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Effects of Acute Stress on Cognition in Older Versus Younger Adults

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Does acute stress differentially alter cognitive functioning in older versus younger adults? While older adults may be better at handling stress psychologically, their physiological systems are less elastic, potentially impairing the cognitive functioning of older adults after a stressor. We examined cognition following an acute stressor among older (n = 65; ages 60–79) and younger (n = 61; ages 25–40) adults. Participants were randomized to complete the Trier Social Stress Test (TSST) in one of three conditions: (a) negative feedback, (b) positive feedback, or (c) no feedback. Participants reported mood states and appraisals of the speech task and we measured cortisol via saliva throughout the study. After the TSST, participants completed standard cognitive tasks to evaluate cognitive flexibility, problem solving, and short-term memory. Results showed that after the TSST, older adults took longer to solve problems compared with younger adults, though they were able to solve the same number of problems. Older adults showed less cognitive flexibility compared with younger adults in all conditions, a finding that was partially exaggerated in the positive feedback condition. There were no age-group differences in short-term memory; however, for older adults greater perceived resources and positive affect were associated with better memory performance. In sum, older and younger adults were both affected by acute stress, and older adults were not more (or less) vulnerable to the effects of stress on cognition, though they did show stronger associations between self-reported affective states and memory performance.

Keywords: Acute stress, aging, cognition, psychological appraisal

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In normal aging, the ability to quickly and efficiently perform executive functions declines (Cabeza, 2002). Executive functions are a set of higher-order cognitive processes that enable purposeful, goal-directed, and future-oriented thinking and action (Suchy, 2009). These cognitive components are guided by neurobiological processes centered in the prefrontal cortex (Miller & Cohen, 2001) and are vital for effective problem solving, planning, and successfully navigating the complex social world. Neuropsychological studies show that healthy older adults fair worse on executive function tasks compared with younger adults, and neurobiological studies show that declines in the frontal lobes are more pronounced across aging than in other cortical areas (Bryan & Luszcz, 2000; Buckner, 2004; Gunning-Dixon & Raz, 2003; Podell et al., 2012).

Acute stress may further exacerbate age-related cognitive deficits. Under acute stress, physiological systems focus their neural reserves toward supporting an organism's survival, which likely leads to fewer resources and/or less energy for the complex cognitions associated with executive functioning (de Kloet et al., 2005). Indeed, studies (Butts et al., 2011; Qin et al., 2009; Starcke et al., 2016) including a meta-analysis (Shields et al., 2016) have found that experiencing acute stress impairs some (but not all) aspects of executive functioning (for exception see Yuen et al., 2009). The impairments that emerge may be due to the increased release of catecholamines and glucocorticoids, like norepinephrine and cortisol, from the limbic system during acute stress. While these neurochemicals support adaptive acute stress responses, they also have a U-shaped relationship with complex executive functions, where sub- or supraoptimal levels of each compound weaken performance on specific cognitive domains (Arnsten, 2009).

Importantly, our ability to respond quickly to external stressors may diminish as we age, as indicated by increased physiological rigidity (Charles, 2010; Fried et al., 2004; Kuchel, 2017). Some argue that the rigidity in the aging system may also impair cognitive abilities during and after a stressor (McEwen & Sapolsky, 1995), whereas others suggest that these conditions will preserve performance via reduced sensitivity to stress neurochemicals (Pulopulos et al., 2015). A handful of studies have examined executive function during or after acute stress in older adults compared with younger adults, with some evidence showing that older adults' performance is resilient to acute stress, some implicating performance detriments, and some demonstrating that age does not moderate the stress-cognition relationship (Hidalgo et al., 2014; Lighthall et al., 2013; Pulopulos et al., 2013, 2015; Qin et al., 2009; Smith et al., 2019). There is yet to be consensus regarding the effects of acute stress on executive functions, potentially because age effects have not been carefully considered.

