely known that the presence of everyday and laboratory-based stressors influences cognitive functioning, including executive functions and memory.

Regarding the effect of stress on executive functions, the existing findings are contradictory (see e.g., Lupien, Maheu, Tu, Fiocco, & Schramek, 2007). However, a recent meta-analytic review (Shields, Sazma, & Yonelinas, 2016) has shown that in most cases acute stress impairs specific components of executive functions including cognitive flexibility, working memory, and cognitive inhibition. Several theorists suggest while stress impairs executive functioning, it prompts a shift to a more associative, automatic, and reflexive processing (Arnsten, 2015; Hermans, Henckens, Joëls, & Fernández, 2014; Schwabe & Wolf, 2013; Shields et al., 2016). Furthermore, it seems that cortisol secretion counteracts the detrimental effect of stress on executive processing by improving the maintenance of task relevant information (Weckesser, Alexander, Kirschbaum, Mennigen, & Miller, 2016).

Interestingly though, in comparison with stress-related executive functions, only a few studies focused on whether and how stress affects the maintenance and execution of delayed intentions. Results suggest that in laboratory settings, baseline stress levels show no relationship with PM performance, irrespective of whether the PM cue is an event (Nakayama, Takahashi, & Radford, 2005) or a specific point in time (Ihle et al., 2014). Accordingly, prolonged exposure to high cortisol levels also shows no relationship with event-based PM performance (McLennan, Ihle, Steudte-Schmiedgen, Kirschbaum, & Kliegel, 2016).

Regarding the relationship between acute stressors and PM, in a study by Walser, Fischer, Goschke, Kirschbaum, and Plessow (2013), psychosocial stress exposure had no effect either on ongoing or on event-based PM performance as measured by hit rates and reaction times (RTs). Accordingly, psychosocial stress did not affect the number of event-based PM responses in a study by Nater et al. (2006). However, in a time-based task, participants in the stress group gave more correct PM responses and showed an increased monitoring activity (i.e., checked a time counter clock more frequently) when compared to control subjects. Recently, Glienke and Piefke (2016) reported somewhat different results. They found enhanced event- and time-based performance (using a task developed to measure PM in a complex realistic situation) in subjects who encountered acute combined (physical-psychosocial) stressors.

In brief, there is no consensus under which circumstances and how stress affects different types of PM, if at all. The contribution of executive control in PM might resolve this controversy. To investigate this issue, following stress induction, we used one time-based PM task and two event-based PM tasks differing in executive control requirement. The rationale for using both event- and time-based PM tasks is that performing an intended time-based action always depends on executive control processes, whereas event-based PM tasks are suggested to be existing on a continuum between controlled and automatic processing (Gilbert, Gollwitzer, Cohen, Burgess, & Oettingen, 2009; Gilbert, Hadjipavlou, & Raoelison, 2013; Scullin, McDaniel, & Shelton, 2013).

Moreover, to acquire further evidence whether stress-related changes in PM performance is associated with altered executive control process, we applied a control task frequently used to measure executive functions. Due to the complex nature and multiple roles of executive control in prospective memory, we applied the letter fluency test which involves various executive processes, such as switching between effective strategies (Abwender, Swan, Bowerman, & Connolly, 2001; Troyer, Moscovitch, & Winocur, 1997), inhibition of responses that do not fit the requirements (McDowd et al., 2011), maintaining sets in working memory (Daneman, 1991), and self-monitoring to avoid repetitions (Phillips, 1997; see also Lezak, Howieson, Bigler, & Tranel, 2012).

In brief, the main purpose of the present study to examine PM performance following stress induction in tasks requiring different executive control demand. Executive control requirement was assessed by multiple measures, including ongoing cost in two event-based PM tasks, hit rate and monitoring behaviour in the time-based PM task, and letter fluency performance.

It is possible that stress exerts its effect on PM through executive control processes. In this case, stress should have an effect on performance depending on to what extent the task requires executive control processes (in the time-based PM task, certainly). Furthermore, we can also assume that, even with no evidence for a relationship between stress and those executive processes, which were involved in the PM tasks we used, stress can exert its effect on PM through altered associative memory processes. In this case, stress should have an effect on PM performance only in those (event-based PM) tasks where executive control processes are less loaded.

2. Materials and methods

2.1. Participants

Participants were 61 Hungarian undergraduate students (23 men; age range: 19–27 years; M_{age} = 21.7 years, SD = 1.9) who received extra course credits for their participation. Subjects were randomly assigned into either a stress (n = 30; 11 men; M_{age} = 21.6 years, SD = 1.9) or a control group (n = 31; 12 men; M_{age} = 21.7 years, SD = 2.0). Based on a self-reported questionnaire, participants had no history of any known psychiatric, neurological, or chronic medical problems. Participants were not on medication except for four subjects who were on contraception (three subjects in the stress group and one subject in the control group).[1]

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[1] When these four subjects were excluded from the sample the pattern of results did not change in either of the three PM tasks or on the letter fluency test.

All participants gave written informed consent. The study was approved by the United Ethical Review Committee for Research in Psychology, Hungary.

