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Acute Psychosocial Stress Impairs Intention Initiation in Young but not Older Adults

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Abstract

Acute psychosocial stress has been shown to impair memory and cognitive control in young adults. So far, only very little empirical research is available concerning possible adult age differences in acute stress effects on cognition in general and cognitive control in particular. Accordingly, the present study set out to test these effects in a controlled laboratory setting comparing performance in a prospective memory task requiring the deployment of proactive cognitive control to successfully implement intentions. Sixty-six young (19-34 years) and 57 older adults (60-82 years) were either exposed to an established psychosocial stress procedure (Trier Social Stress Test) or an active control condition. Stress responses were measured on a fine-grained level across the entire procedure using subjective and physiological stress markers. Results suggest that the stress induction was equally successful in both age groups. While stress impaired prospective memory ability in young adults, it did not affect performance in the older adults. In particular, young adults under acute stress were more likely to completely fail the initiation of the prospective memory task resulting in zero performance. The missing stress effect on prospective memory in older adults is in line with previous studies examining broader mood effects on PM and suggests the exciting possibility that increasing age may act as a resilience factor against deterioration of cognitive control in emotionally challenging situations.

Keywords: prospective memory, cognitive control, stress, Trier Social Stress Test, aging

Stress and its influence on age effects in complex cognition is a highly relevant topic given the demographic ageing, numerous everyday burdens in modern society, and the importance of an intact cognitive functioning to ensure independence. Nevertheless, our understanding of how acute stress influences cognitive control in young and especially in older adults is still limited. The goal of the present research was therefore to tackle this research gap by examining how acute psychosocial stress influences cognitive control in young and older adults.

Cognitive control describes the ability to regulate, coordinate, and sequence thoughts and actions in accordance with internal goals (Braver, 2012). One situation which requires cognitive control is so called “prospective memory” (PM; Rummel & McDaniel, 2019). PM describes the ability to remember and realize a planned action at a particular moment in the future while being engaged in an ongoing activity (Ellis & Kvavilashvili, 2000). It has been identified as one of the most frequent everyday cognitive challenges (Haas, Zuber, Kliegel, & Ballhausen, 2020). Furthermore, it has been suggested to be particularly important in older adults, as it is related to independence in old age (Hering, Kliegel, Rendell, Craik, & Rose, 2018).

While no previous study examined acute stress effects on age-related PM, several studies tested acute stress effects on PM in young adults. Nater and colleagues (2006) found no stress effect on an event-based PM task (i.e., remembering to do something after the recognition of an external cue in the environment) and enhanced performance in a time-based PM task (i.e., remembering to do something at a certain time) under stress compared with a resting condition. Similarly, acute psychosocial stress did not influence event-based PM in more recent studies (Möschl, Walser, Plessow, Goschke, & Fischer, 2017; Möschl, Walser, Surrey, & Miller, 2019; Walser, Fischer, Goschke, Kirschbaum, & Plessow, 2013), despite biological and subjective stress responses in the stress groups compared to the control groups.

A study focusing on reaction times instead of PM accuracy (Szőllősi, Pajkossy, Demeter, Keri, & Racsmany, 2018) reported faster key presses for event-based PM cues under acute stress, while time-based PM was not affected by stress. The missing or even enhancing effects of acute stress on PM seem surprising given that meta-analyses report negative stress effects on different cognitive functions associated with PM like retrospective memory retrieval (Het, Ramlow, & Wolf, 2005; Shields, Sazma, McCullough, & Yonelinas, 2017), working memory, cognitive flexibility and interference control (Shields, Sazma, & Yonelinas, 2016).

One meta-analysis (Shields et al., 2016) further reports that task difficulty moderated stress effects on working memory: Stress effects were greater in difficult compared to easier tasks. We suggest that the difficulty of the PM task could similarly serve as a possible moderator of the relation between stress and PM. First studies on stress and PM used relatively simple ongoing task and PM cues that were processed in the course of the ongoing task. Such tasks might lack sufficient sensitivity for the detection of acute stress effects.

The present study therefore used a cognitively demanding PM paradigm. In addition, task difficulty was further varied within participants by manipulating the salience of the PM target cues. Salient cues have been argued to facilitate PM by involuntarily capturing attention and prompting a switch from the ongoing activity to the prospective cue (McDaniel & Einstein, 2000). Accordingly, PM in young and older adults was significantly enhanced if a cue was presented in a salient compared to a non-salient format (Cohen, Dixon, Lindsay, & Masson, 2003). Thus, general negative stress effects on PM were expected in the present study that should be more pronounced for non-salient PM cues.

Only a few studies have tested how acute stress interacts with age and affects cognition in young and older adults by experimentally manipulating stress in the laboratory using the Trier Social Stress Test (Kirschbaum, Pirke, & Hellhammer, 1993), a standardized psychosocial laboratory stressor. Hidalgo, Almela, Villada and Salvador (2014) examined stress and age effects on declarative memory using a verbal learning test. Stress did not influence learning, delayed recall and recognition, but there was an age by stress interaction on recall after interference. Specifically, performance was impaired under stress in the older, but not in the young adults. In a second study (Hidalgo et al., 2015), age and stress effects on the retrieval of emotional pictures were examined. Stress impaired free recall of emotional and neutral pictures only in the group of young men. Recognition of positive pictures was impaired under stress for both age groups and sexes. No age by stress interaction was also reported by a recent study on word retrieval (Schmank & James, 2020, Experiment 2) that reported similar impairments under acute stress in young and older adults.

Considering a range of different cognitive tasks, a recent study (Crosswell, Whitehurst, & Mendes, 2021) further showed no stress effects on cognitive flexibility and problem solving in young and older adults, while short-term memory was reduced following the TSST compared to control conditions in both age groups. Another study (Dierolf et al., 2018) focusing on response inhibition in men measured with a Go/No-Go task also found no age by stress interaction. However, young and older adults in the stress condition actually performed better than controls in the easier condition of an overall challenging task.

Interestingly, studies in animals and humans suggest that the aging brain should be especially vulnerable to acute stress effects (Lupien, McEwen, Gunnar, & Heim, 2009). Especially areas that are essential for performing complex cognitive tasks such as the frontal lobe seem to be negatively affected by acute stress during human aging (Dai, Buijs, & Swaab, 2004). Accordingly, one would predict that cognitive performance in older adults is more strongly impaired by acute stress than performance in young adults. However, the behavioural research summarized above suggests a more complex pattern as the effects of stress on age-related cognition seem to differ depending on the specific cognitive outcome variable. The goal of the present study was therefore to investigate, whether different effects of stress on PM can be observed in younger and older adults.