2.2. Prospective memory tasks

Three computer-controlled paradigms were used to measure PM performance: two tasks to test event-based PM and one task to measure time-based PM. In each task, subjects performed an ongoing task while they had to maintain a delayed intention: they had to execute a prospective response (had to press a key button) when a specific event happened (in the event-based tasks) or at a certain time point (in the time-based task).

2.2.1. Event-based prospective memory tasks

We designed two tasks with different stimuli to dissociate less and more controlled processes in PM cue identification (we refer to them as the *dot task* and the *digit task*, respectively). In both tasks, participants performed an ongoing task while they had to maintain a delayed intention (PM condition) or while they had no delayed intention to execute (baseline condition). The baseline condition was performed first in both tasks. The two tasks are illustrated on Fig. 1.

The ongoing task was a simple dual choice task in both the dot and the digit tasks. In the dot task, three dots were presented at random locations on the computer screen with only one constraint: two dots were presented on one side of the screen (left or right), whereas the third dot was shown on the other side of the screen. Participants had to indicate on which side of the screen two dots are located by pressing the corresponding key (the Left or the Right arrow key). In the digit task, two digits (ranging between one and nine) were presented on the screen located to the left and to the right of a fixation cross. Participants had to indicate the side on which the larger digit was presented again by pressing the corresponding key (the Left or the Right arrow key).

In the PM condition, an additional PM instruction accompanied the dual choice task. For both tasks, we defined a PM cue that was a specific arrangement of the stimuli and we instructed the participants to execute a PM response (pressing the Up arrow key) in case they encountered the PM cue. In the dot task, participants were instructed to execute the PM response if a continuous straight line could be drawn through the three dots, whereas in the digit task, the PM cue was the simultaneous presentation of two even digits. There were no PM cues in the baseline condition. Note that the identification of the PM cue in the dot task can be assumed as less controlled than in the digit task, as the different perceptual features of the stimulus configuration (three dots on a line) might have pop out with the minimal requirement of controlled processing. In contrast, identification of the PM cue in the digit task relied more on controlled effortful processing (the serial processing and comparison of the parity of the two digits), because the PM cue in the digit task was less salient than it was in the dot task.

For both tasks, the baseline condition contained 120 trials, whereas the PM condition contained 200 trials. In the latter case, in 15% of the trials (30 trials), a PM cue was presented. There were eight practice trials before the baseline condition, and there were 12 practice trials before the PM condition containing four PM cues. Furthermore, in the PM condition, there were no PM cues in the first and last five trials, and two PM cues never followed each other. Each trial started with a fixation cross presented for 500 ms, followed by the presentation of the task stimuli, which were on the screen either until a response or for 6000 ms.

Viewing distance was approximately 60 cm (the head of the participants was not fixed). The background colour was grey. The diameter of the dots was 1 cm (approximately 1° visual angle), whereas the size of the digits was 0.5 cm horizontally and 1.2 cm vertically (approximately $0.47^\circ \times 1.15^\circ$ in visual angle).

2.2.2. Time-based prospective memory task

The ongoing task was a quiz containing trivia questions with three response options (e.g., in what year did Neil Armstrong land on the moon). Participants responded by pressing the key corresponding to the respective response option (1, 2, or 3 on the numeric keypad). The questions together with the response options were presented in the centre of the screen. The size of the letters was 0.5 cm horizontally and 1.2 cm vertically ($0.47^\circ \times 1.15^\circ$ in visual angle). The background colour was white; the colour of the letters was black.

No baseline condition was applied and the PM instruction was given at the beginning of the task: participants had to press a specific key (the Up arrow key) at the beginning of every second minute (i.e., the 2nd, 4th, 6th, […], 14th, 16th minute, resulting in a maximum of eight PM responses). To check the time, participants could press the Space button, which caused the presentation of a digital time counter clock