Thus, contradictory predictions are possible concerning interaction effects between stress and age. Neurophysiological research would suggest greater cognitive vulnerability towards acute stress effects in older adults that should result in stronger PM impairments under acute stress compared to young adults. However, empirical studies suggest that older adults are not always more strongly impaired than young adults or even reported an age benefit. Accordingly, Hidalgo, Pulopulos, and Salvador (2019) conclude in their recent review that acute stress does not seem to impair retrospective memory retrieval and working memory in older adults which is in contrast with findings in young adults (Shields et al., 2020). It can therefore be expected that PM will only be impaired by acute stress in young adults.

Method

Participants and Design

The sample included 123 adults, 66 young (M_{age}= 24.55 years, *SD* = 3.87, age range: 19-34 years; 31 men) and 57 older volunteers (M_{age}= 69.17 years, *SD* = 4.25, age range: 60-82 years; 26 men). Gender was equally distributed within the two age groups, χ^2 (df = 1) = 0.02, p = .88. All young adults were undergraduate students from the University of Geneva who volunteered in exchange for partial course credit or a monetary reward of CHF30. The older adults received monetary compensation (CHF40) for their participation. Participants had normal or corrected-to-normal vision. Exclusion criteria were history of or current mental health problems. Further exclusion criteria were physical complaints and intake of medication (e.g., oral contraceptives) influencing the physiological stress responses measured in the current study. All older adults had to gain a score of 27 or higher in the Mini-Mental State

Examination (MMSE; Folstein, Folstein, & McHugh, 1975) to exclude age-related cognitive impairments.

Young (*M* = 1.52, *SD* = .50) and older adults (*M* = 1.56, *SD* = .54) did not differ in self-rated health, *t*(121) = -0.49, *p* = .62, as measured with a 4-point Likert scale (1 = very good; 4 = very poor), but young adults (*M* = 36.27, *SD* = 7.52) reported significantly higher levels of perceived stress during the month prior to the testing than older adults (*M* = 32.63, *SD* = 7.27), *t*(121) = 2.72, *p* = .008, as measured with the Perceived Stress Scale (PSS; Cohen, Kamarck, & Mermelstein, 1983). Most participants were non-smokers (82%). The amount of smokers did not differ between sex or condition groups (*p*s ≥ .078), but a higher percentage of young adults (25%) reported to smoke compared to the percentage of smokers within the older adults (11%), *p* = .043. Men (*M* = 23.81, *SD* = 3.97) had higher self-reported BMIs than women (*M* = 23.07, *SD* = 3.70) and the BMI was generally higher in older (*M* = 24.32, *SD* = 4.12) compared to young adults (*M* = 22.00, *SD* = 2.92), *p*s ≤ .022, while BMI between conditions did not differ (*p* = .357).

In terms of general cognitive abilities, the two age groups differed in both crystallized and fluid intelligence in the anticipated directions. Crystallized intelligence was assessed with the French version of the Mill Hill vocabulary test (Deltour, 1993) in which older adults (*M* = 27.26, *SD* = 4.00) attained significantly higher scores than young adults (*M* = 22.53, *SD* = 5.63), *t*(121) = -5.30, *p*< .001. Fluid intelligence was indexed using the Digit-Symbol-subtask from the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008) with young adults obtaining significantly higher scores (*M* = 85.15, *SD* = 13.13) than older adults (*M* = 59.55, *SD* = 12.19), *t*(119) = 11.03, *p*< .001.

Participants were asked to abstain from excessive physical activity within 48 h prior to their study visits, any sports activities within 24 h, intake of alcohol and caffeine within 18 h, and eating within 60 min before study participation.

The study was approved by the local ethics committee and conducted in accordance to ethical standards of the 1964 Declaration of Helsinki. The participants were randomly assigned to the stress or the control condition. Thus, the study followed a 2 (age: young vs. old) x 2 (experimental manipulation: stress vs. control) x 2 (PM target: salient vs. non-salient) mixed-design. An a priori power analysis ($\alpha = .05$, power = .80) using G*Power indicated that a sample of 120 is large enough to detect medium-sized interaction and main effects.

Materials

Stress induction. To induce stress, participants in the stress condition were exposed to the Trier Social Stress Test (TSST; Kirschbaum et al., 1993), a standardized stress-induction protocol consisting of a public speaking and a mental arithmetic task in front of a committee and a video camera preceded by an anticipatory period (total time: 20 min). The protocol was initially developed for use in young adults and was slightly adapted for the older adults in the present study. In particular, for the public speaking task, young adults were asked to imagine that they apply for the job of their dreams. We asked older adults instead to imagine that they apply for a volunteering position at a charity focusing on a topic that is dear to their heart. Further, we slightly adapted the difficulty of the mental arithmetic task. While young adults were asked to count backwards in steps of 17 starting from 2043 as suggested in previous studies, older adults were asked to count backwards in steps of 13 starting from 1023. Participants of the control group underwent a standardized control situation strongly matching the TSST, but lacking its stress-inducing features (Het, Rohleder, Schoofs, Kirschbaum, & Wolf, 2009).

Stress validation. To determine salivary α-amylase (sAA) and cortisol stress responses, saliva samples were collected with Salivette sampling devices (Sarstedt, Sevelen, Switzerland). The saliva samples were analyzed in singlets. However, as a standard procedure QC saliva samples were run in duplicates. The inter-assay coefficient of variation was 5.4%. Saliva samples were taken at seven measurement time-points (60, 30, and 10 min before, and 1, 10, 20, and 30 min after end of either treatment). For sAA analysis, we applied a quantitative enzyme-kinetic method (cf. Rohleder & Nater, 2009). Salivary free cortisol was analysed using a commercial chemiluminescence immunoassay (IBL, Hamburg, Germany).

Subjective stress levels were assessed using the negative affect scale from the Positive and Negative Affect Scale (PANAS; Watson, Clark, & Tellegen, 1988) at exactly the same seven measurement time-points as the saliva samples. Furthermore, participants were asked to rate the stressfulness of the TSST or the control situation, respectively, before and directly after experiencing it using the Primary Appraisal Secondary Appraisal scale (PASA; Gaab, Rohleder, Nater, & Ehlert, 2005) and two visual analogue scales (VAS) (see Appendix A for further information and analyses).

PM task. A classical dual-task PM paradigm was used in which the PM task is embedded in an ongoing task. In the ongoing task, participants were presented with an n-back working memory task. Upper case consonants surrounded by a coloured frame were displayed one by one on a computer screen. With each display a new letter with a differently coloured frame was shown. Participants were asked to decide whether or not the present consonant has occurred ‘n’ (i.e., two) stimuli ago by pressing one of two highlighted buttons on the keyboard. In the course of the n-back task, 25% of all stimuli presented were hit items.

For the PM task, participants were instructed to remember to press another highlighted button when the colour frame appeared in one of two predefined colours (i.e., yellow and blue). The cue salience was varied within participants by manipulating the font of the coloured frames depicting the PM target cues. Half of them were standard frames as all other frames appearing during the ongoing task, while the other half was printed in bold.

There were 160 trials containing 12 PM target cues (i.e., six salient and six non-salient ones). After half of the trials, there was a short break of one minute before the task continued automatically. PM cues and n-back hit items never occurred at the same time. Each stimulus was presented for 500 ms and followed by the appearance of a black screen with a fixation cross for 2500 ms.

Procedure

Individual testing took place between noon and 7pm. As acute glucose availability represents a pre-condition for the stress-related increase of HPA-axis activity (Kirschbaum et al., 1997), all participants were asked to drink 200 ml grape juice at the beginning of the session.

After signing consent forms and filling in the socio-demographic questionnaire, the initial stress level was measured with the first PANAS and saliva sample. The older adults were asked to perform the MMSE afterwards. All participants continued with the Digit-Symbol-Task, followed by the Mill Hill vocabulary test. Then participants filled in the PSS and performed another stress measure. Instructions for the n-back task were given, followed by two practice runs. The first consisted of ten trials. Stimuli were shown slower than in the later task (i.e., 3000 ms) and feedback was provided. Participants had to perform 80 % correct in this first training run; otherwise they had to repeat it until they reached the criterion. The second training run comprised 20 trials using the same presentation times as in the later task without any feedback. Afterwards, participants completed an ongoing-task only block comprising 80 trials. The instructions for the PM task followed. Participants were given a break of five minutes, before the instructions for the TSST or the control condition were given. Participants' stress level was measured for the third time and they were asked to answer the PASA. They could use the remaining time to prepare for the upcoming situation. Exactly ten minutes after receiving the instructions, the TSST or the control situation had to be performed followed by another stress measurement and the VAS. Exactly ten minutes after the TSST/ control situation, participants completed another stress measure. Next, the experimenter started the PM task. Immediately after the task, participants completed a sixth stress measurement. At the end of the experiment, participants recalled which key they were supposed to press in response to a PM target and which colours indicated a PM response. Finally, participants completed a last stress measurement. They were debriefed and received their monetary reward. The whole session lasted approximately 120 min.

Analytic strategy

Stress validation. Since the residuals for cortisol and sAA were not normally distributed, mixed ANOVAs with condition (stress vs. control), age (young vs. old) and sex (male vs. female) as between-participants factors and stress measurement time-point as within-participants factor (seven levels) were computed on logarithmized cortisol and sAA data[1] (Miller & Plessow, 2013) and the negative affect scores from the PANAS. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity whenever the assumption of sphericity had been violated. The mixed ANOVAs allowed to analyse changes in physiological and subjective stress levels over the time-course of the experiment. Given the observed group differences concerning smoking status and BMI reported above, both factors were entered as covariates in the analysis on cortisol. However, since both covariates were not associated with cortisol levels, we dropped them from the final analysis reported below.

PM performance. Two analytical approaches were used to examine PM performance since an initial exploration of the data showed that it was right skewed and overdispersed with excessive observations of zeros (Zuur, Ieno, Walker, Saveiev, & Smith, 2009) indicating that a considerable amount of participants failed to perform the PM task at all. As a result, two outcome variables were computed for PM performance: a dichotomous variable for PM ability (i.e. the ability to successfully perform the PM task at least once; 0 = failed to perform the task at all, 1= successfully performed the task at least once) and a continuous variable for PM accuracy (i.e. the mean accuracy across all PM trials for participants who were able to perform at least one PM trial successfully).

The dichotomous variable PM ability included data from all participants and was examined by a logistic regression model (Field, Miles, & Field, 2012; see Appendix B for the model equation). The logistic regression model predicts the probability of successful PM ability as a function of between-subject factors: experimental manipulation (stress vs. control) and age group (young vs. old).

The continuous variable PM accuracy comprised only participants who carried out at least one PM trial correctly. By doing so, the mean accuracy data became normally distributed and could be analysed by a linear mixed effects model (Field et al., 2012; see Appendix C for the model equation). The linear mixed effects model examined PM accuracy as a function of between-subject factors: condition, age group and within-subject factor: PM cue salience (salient vs. non-salient). In addition to the fixed effects, random effects were included in the model to account for the correlation between participants' performance in the salient and non-salient PM cue conditions. Since young participants reported higher chronic stress than older adults, PSS scores were entered as covariates in both models. However, since PSS scores were not significantly associated with PM ability or accuracy, we report the analyses without the covariates below. Similarly, we tested if sex was associated with PM but dropped the covariate since sex was not associated with PM ability or accuracy[2].

Ongoing-Task performance. A linear mixed effects model (see Appendix D for the model equation) was used to analyse the effects of between-subject factors: condition, age group and the within-subject factor: block type (ongoing-task only vs. ongoing-task in PM block) on participants' ongoing task performance accuracy. Random effects were added to the model to account for the correlation between performance in the ongoing-task only and the ongoing-task during the PM block within participants.

Results

Stress Induction Measures

Physiological Stress Responses: Cortisol. Main effects of stress measurement time-point, F (1.90, 194.16) = 6.36, $p = .002$, $\eta_p^2 = .06$, and condition, F (1, 102) = 4.96, $p = .028$, $\eta_p^2 = .05$, were qualified by a significant interaction of both factors, F (1.90, 194.16) = 25.33, $p < .001$, $\eta_p^2 = .20$. There was also a main effect of sex, F (1, 102) = 12.91, $p < .001$, $\eta_p^2 = .11$. There was no main effect of age and no further interactions between any of the factors, all ps $\geq .082$. Participants in the stress conditions showed higher cortisol values after the stress induction until the end of the testing session than the controls (see Figure 1). Men showed higher cortisol levels ($M = 1.04$, $SD = .21$) than women ($M = .89$, $SD = .23$).

Physiological Stress Responses: sAA. Main effects of stress measurement time-point, F (5.12, 511.57) = 31.12, $p < .001$, $\eta_p^2 = .24$, and condition, F (1, 100) = 5.10, $p = .026$, $\eta_p^2 = .05$, were qualified by a significant interaction of both factors, F (5.12, 511.57) = 3.48, $p = .004$, $\eta_p^2 = .03$. No other main or interaction effect reached significance, all ps $\geq .078$. Participants in the stress conditions showed higher sAA values than the controls directly after the stress induction (see Figure 2).