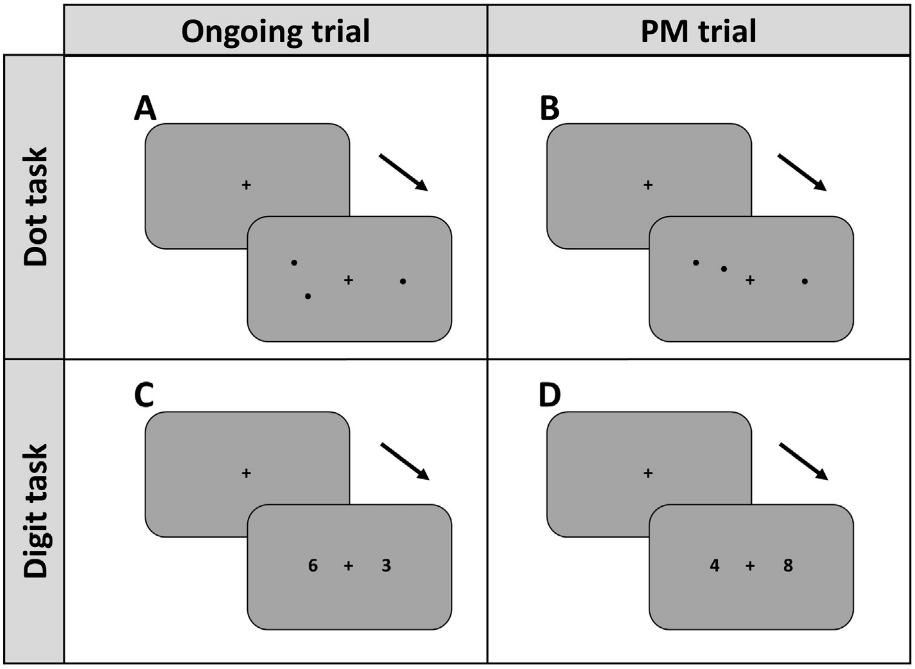

Fig. 1. Illustrations of the two event-based prospective memory tasks.
(A) An ongoing trial in the "dot task". Participants had to indicate on which side of the screen two dots are located. (B) PM cue presentation in the "dot task". Participants task was to execute the PM response (press of the Space button) when a continuous straight line could be drawn through the three dots. (C) An ongoing trial in the "digit task". Participants had to indicate the side on which the larger digit was presented. (D) PM cue presentation in the "digit task". Participants task was to execute the PM response (press of the Space button) when they saw two even digits on the screen.
Notes. In both tasks, each trial started with a fixation cross presented for 500 ms in the middle of the computer screen, followed by the stimulus presentation either until a response or for 6000 ms. (PM = prospective memory).

until the key was released. The presentation of the time counter clock did not stop the ongoing task. The clock appeared below the response options, its colour was yellow and its size was 2.5 cm horizontally and 1.2 cm vertically (2.40° × 1.15° in visual angle).

2.3. The letter fluency test

In the letter fluency task (Hungarian: Tánczos, Janacsek, & Németh, 2014) participants' task was to generate words beginning with specific letters. For each of three letters (K, A, L), subjects had 1 min to retrieve as many items, as they could. They were instructed not to say proper names and the same word with different endings. The experimenter recorded subjects' responses and checked the time elapsed.

2.4. Stress induction and control protocol

Participants in the stress group were exposed to the Socially Evaluated Cold Pressor Test (Schwabe, Haddad, & Schachinger, 2008), which was developed to induce acute combined (physical-psychosocial) stress in a laboratory setting. Their task was to immerse their non-dominant hand into ice cold (0–3 °C) water for 3 min. Subjects were told that they could interrupt the task (i.e., remove their hand from the water) in case the procedure would be too uncomfortable and/or painful. They were told that video recording would be made for later analysing their behaviour, however, no recording was actually made. Subjects had to perform the task in front of a female observer who passively monitored their behaviour without any comment and feedback.

There were no stress-inducing factors (ice cold water, video recorder, and observer) in the control condition. Participants in the control group were instructed to immerse their non-dominant hand into warm (35–37 °C) water for 3 min. The same female experimenter assisted as in the stress condition who stayed in the experimental room, but contrary to the stress condition, she did not observe subjects' behaviour.

2.5. Stress assessment

2.5.1. Saliva sampling

Free salivary cortisol levels and salivary alpha-amylase (sAA) activity are reliable markers of the activations of the HPA axis (see Kirschbaum & Hellhammer, 1994) and the sympathetic nervous system, respectively (see Nater et al., 2005). Therefore, saliva samples were collected from each participant at different points of the experiment (immediately before and then 15 and 32 min after the stress/control task). Samples were collected using Eppendorf Safe-Lock Tubes (1.5 ml) and were kept at −10 °C between the experimental session and the analysis. Free salivary cortisol concentrations and sAA activity were determined by using Salimetrics immunoassays.

2.5.2. Subjective ratings

Following each saliva sampling (immediately before and then 15 and 32 min after the stress/control task), subjects were asked about their current affective state. Participants rated on a scale (ranging from 0 = *not at all* to 100 = *very much so*) how stressful and unpleasant their current state was. Furthermore, 15 min after the stress/control procedure, participants were asked to rate on a scale (also ranging from 0 = *not at all* to 100 = *very much so*) how stressful, unpleasant, and painful they experienced the previous treatment (i.e., the stress or the control procedure).

2.6. General procedure

To eliminate the possible effects of certain factors on sAA activity and on free salivary cortisol levels, participants were asked to abstain from alcohol (see Badrick et al., 2007), physical exercise and smoking (see Kirschbaum & Hellhammer, 1994), as well as caffeine and meal (see Lovallo, Farag, Vincent, Thomas, & Wilson, 2006). In order to avoid any interference with the circadian rhythm-dependent change in daily sAA activity (Rohleder, Nater, Wolf, Ehlert, & Kirschbaum, 2004) and with the cortisol circadian cycle (see e.g., Clow, Hucklebridge, Stalder, Evans, & Thorn, 2010; Fries, Dettenborn, & Kirschbaum, 2009), the experimental sessions were run between 4 p.m. and 7 p.m.

In order to avoid any influence of potentially stress-inducing factors (e.g., new environment; see e.g., Lupien, et al., 2007) in the initial phase of the experiment, the experimental session was preceded by a 10-minute preparatory phase. During this preparatory phase, participants completed a questionnaire including questions on demographic data and any known psychiatric, neurological, and chronic medical problems. If subjects then still had time until the end of the preparatory phase, we gave them magazines to read. Then participants were exposed to either the stress inducing task or the control procedure that was followed by a 15-minute delay (in order to reach the cortisol peak, or at least close to it; see e.g., Kirschbaum & Hellhammer, 1994; Schwabe et al., 2008) while participants had the chance to read magazines alone in a quiet room.

Participants were presented with the three PM tasks and the letter fluency task in a counterbalanced order. In both experimental groups, half of the subjects were presented with the event-based PM tasks first with the letter fluency test between them (that took a total of 16 min), and this block was followed by the time-based PM task (that took a total of 16 min as well). The remaining participants were presented with the time-based PM task first, followed by the two event-based PM tasks (also with the letter fluency test between them).[2] The order of the two event-based tasks was also counterbalanced across the participants.

Saliva samples were collected three times. The first (baseline) sample was collected immediately before the stress/control task. The second sample was collected 15 min after stressor offset (immediately after the 15-minute delay following the stress/control treatment). The third sample was collected 32 min after stressor offset. If a subject was presented with the two event-based PM tasks first (with the letter fluency between them), the third sample was collected immediately after this block. If a subject was presented with the time-based PM task first, the third sample was collected immediately after that. Each saliva sampling was followed by the subjective rating of affective state.

3. Results

We used an alpha level of 0.05 for all statistical tests.

3.1. Validation of the stress induction

3.1.1. Salivary cortisol levels and salivary alpha-amylase activity

For salivary cortisol levels and also for sAA activity (see Fig. 2), a mixed-design ANOVA was conducted with Stress (Stress, Control) as a between-subjects variable and Time (t1 = baseline, t2 = 15 min after the stress/control task, t3 = 32 min after the stress/control task) as a within-subjects variable. During post hoc analysis, a series of independent samples *t*-tests was used for between-subjects comparisons and simple contrasts for within-subjects comparisons with baseline cortisol and sAA levels as reference points during contrast analysis. Due to technical errors, results of two participants (one subject in the stress group and one subject in the control group) were not included in cortisol analysis. For similar reasons, results of two control participants were not included in amylase analysis.

For cortisol levels, the ANOVA indicated significant main effects of Stress, $F(1, 57) = 4.42$, $p = 0.040$, $\eta_p^2 = 0.07$, and Time, $F(2, 114)$

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[2] There was no statistically significant difference in task performance between subjects who performed the event-based PM tasks first and subjects who performed the time-based PM task first.

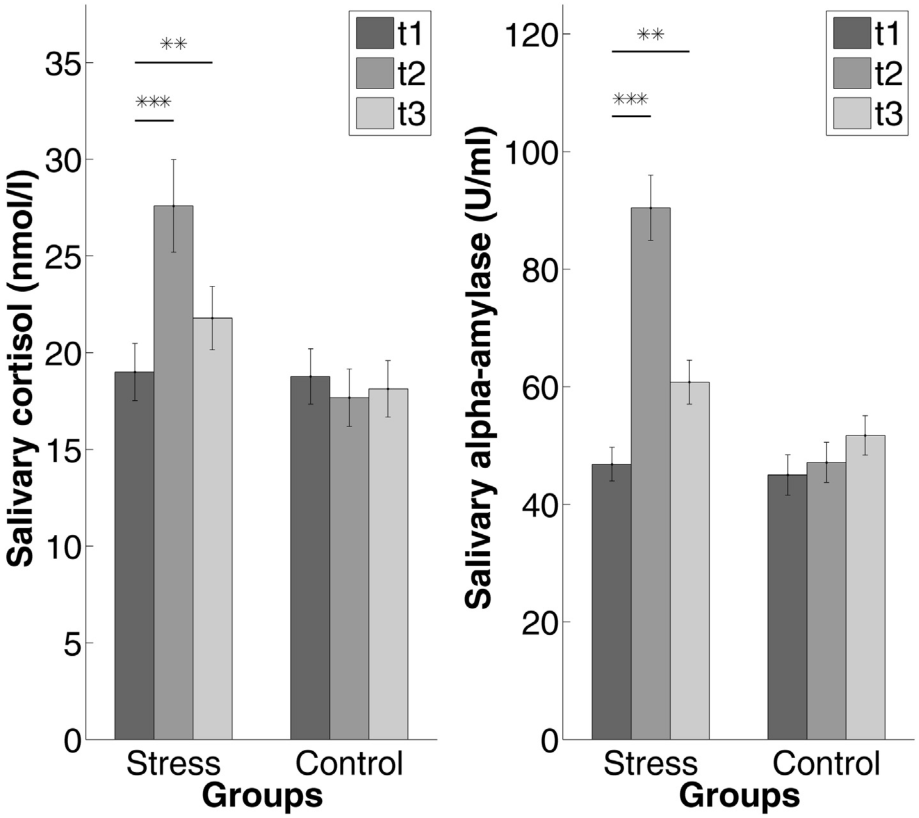

Fig. 2. Free salivary cortisol levels and salivary alpha-amylase activity at different time points of the experiment. Notes. ** Significant within-subjects difference at the level of $p < 0.01$; *** significant within-subjects difference at the level of $p < 0.001$; t1 = immediately before the stress/control task (baseline); t2 = 15 min after the stress/control task; t3 = 32 min after the stress/control task. Error bars represent the standard error of the mean.