Subjective Stress Measures: PANAS. There were main effects of stress measurement time-point, F (3.81, 430.85) = 23.43, $p < .001$, $\eta_p^2 = .17$, and condition, F (1,

113) = 9.12, $p = .003$, $\eta_p{}^2 = .08$. There was also a significant interaction effect between time-point and condition, F (3.81, 430.85) = 11.51, $p < .001$, $\eta_p{}^2 = .09$. Looking at Figure 3, this effect reflects that participants in the stress condition reported higher levels of negative mood after the stress induction than participants in the control condition after the control situation. The main age effect and the interaction between age and condition did not reach significance, both ps ≥ .273. The time-point x condition x age interaction reached significance, F (3.81, 430.85) = 3.78, $p = .006$, $\eta_p{}^2 = .03$. However, contrasts only revealed a trend for a significant interaction when comparing young and older participants in the stress and control conditions at T1 compared to T7, F (1, 117) = 3.63, $p= .059$, $r = .17$. Older adults go back to their baseline mood level, while young adults start in a more negative mood than older adults, but then report a slightly better mood at the end of the testing session (see Figure 3). Concerning sex, there was a significant interaction between sex and condition, F (1, 113) = 4.04, $p = .047$, $\eta_p{}^2 = .04$, while the sex main effect and no interaction between sex and the other factors reached significance (all ps ≥ .164). Following up on the interaction, the only significant difference was higher negative affect in women compared to men in the stress condition at the very first baseline measurement, F (1, 60) = 4.15, $p = .046$, $\eta_p{}^2 = .07$. However, to avoid an inflated type I error rate, the alpha level for the interpretation of the follow-up analyses should be set at .007 according to the number of performed tests (i.e. .05/7 = .007).

Stress Effects on Cognitive Performance

PM performance

PM ability. The logistic regression model revealed a significant effect of condition, $\chi^2(1) = 7.03$, $p = .008$. There was no main effect of age and no interaction between condition and age group, $ps \geq .39$. As shown in Figure 4, further analyses testing separately for the two age groups demonstrated that the significant main effect of condition resided in young adults only, ($b = -1.55$, $z = -2.42$, $p = .02$). Acute stress decreased the odds of successful PM ability by 51% in young adults and made them 0.21 times (OR = 0.21 [-2.93, -0.36]) less likely to perform the PM task at least once in the stress ($n_{stress} = 13$) condition compared to the control ($n_{control} = 4$) condition. In contrast, acute stress had no substantial impact on older adults' PM ability, ($n_{control} = 4$, $n_{stress} = 8$, $b = -0.74$, $z = -1.08$, $p = .28$).

PM accuracy. The linear mixed effects model yielded a main effect of cue salience on PM accuracy, $\chi^2(1) = 16.36$, $p < .001$. Performance was significantly higher in the salient compared to the non-salient PM target condition, $b = -.10$, $t(90) = -2.40$, $p = .02$, $r = .25$ (see Figure 5). There were no other significant main effects of condition, age group nor interaction between these three factors, all $ps \geq .30$. Further separate analyses were conducted for the two age groups showing that the significant main effect of cue salience was observed for both young adults, $\chi^2(1) = 13.15$, $p < .001$ and older adults, $\chi^2(1) = 4.33$, $p = .04$.

Ongoing Task performance

Accuracy. There was a main effect of age group, $\chi^2(1) = 16.09$, $p < .001$, as young adults ($M = 80.25\%$, $SD = 18.18$) significantly outperformed older adults ($M = 69.96\%$, $SD = 18.99$), $b = -.10$, $t(119) = -2.38$, $p = .02$, $r = .21$. Additionally, there was a significant main effect of block type, $\chi^2(1) = 49.88$, $p < .001$. Across age groups, participants showed significantly better performance in the ongoing-task only block ($M = 82.63\%$, $SD = 19.19$) compared with the dual-task block ($M = 68.33\%$, $SD = 17.55$), $b = -.15$, $t(119) = -4.35$, $p < .001$, $r = .37$. There was no effect of condition and no interaction among the three factors, all $ps \geq .25$.

Discussion

The present study was the first to target possible age differences in acute stress effects on PM. Even though the results did not show an interaction between condition and age, further hypotheses-driven analyses within each age group suggest that acute stress impaired cognitive control in young, but not in older adults. More precisely, young adults were less likely to perform the PM task at least once under acute stress compared to controls. However, considering only participants who performed the PM task at least once in at least one of the two salience conditions, there was no significant stress effect on PM accuracy in neither age group. Ongoing task accuracy was not influenced by stress, but only by age. As expected, young adults outperformed older adults.

It is important to note that all participants were able to correctly recall the PM task instructions before the TSST/ control situation and following completion of the PM task. Thus, reduced PM ability in young adults under acute stress cannot be explained by retrospective forgetting of the task instructions. Participants knew what to do but still struggled to implement the delayed intention. Since there were no stress effects on ongoing task performance, it also seems unlikely that the PM ability impairment under stress can be explained by changes in underlying monitoring behavior. Future studies are needed to clarify the processes underlying the observed behavioral impairment. Adding neuropsychological tests and interindividual difference measures could further help to define the subgroup of young adults who struggled with intention initiation under stress by testing if they are characterized by higher anxiety, poorer stress regulation skills or lower cognitive resources.

In the present study, stress did not affect PM in older adults. This is in line with former research showing that older adults' recall (Hidalgo et al., 2015; Pulopulos et al., 2013), working memory (Murphy et al., 2020; Pulopulos et al., 2015) and other executive functions such as cognitive flexibility (Crosswell et al., 2021) were not impaired under acute stress. Further, it is in line with studies examining broader mood effects (i.e. sadness and happiness compared to a neutral mood control condition) on age-related PM (Pupillo, Phillips, & Schnitzspahn, 2021; Schnitzspahn et al., 2014) which observed the exact same pattern of a PM impairment in the emotional mood conditions in the young, but not in the older adults.

The missing interaction between age and condition on PM is in line with other recent studies (Crosswell et al., 2021; Dierolf et al., 2018; Schmank & James, 2020). We believe that it might be explained by insufficient power to detect a small interaction effect. Due to a lack of comparable studies when planning the current one, we calculated the sample size based on the assumption of medium-sized interaction and main effects. However, given the present results and reported effect sizes in other recent studies (e.g. Crosswell et al., 2021), small- to medium-sized interaction effects seem more reasonable and should be used to calculate sample sizes for future research. Yet, the present study still presents with a sample size that is larger or comparable with other ageing studies in experimental cognitive stress research (see Crosswell et al. 2021; Dierolf et al., 2018; Hidalgo et al., 2014; Schmank & James, 2020).