$= 12.03, p < 0.001, \eta_p^2 = 0.17$, and a significant interaction between the independent variables, $F(2, 114) = 19.55, p < 0.001, \eta_p^2 = 0.27$. In comparison with the baseline level, stressed subjects showed an increased cortisol level at t2, $F(1, 28) = 24.93, p < 0.001, \eta_p^2 = 0.47$, and also at t3, $F(1, 29) = 8.48, p = 0.007, \eta_p^2 = 0.23$. In the control group, there was no statistically significant difference between the baseline level and cortisol levels at t2, $F(1, 29) = 1.85, p = 0.184, \eta_p^2 = 0.06$, and at t3, $F(1, 29) = 0.75, p = 0.394, \eta_p^2 = 0.03$. Cortisol concentration was higher in the stress group than it was in the control group at t2, $t(57) = 3.55, p < 0.001, d = 0.94$, but not at t1, $t(57) = 0.11, p = 0.910, d = 0.03$, and at t3, $t(57) = 1.67, p = 0.100, d = 0.44$.

For sAA activity, a similar pattern of results was found as for cortisol levels: the main effects of Stress, $F(1, 57) = 17.07, p < 0.001, \eta_p^2 = 0.23$, and Time, $F(2, 114) = 34.04, p < 0.001, \eta_p^2 = 0.37$, as well as the Stress x Time interaction, $F(2, 114) = 31.84, p < 0.001, \eta_p^2 = 0.36$, were significant. In comparison with their baseline levels, subjects in the stress group showed an increased sAA activity at t2, $F(1, 29) = 58.04, p < 0.001, \eta_p^2 = 0.67$, and also at t3, $F(1, 29) = 13.95, p = 0.001, \eta_p^2 = 0.33$. Such difference was not observed in the control group at t2, $F(1, 28) = 0.55, p = 0.465, \eta_p^2 = 0.02$, however, sAA level was higher at t3 than it was at t1 in the control group as well, $F(1, 28) = 6.71, p = 0.012, \eta_p^2 = 0.19$. When compared to the control group, stressed subjects had higher sAA level at t2, $t(57) = 6.60, p < 0.001, d = 1.75$, but not at t1, $t(57) = 0.41, p = 0.682, d = 0.11$, and at t3, $t(57) = 1.80, p = 0.077, d = 0.48$.

In brief, in comparison with their own baseline level, subjects showed increased salivary cortisol concentrations and sAA activity 15 and 32 min after they encountered physical and psychosocial stressors. Altogether, this pattern of results established the success of the stress induction.

3.1.2. Subjective ratings

Ratings on current affective states were analysed in a similar way as cortisol and sAA levels. Only the main effect of Time was significant for "stressful ratings", $F(2, 118) = 14.00, p < 0.001, \eta_p^2 = 0.19$. For "unpleasant ratings", the Stress x Time interaction was significant, $F(2, 118) = 9.53, p < 0.001, \eta_p^2 = 0.14$, with stressed subjects' higher ratings at t2 in comparison with ratings of the control group, $t(59) = 2.66, p = 0.010, d = 0.70$. Additionally, participants in the stress group rated the stress treatment as more stressful, $t(59) = 4.71, p < 0.001, d = 1.23$, unpleasant, $t(59) = 7.01, p < 0.001, d = 1.83$, and painful, $t(59) = 7.17, p < 0.001, d = 1.87$, in comparison with control subjects' ratings on the control procedure.

3.2. Prospective memory performance

3.2.1. Event-based prospective memory performance

To check whether the two event-based paradigms we used differed in executive functions requirement (as hypothesized), we compared RTs for the ongoing trials between the two tasks. An ongoing cost was determined for both tasks by calculating the difference between RTs for the ongoing trials in the PM condition and RTs for the ongoing trials in the baseline condition. The ongoing cost was higher in the digit task than it was in the dot task in both groups, stress group: $t(29) = 9.76, p < 0.001, d = 1.78$, control group: $t(30) = 9.06, p < 0.001, d = 1.63$. This result indicates that executive control processes contributed differentially to performance in the two event-based tasks we used.

In the second cycle of the analysis, we compared ongoing task performance between the two groups (Fig. 3a). Due to a high rate of correct responses (≥ 95% in each condition), we analysed only RTs by conducting mixed-design ANOVAs with Stress (Stress, Control) as a between-subjects factor and Condition (Baseline, PM) as a within-subjects factor. We conducted separate analyses for the two event-based PM tasks (instead of using Task [Dot task, Digit task] as an independent variable), because the instructions and stimuli were different in these two tasks. Results in the two event-based tasks showed similar patterns. We found significant main effects of Condition, dot task: $F(1, 59) = 234.46, p < 0.001, \eta_p^2 = 0.80$, digit task: $F(1, 59) = 328.03$,

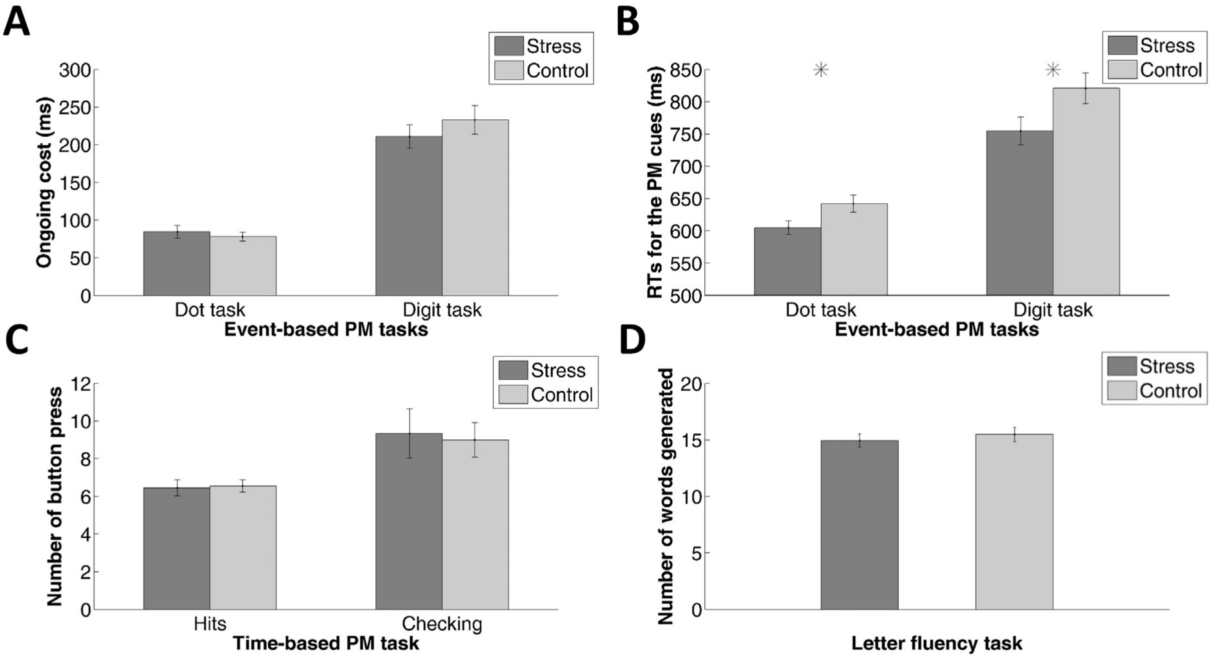

Fig. 3. Performance in the prospective memory tasks and on the letter fluency test.
(A) Ongoing costs in the two event-based PM tasks. (B) RTs for the prospective cues in the two event-based PM tasks. (C) Hits and monitoring activity in the time-based PM task. Hits: number of correct PM responses (press of the Up arrow key within the PM window). Monitoring: number of button press (press of the Space bar) when participants checked the time counter clock throughout the whole time-based PM task. (D) Mean number of words generated in response to the three key letters in the letter fluency task.
Notes. * Significant group difference at the level of $p < 0.05$. Error bars represent the standard error of the mean. RT = reaction time; PM = prospective memory.

$p < 0.001$, $\eta_p^2 = 0.85$, whereas neither the main effects of Stress, dot task: $F(1, 59) = 0.40$, $p = 0.531$, $\eta_p^2 = 0.01$, digit task: $F(1, 59) = 2.50$, $p = 0.119$, $\eta_p^2 = 0.04$, nor the Stress x Condition interactions, dot task: $F(1, 59) = 0.36$, $p = 0.551$, $\eta_p^2 = 0.01$, digit task: $F(1, 59) = 0.82$, $p = 0.369$, $\eta_p^2 = 0.01$, were significant. This pattern of results indicates that ongoing task performance did not differ between the stress and the control group either in the baseline or in the PM condition. Additionally, an ongoing cost could be detected in both tasks, as indicated by the lower response speed for the ongoing trials in the baseline than in the PM condition. Finally, and importantly, the magnitude of this ongoing cost was not influenced by stress in either of the two event-based tasks.[3]

To analyse whether stress induction had an effect on PM performance, at first, we analysed hit rates for the PM cues (dot task: stress group – $M = 89.7\%$, $SD = 6.4$; control group – $M = 84.4\%$, $SD = 15.3$; digit task: stress group – $M = 86.1\%$, $SD = 10.9$; control group – $M = 82.8\%$, $SD = 14.4$). We found no statistically significant group differences in hit rates, dot task: $t(59) = 1.74$, $p = 0.087$, $d = 0.45$, digit task: $t(59) = 1.01$, $p = 0.315$, $d = 0.26$.