Our two age groups did not differ in their physiological stress reactions or in their self-reported negative mood after the stress/ control situation. The missing stress effect in the older adults can therefore not be explained by a weaker stress reaction. As described in Appendix A, the only age differences related to the stress experience were observed in two subscales of the PASA measuring anticipatory appraisal processes. Specifically, young adults assessed the upcoming TSST situation as more threatening and challenging than the older adults. However, importantly, statistically controlling for the anticipatory appraisal by entering the questionnaire scores as covariates in the main analyses on PM performance did not change the reported pattern of stress effects and the covariates were not associated with PM ability and accuracy. Thus, age differences in the pre-evaluation of the situation do not seem to explain the differential stress effects on PM in young and older adults.

The absent stress effect in the older adults may seem surprising given that old adulthood has been suggested to be a period in which the brain is especially sensitive to stress or more precisely towards the stress-related cortisol rise based on former studies in animals and humans (Lupien et al., 2009). However, further research is needed before strong conclusions on age-related changes of the stress vulnerability in the human brain can be drawn. A first study testing cortisol effects on different cognitive abilities in young and older adults (Wolf et al., 2001) showed that cortisol administration similarly impaired retrospective memory recall and did not influence attention in both age groups. Most interestingly, age differences only emerged for working memory which was impaired by cortisol administration in young but not older adults. Another pharmacological study examining only a group of older adults (Porter, Barnett, Idey, McGuckin, & O'Brien, 2002) reported no cortisol effects on attention, working memory, declarative memory and executive function supporting the general idea that the aging brain may be less sensitive to acute effects of cortisol on memory due to a loss and/or dysfunction of corticoid receptors (Heffelfinger & Newcomer, 2001).

In line with former studies (e.g., Walser et al., 2013), the present study was designed in a way that the PM task took place ten minutes after the TSST or control situation, respectively, when the cortisol rise was expected to reach its peak (Dickerson & Kemeny, 2004). The physiological data confirmed a slow cortisol rise. In contrast, as expected, the SNS showed a rapid activation reflected by the sAA peak directly following the stressful situation and was already strongly decreased and not significantly different from the baseline anymore when the PM task started. Similarly, participants in both age groups only reported higher levels of negative mood directly following the TSST compared with the control situation, while they already reported a rather neutral state ten minutes later when the PM task started. It might be interesting to consider possible effects of the immediate stress-related changes in mood and SNS activity on cognitive control in different age groups in future studies, as the release of adrenalin and noradrenalin following increased SNS activity has also been suggested to impair prefrontal cortical functioning (Ramos & Arnsten, 2007).

Previous studies testing acute stress effects on PM in young adults (Möschl et al., 2017; Möschl et al., 2019; Nater et al., 2006; Walser et al., 2013) did not find an influence of stress on PM performance, while the present results suggest a stress-related PM impairment in the young adults. The PM task used in the present study was clearly more difficult than the ones used in former research. The present finding therefore supports the idea that the difficulty of the PM task could serve as a possible moderator of the relation between stress and PM and that only cognitively demanding PM tasks produce sufficient performance variability to detect acute stress effects (Shields, 2020). One previous study on stress and PM manipulated ongoing-task difficulty (Möschl et al., 2019) in order to increase PM task difficulty, but still resulted in overall high PM performance of 72% correct. Further, the study by Möschl et al. (2019) asked participants to perform the same PM task before and after the stress induction. It has been shown that practicing a cognitive task alters how stress influences it and that stress effects on tasks measuring executive control can even be reversed if the task is practiced (Shields, 2020). The present study therefore did not ask participants to perform the PM task before the stress induction which may explain why we observed impairing stress effects on PM in young adults in contrast to Möschl et al. (2019).

While the task difficulty manipulation within the present PM task was successful, as can be seen by the significantly better performance for salient compared to non-salient PM target cues across age groups and conditions, the observed stress effects on PM in the young adults were not significantly stronger for non-salient compared to salient cues. This is in line with a former study on working memory (Schoofs et al., 2008) observing similar stress-related impairments in 2- and 3-back tasks. Maybe task difficulty manipulations must be more extreme to observe differential stress effects.

From a methodological perspective, it is worth mentioning that the older adults in the present study were not stressed by the lab situation or the cognitive task demands per se, as those in the control condition did not differ from their younger counterparts in their cortisol response or their subjective mood ratings. Both measures stayed on a low level throughout the testing session. This result is important given that it has been argued that the laboratory environment and the anticipation of a cognitive testing might already increase cortisol levels in older adults causing difficulties to conduct stress studies in different age groups and interpret findings of lab-based cognitive aging research (Lupien, Maheu, Tu, Fiocco, & Schramek, 2007). Further research is needed to replicate our finding, but the present results support an earlier study (Ihle et al., 2014), suggesting that the testing situation and lab-based tasks in the domain of PM are not stressful per se for participants from different age groups.

From an analytical perspective, it is worth noting that we are not the only study reporting an absence of stress effects on PM accuracy, while observing stress effects on other parameters of PM such as PM response speed (Szőllősi et al., 2018), PM consistency (Glienke & Piefke, 2016) or PM monitoring (Möschl et al., 2017, 2019). Previous studies (Möschl et al. 2019) concluded that acute stress may only affect sub-components in PM tasks, while other components remain unaffected. Our results add that some participants are especially vulnerable to fail PM initiation completely under acute stress. Taken together, these findings highlight the need to include different markers of cognitive behavior in future studies in order to fully understand who is affected by acute stress and how.

In line with previous literature (Hidalgo et al., 2019), men had overall higher cortisol levels in the present study, while there were no sex differences in sAA. For both physiological stress markers, there were no interactions between sex and age or sex and condition. Most importantly for the present research goal, sex was not associated with PM performance. Thus, the present data suggests that the higher cortisol levels in men were not affected by our experimental and quasi-experimental manipulations and did not impact PM performance. Nevertheless, future studies should continue to consider sex differences, as studies in young adults suggest that they sometimes influence acute stress effects on cognition (Hidalgo et al., 2019) and we do not have enough data in older adults yet to allow strong conclusions. While women taking oral contraceptives were not included in the present study, we did not control for menstrual cycle phase in our young female participants and did not ask our older female participants about their menopause or potential hormone replacement therapies. Given reported effects of menstrual cycle phase and hormone replacement therapies on cortisol stress responses (Kudielka, Hellhammer, & Wüst, 2009), future studies should control for these factors.