Besides this pattern of hit rate data, RTs of correctly executed PM responses (Fig. 3b) differed between the groups, dot task: $t(59) = 2.15$, $p = 0.035$, $d = 0.56$, digit task: $t(59) = 2.05$, $p = 0.045$, $d = 0.53$. In other words, stressed subjects responded to the PM cues faster in comparison with a group of subjects who encountered a non-stressful control protocol.

As the ongoing cost is accepted to be a reliable measure of executive control requirement (see e.g., Cohen & Gollwitzer, 2008; Smith, 2003), we conducted an analysis on whether group differences (stress vs. control) in RTs for the PM cues remained significant while ongoing cost was used as a covariate. Group differences remained significant, dot task: $F(1, 58) = 6.50$, $p = 0.013$, $\eta_p^2 = 0.10$, digit task: $F(1, 58) = 4.25$, $p = 0.044$, $\eta_p^2 = 0.07$.

3.2.2. Time-based prospective memory performance

Due to technical errors, data of one subject (in the stress group) was not recorded in the time-based PM task. We conducted independent samples *t*-tests for hit rates and also for monitoring (i.e., checking) behaviour (Fig. 3c). Hit rate was calculated on the basis of the number of button press (press of the Up arrow key) within the PM window of 20 s (± 10 s) around the target time in every 2 min. Monitoring behaviour refers to the number of button press (press of the Space bar) when participants checked the time counter clock throughout the whole task. There was no statistically significant group difference either in hit rate, $t(58) = 0.18$, $p = 0.855$, $d = 0.05$, or in subjects' monitoring behaviour, $t(58) = 0.82$, $p = 0.413$, $d = 0.22$.

3.3. Performance on the letter fluency test

Few errors were made in the letter fluency task; thus, only correct responses were analysed. Participants generated words in response to three letters, and we averaged these three values (i.e., number of words generated) for each subject (see Fig. 3d). Then statistical analysis (independent-samples *t*-test) was conducted for this averaged value, and we found no significant difference between the groups, $t(59) = 0.63$, $p = 0.530$, $d = 0.16$.

4. Discussion

The aim of the present study was to examine the relationship between acute stress and PM. Furthermore, we aimed at investigating whether the effect of stress on PM is associated with altered executive control functioning.

The success of the stress induction was confirmed by increased free salivary cortisol concentrations and sAA activity as well as higher subjective ratings on negative affective state following combined

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[3] We found significant ongoing costs when we excluded post-PM trials indicating that executive control requirement was not limited around trials following successful PM responses. Additionally, we found no stress effects on RTs in the ongoing trials, when we excluded post-PM trials, indicating that the lack of stress effects on ongoing costs was not due to stress effects on after-effects of responding to the PM cue (for details on the after-effects of responding to PM targets, see e.g., Meier & Rey-Mermet, 2012).

(physical-psychological) stress exposure. Acute stress had no statistically significant impact either on time-based PM or on verbal fluency, whereas it affected event-based PM. Specifically, in the event-based PM tasks, stressed subjects showed faster response speed for the PM cues, whereas stress did not influence performance on the ongoing task. Importantly, the same pattern of results was found in both event-based PM tasks, indicating the robustness of our findings on the beneficial effect of acute combined stress on the execution of delayed intentions in situations where PM responses were initiated by external cues. It should be noted that although ongoing costs were different in the two even-based tasks, the fact that stress effects did not differ between the two tasks suggests that executive control demands might not differ between these two tasks.

Despite faster response speed for the event-based PM cues, stress did not affect executive control processes as indicated by different measures. First, stress did not affect the ongoing cost, which is known to be a reliable index of executive control requirement (see Smith, 2003). Second, stress had no statistically significant influence on time-based PM performance (either on hit rate or on checking behaviour) where the successful execution of a prospective response always involves executive control processes (see e.g., Guynn, 2008; Smith, 2003; Smith & Bayen, 2004). Finally, stress induction did not affect performance on the verbal fluency test, in a control task widely used to measure various executive control processes.

Interestingly though, most previous studies of acute stress effects focused on a relatively narrow range of executive processes (e.g., attentional shifting, inhibition, and manipulating information in working memory; see Shields et al., 2016), but not on monitoring or on complex executive functioning. Here we found no acute stress effects on ongoing costs in the two event-based PM tasks as well as correct responses and checking behaviour in the time-based PM task, suggesting that stress did not affect monitoring in PM, which dovetails with similar findings of unaffected monitoring in working memory (Starcke, Wiesen, Trotzke, & Brand, 2016). Furthermore, we found no statistically significant stress effect on performance in a complex executive task (letter fluency), which involves a wide range of executive control processes.

We suggest that, in our study, acute stress affected event-based PM via associative memory processes. First, we found a dissociation between performance in the event- and time-based PM tasks. Whereas in a time-based PM situation performing the intended action always depends on executive control processes in the absence of external cues, event-based PM can involve associative memory processes as well (Einstein & McDaniel, 1996; McDaniel & Einstein, 2000, 2007). We argue that, beyond executive control involvement, associative memory processes also contributed to performance in the two event-based PM tasks we used. According to several theorists, the contributions of control processes and of associative processes are not mutually exclusive; instead, they interact during prospective remembering. Therefore, event-based PM tasks can be described as existing on a continuum between controlled and automatic processing (Gilbert et al., 2013; Scullin et al., 2013). Second, we found significant stress effects when we controlled for control demand as indicated by the ongoing costs. Third, acute stress had an exclusive effect on response speed for the PM cues, and it has been demonstrated that automatic behaviour is reflected in decreased response speed for a given stimulus (e.g., Logan, 1988; Logan & Etherton, 1994; Verbruggen & Logan, 2008). In other words, when one forms a direct association between a cue and a response, retrieval becomes fast and automatic (even with no change in the number of correct responses). Finally, our results are in line with previous findings demonstrating that acute stress promotes the automatic, reflexive, and associative control of behaviour (Arnsten, 2015; Hermans et al., 2014; Schwabe & Wolf, 2013; Shields et al., 2016) and stimulus-driven attentional selection (Sänger, Bechtold, Schoofs, Blaszkewicz, & Wascher, 2014), and also with former studies demonstrating that automatic processes leads to better PM performance, rather than when the execution of a PM response is driven by more controlled strategies (Einstein et al., 2005). In sum, we suggest that acute stress prompted a shift to more automatic processing resulting in decreased response speed for the external PM cues in the event-based tasks.

According to the best our knowledge, only a few previous studies investigated the relationship between acute stress and PM (Glienke & Piefke, 2016; Nater et al., 2006; Walser et al., 2013), and our results are somewhat at odds with the earlier findings. The question arises whether the controversial results can be explained by methodological differences or by other attributes of these studies. Although Nater et al. (2006) and Walser et al. (2013) investigated acute stress effects using computerized PM paradigms similarly to us, they used only psychological stressors, whereas we applied a procedure developed to induce combined physical-psychological stress. This factor might be important, because it is known that physical and psychological stressors trigger the activations of the HPA axis and the sympathetic nervous system in a different way. Whereas physical stressors elicit the activation of sympathetic nervous system, they cause only moderate or no increase in cortisol (e.g., Duncko, Cornwell, Cui, Merikangas, & Grillon, 2007; Maruyama et al., 2012; McRae et al., 2006). Conversely, the presence of psychosocial stressors leads to higher cortisol elevations indicating the activation of the HPA axis (e.g., Maruyama et al., 2012; for a meta-analytic review, see Dickerson & Kemeny, 2004). Previous studies have pointed out that the simultaneous activations of the HPA axis and the sympathetic nervous system is needed to prompt a shift to the automatic control of behaviour (Schwabe, Höffken, Tegenthoff, & Wolf, 2011; Schwabe, Tegenthoff, Höffken, & Wolf, 2010, 2012). Consequently, since we used combined (physical-psychosocial) stressors, it might explain some diverging results of the present study and of previous studies that used only psychological stressors. In addition, physical, psychological, and combined stress situations differ in several aspects not only in the biological responses they trigger, such as differences in ruminative tendencies and motivation level following different stress procedures (see e.g., De Lissnyder et al., 2012).

One further important methodological difference is that Nater et al. (2006) and Walser et al. (2013) used focal event-based PM tasks (and found no stress effects on event-based PM), whereas we used non-focal event-based PM tasks. The PM task is focal when the task-inherent processing of the PM stimuli overlaps with the processing of the stimuli in the ongoing task (Einstein et al., 2005; McDaniel & Einstein, 2000). Since in non-focal PM situations there is no overlap between the relevant aspects of the ongoing and the PM cues, performing a non-focal PM task requires attention demanding executive control processes, rather than when one performs a focal PM task (Einstein et al., 2005). Based on our findings and the results of previous studies (Nater et al., 2006; Walser et al., 2013), it is possible that acute stress prompts a shift to the automatic control of behaviour only under a relatively high (or moderate) control demand. In other words, when one performs a focal PM task, it always involves associative memory processes and stress can prompt to a shift to automatic behaviour only in those (non-focal) tasks where executive control and associative memory processes interact during prospective remembering.

As a final remark, it should be noted that we have no data on our participants' smoking habits and weight, which could have affected the results (see e.g., Badrick, Kirschbaum, & Kumari, 2007; Gluck, Geliebter, & Lorence, 2004, respectively). Although we asked our participants not to smoke 2 h prior to the experimental session, general smoking habits and weight might diminish the comparability of our results to findings of previous studies.

5. Conclusion

In sum, according to our results, acute stress affected event-based PM performance (in terms of faster response speed for the PM cues) along with no evidence for acute stress effect on executive control. We suggest that, here, stress affected event-based PM via associative memory processes.

In addition to its theoretical importance, this pattern of results has implications for everyday life as well. There are several stressful situations when the delayed execution of intentions is particularly important. Fortunately, it seems that stress does not impair but rather improves PM under certain circumstances.

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