To sum up, the present study suggests that acute psychosocial stress impairs cognitive control in young, but not older adults. In particular, acute stress impaired young adults’ ability to initiate a PM response and perform the PM task at least once. The missing stress effect in the older adults cannot be explained by reduced stress reactivity or a different evaluation of the stressful situation. Future studies should examine if the present age differences are caused by age-related changes in the frontal lobes and a reduced sensitivity to acute cortisol elevations in the older adults. Independent of the underlying mechanisms, the stability of PM performance under emotionally challenging situations observed in the group of older participants raises the question whether increasing age may act as a resilience factor against stress-induced deterioration of cognitive control functioning.

Footnotes

[1] Using the raw instead of the logarithmized cortisol and sAA data did not change the pattern of our findings.

[2] Controlling for stress perceived during the month prior to the testing by entering PSS scores (Cohen et al., 1983) as a covariate in the main analyses on PM performance did not change the reported pattern of acute stress effects. Similarly, entering sex as a covariate did not change the reported pattern of PM performance either.

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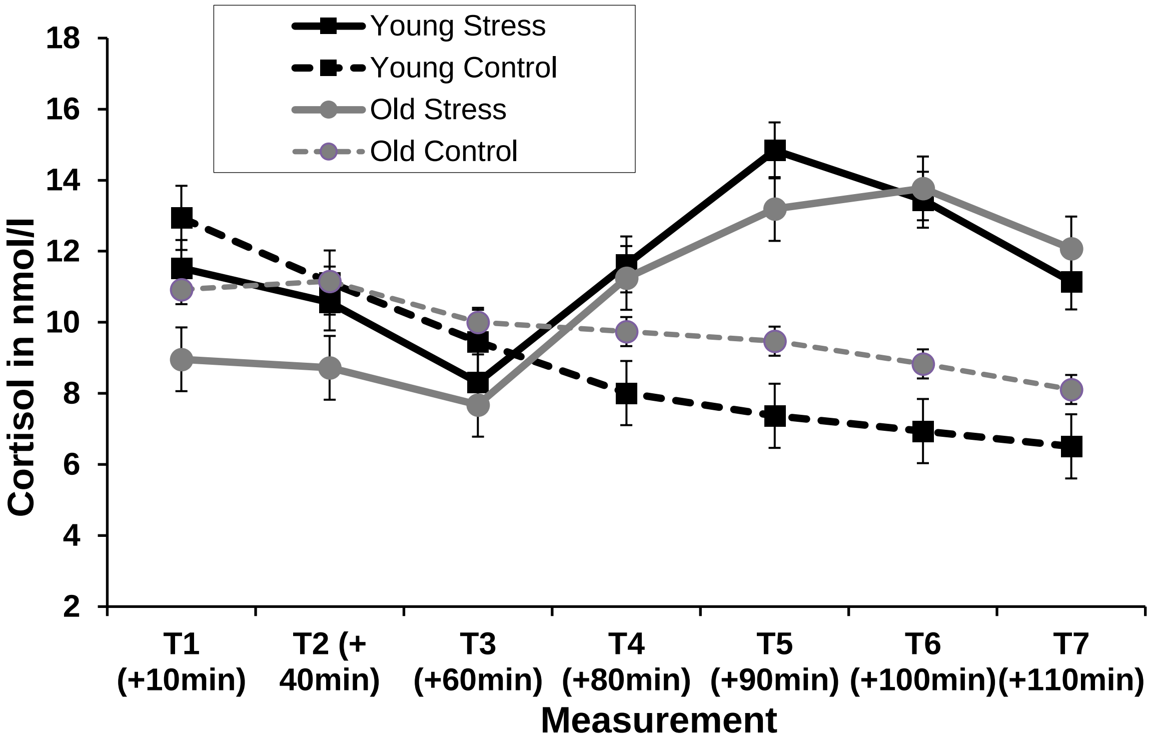

Figure 1. Mean cortisol levels by stress condition and age group across sample intervals. Analysis of log-transformed cortisol levels revealed that baseline values (T1) did not differ between control and stress groups, but diverged after the stress manipulation (T4) and before the start of the PM task (T5) similarly in young and older adults. Raw cortisol values used in display; error bars represent SEMs.

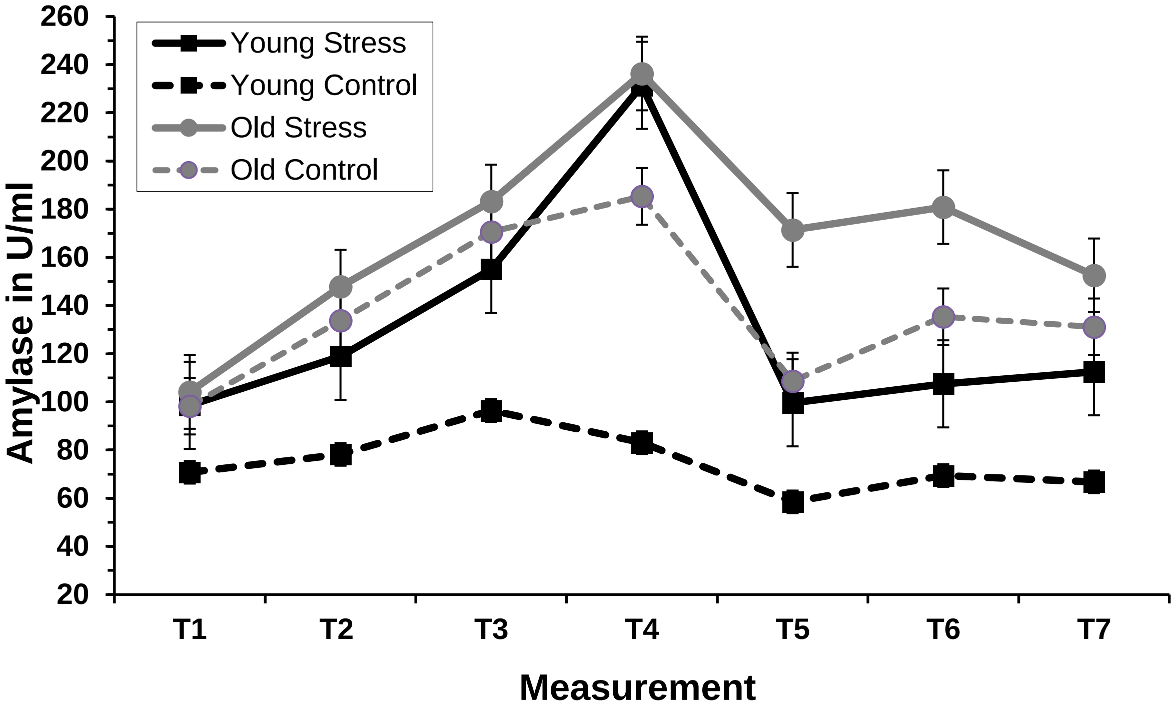

Figure 2. Mean amylase levels by stress condition and age group across sample intervals. Analysis of log-transformed amylase levels revealed that baseline values (T1) did not differ between control and stress groups, but diverged after the stress manipulation (T4) similarly in young and older adults. Raw amylase values used in display; error bars represent SEMs.

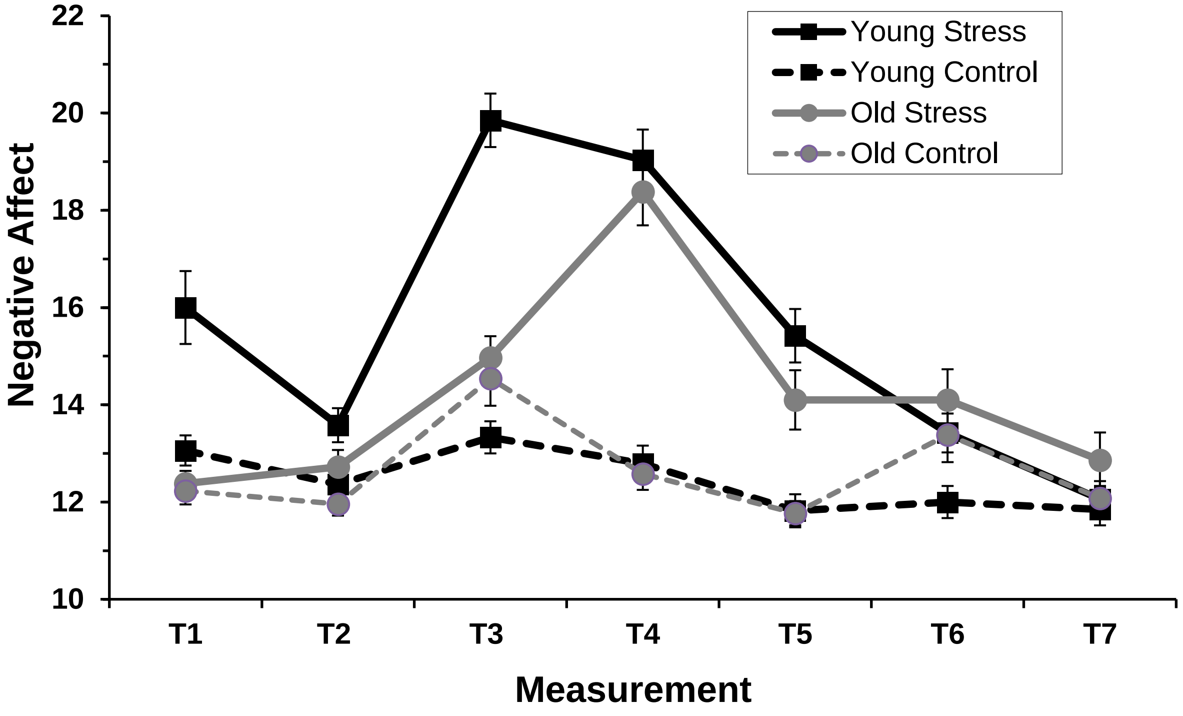

Figure 3. Mean negative affect levels by stress condition and age group across sample intervals. Analysis revealed that baseline values (T1) did not differ between control and stress groups, but diverged after the stress manipulation (T4) similarly in young and older adults. Error bars represent SEMs.

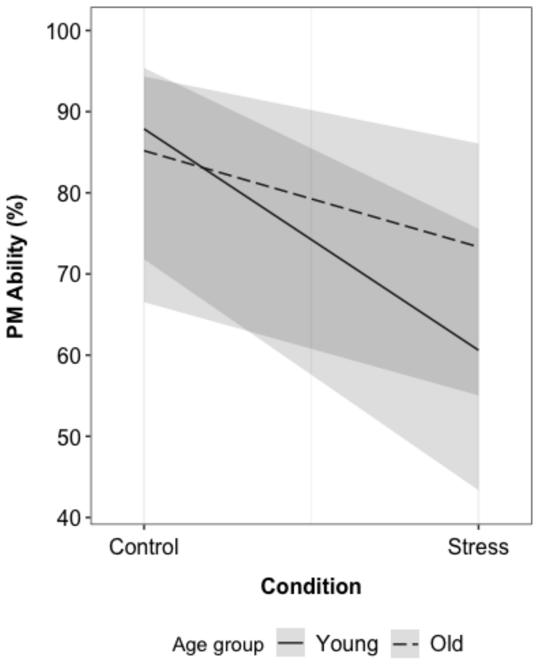

Figure 4. PM ability performance (probability of performing the PM task at least once) in both age groups as a function of condition. The shaded areas represent the 95% confidence intervals.

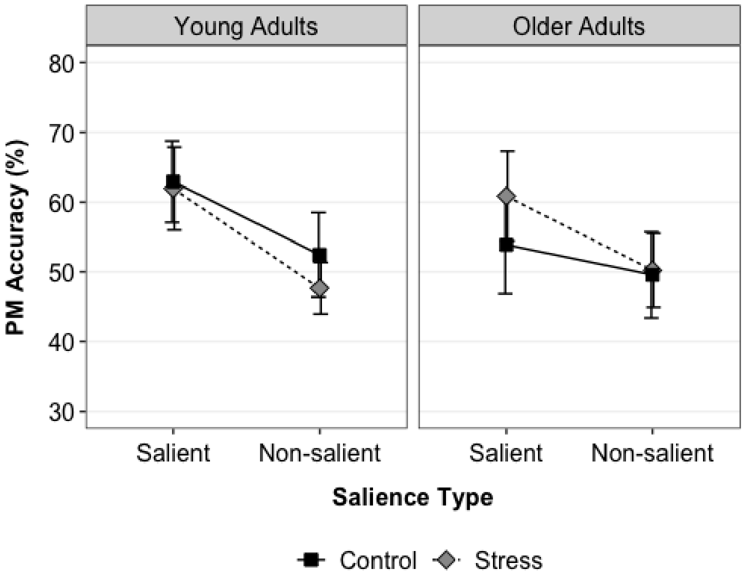

Figure 5. PM accuracy performance (percentage of correct PM trials) in both age groups as a function of condition and PM target cue salience. The error bars represent the SEMs.

Appendix A

Subjective evaluation of TSST/ control situation

Participants were asked to rate the stressfulness of the TSST or the control situation, respectively, before and directly after experiencing it. Before the situation, the Primary Appraisal Secondary Appraisal scale (PASA; Gaab, Rohleder, Nater, & Ehlert, 2005) was used. The questionnaire assesses primary (i.e., threat and challenge) and secondary (i.e., ability and control) anticipatory cognitive appraisal processes. To assess the stressfulness and controllability of the situation after experiencing it, two visual analogue scales (VAS) were used ranging from 0 to 100.

The PASA and VAS scores were each submitted to a 2 x 2 ANOVA with condition (stress vs. control) and age (young vs. old) as between-participants factors to examine whether the stress and the control situation were evaluated as anticipated.

PASA. For the threat subscale score, main effects of age, F (1, 110) = 5.73, p = .018, ηp^2 = .05, and condition, F (1, 110) = 13.93, p < .001, ηp^2 = .11, were qualified by a significant interaction of both factors, F (1, 110) = 8.45, p = .004, ηp^2 = .07. Young adults (M = 2.98, SD = 1.28) rated the situation as more stressful than older adults (M = 2.53, SD = 1.06). Further, participants in the stress condition (M = 3.15, SD = 1.29) rated the situation as more stressful than participants in the control condition (M = 2.38, SD = 0.95). Exploring the age x condition interaction, further analyses were conducted separately for the two age groups. They revealed a significant main effect of condition for young adults, t (64) = 5.01, p < .001, d = 1.24, but not for older adults, p= .329. Specifically, young adults in the stress condition (M = 3.64, SD = 1.14) rated the situation as more stressful than participants in the control condition (M = 2.34, SD = 0.95), while there were no significant threat evaluation differences between condition groups in the older adults.

For the challenge subscale score, there was a main effect of condition, F (1, 110) = 12.02, p = .001, $\eta p^2 = .10$ and a significant interaction between age and condition, F (1, 110) = 3.96, p= .049, $\eta p^2 = .04$, while the age effect did not reach significance, p = .205. Participants in the stress condition (M = 3.85, SD = 0.98) rated the situation as more challenging than participants in the control condition (M = 3.24, SD = 0.86). Exploring the age x condition interaction, further analyses were conducted separately for the two age groups. They revealed a significant main effect of condition for young adults, t (63) = 3.63, p = .001, d = 0.90, but not for older adults, p= .206. Specifically, young adults in the stress condition (M = 4.07, SD = 1.08) rated the situation as more challenging than participants in the control condition (M = 3.20, SD = 0.83), while there were no significant challenge evaluation differences between condition groups in the older adults.3

For the ability subscale score, there was only a main effect of condition, F (1, 110) = 4.62, p = .034, $\eta p^2 = .04$, all other ps> .126. Participants in the control condition reported a stronger self-concept of own abilities (M = 4.28, SD = 0.77) compared with participants in the stress condition (M = 3.92, SD = 1.00).

For the control subscale score, no effect reached significance, all ps > .208.

VAS. For the scale assessing stressfulness of the situation, there was only a main effect of condition, F (1, 110) = 47.29, p< .001, $\eta p^2 = .30$, all other ps > .126. Participants in the stress condition (M = 65.96, SD = 25.91) rated the situation as more stressful than participants in the control condition (M = 31.49, SD = 27.80).

For the scale assessing controllability of the situation, there was only a main effect of condition, F (1, 110) = 23.60, p < .001, $\eta p^2 = .18$, all other ps> .616. Participants in the control condition (M = 68.00, SD = 27.78) reported higher controllability of the situation than participants in the stress condition (M = 42.46, SD = 28.21).

Controlling for primary anticipatory cognitive appraisal processes by entering scores from the PASA subscales assessing threat and challenge as covariates in the main analyses on prospective memory (PM) performance did not change the pattern of acute stress effects reported in the manuscript. The PASA subscales were further not associated with PM ability or accuracy.

Appendix B

The logistic regression model estimates the odds of successful PM ability as a function of condition and age group by comparing the probability of the zero ($y = 0$) against the non-zero values ($y = 1$) in the outcome variable. It is denoted as:

$\text{Logit}(P(Y_{ikj} = 1)) = \beta 0_{ik} + \beta 1(\text{Condition=placebo})_{ij} + \beta 2(\text{Age=younger adult})_{kj}$

$\beta 3(\text{Condition=placebo})_{ij} \text{ X } (\text{Age=younger adult})_{kj} + \varepsilon_{ikj}$

Let $\text{Logit}(P(Y_{ikj} = 1))$ be the log odds of successfully responding to at least one PM cue for participant *j* in condition *i* and age group *k*, β0 is the intercept, β1, β2 and β3 are the covariate vectors to the fixed effects for condition *i* and age group *k* and the interaction between them respectively.

Appendix C

The linear mixed effects model predicts the accuracy performance of the PM task:

$Y_{iklj} = \beta 0_{ikl} + \beta 1(\text{Condition=placebo})_{ij} + \beta 2(\text{Age=younger adult})_{kj} +$

$\beta 3(\text{Salience=salient})_{lj} + \beta 4(\text{Condition=placebo})_{ij} \text{ X } (\text{Age=younger adult})_{kj} \text{ X}$

$(\text{Salience=salient})_{lj} + b_l(\text{Salience=salient})_{lj} + \varepsilon_{iklj}$

Where Y_{iklj} denotes participant *j*’s mean scores for PM accuracy in condition *i*, age group *k* and salience *l*, Coefficients β_1, β_2, β_3, and β_4 indicate the fixed effect for participant *j* in condition *i*, age group *k*, salience *l*, and the interaction between condition *i*, age group *k* and salience *l* respectively. The b_l coefficient is the random effect for salience *l* and the error term ε_{iklj} is participant’s deviation from the intercept.

Appendix D

The linear mixed effects model predicts the performance of the ongoing task:

$Y_{iklj} = \beta_{0ikl} + \beta_1(\text{Condition=placebo})_{ij} + \beta_2(\text{Age=younger adult})_{kj} + \beta 3(\text{Block=ongoing-task})_{lj} + \beta 4(\text{Condition=placebo})_{ij} \text{ X } (\text{Age=younger adult})_{kj} \text{ X } (\text{Block=ongoing-task})_{lj} + b_l (\text{Block=ongoing-task})_{lj} + \varepsilon_{iklj}$

Let Y_{iklj} be the average score for ongoing task performance accuracy for participant *j* in condition *i*, age group *k* and block type *l*, β_1, β_2, β_3, and β_4 are the fixed effect coefficients for participant *j* in condition *i*, age group *k*, block type *l*, and the interaction between condition *i*, age group *k* and block type *l* respectively. b_l is the random effect coefficient for block type *l* and ε_{iklj} is the error term which indicates participant's deviation from the intercept.