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In contrast to the evidence that suggests neurobiological limitations might hinder older adults' cognitive performance, there is also behavioral research suggesting that older adults may perform better on cognitive tasks post-stress. Specifically, older adults may differ in their psychological response to acute stressors (Gaffey et al., 2016; Mather, 2012; Otte et al., 2005). The socioemotional selectivity theory suggests that as we age, we become better at handling the psychological aspects of being in acutely stressful social situations (Blanchard-Fields, 2007), which may, in turn, downregulate physiological reactivity. For example, compared with younger adults, older adults utilize more strategies that de-escalate conflict in interpersonal tensions (Birditt et al., 2005; Charles & Carstensen, 2008), have higher levels of baseline positive mood, which may provide a buffer to the negative emotions acute stressors can induce (Mroczek & Kolarz, 1998), are quicker to return to a positive state after experiencing a brief dip in mood (Carstensen et al., 2000), and tend to avoid processing of negative stimuli (Mather, 2012). Reduced negative affect in response to acute stress may also allow for better decision-making as feedback processing (ability to update learning based on input received in the moment) is not interrupted by emotional processing (Akinola & Mendes, 2012; Preston et al., 2007). Together, this suggests that older adults may engage top–down control when encountering acute stress, which may facilitate better performance on complex cognitive tasks.

The direction of the effect of acute stress on cognitive performance may also depend on the emotional and psychological states the acute stressor induces and the cognitive domain being measured. The Broaden-and-Build Theory of Positive Emotions (Fredrickson, 2001) suggests that negative emotional states narrow a person's focus of attention in order to promote quick and decisive action in the face of threat. Positive emotional states, on the other hand, are proposed to broaden a person's momentary thought–action repertoire, allowing novel unscripted paths of thought and action to freely form. Thus, negative emotional states may lead to enhanced performance on tasks that are detail oriented and require intense focused attention, while positive emotional states may lead to enhanced performance on tasks that require divergent thinking such as problem solving or creativity. Empirical evidence supports these hypotheses, with studies linking negative affect to narrowing of attentional focus (Lang et al., 1990) and positive affect to increasing the scope of visuospatial attention and divergent thinking (Baas et al., 2008), though there is still considerable debate (e.g., see the debate over mood states and creativity; Davis, 2009). Given this theoretical perspective and initial empirical evidence, it is possible that the emotional and psychological state of an individual during an experience of high arousal, like an acute stressor, may influence cognitive performance during and after the stress experience.

Furthermore, inducing high arousal positive versus negative emotional states can induce differential physiological activation patterns. These differential patterns (termed "threat" vs. "challenge" states; Blascovich & Tomaka, 1996) have been characterized in a series of lab-based psychophysiological studies, in which cardiovascular and hypothalamic–pituitary–adrenal axis responses have been measured in tandem (Jamieson et al., 2012; Kassam et al., 2009). Most relevant for understanding the role of acute stress on cognitive function is that threat states are characterized by relatively high concentrations of cortisol, whereas challenge states show lower levels (e.g., Koslov et al., 2011). Glucocorticoids have long been hypothesized to play an essential role in the relationship between stress and cognitive performance. Given the U-shaped relationship between glucocorticoids and performance, high concentrations can compromise functioning in portions of the hippocampus (Lupien et al., 1998; Meaney et al., 1995) and the prefrontal cortex, which are essential to memory (Squire, 1992) and executive functioning (O'Shea et al., 2016).

The purpose of this study was to investigate how age influences performance on cognitive flexibility, problem solving, and short-term memory following an acute stress task. We conducted this study in two age groups: younger adults (25–40 years old) and older adults (60–80 years old). We employed the Trier Social Stress Test (TSST; Kirschbaum et al., 1993) as our acute stress manipulation, and participants were randomized to one of three conditions. Based on previous studies that manipulated challenge versus threat states (high arousal with either positive or negative affect, respectively; Akinola & Mendes, 2008; Kassam et al., 2009; Koslov, et al., 2011), we manipulated the evaluators presence or feedback as follows: (a) evaluators provided negative feedback; (b) evaluators gave positive feedback; or (c) no evaluators were present (participants completed the task alone). This third, control condition, controls for the metabolic and cognitive demands of delivering an extemporaneous speech without triggering the social evaluation and resulting physiologic responses of the other two conditions, (Akinola & Mendes, 2008). After instructions for the TSST were given, participants reported on their appraisals of the task—how demanding they thought it would be, whether they believed they had the resources to successfully handle the challenge, and their level of positive and negative affect. After the TSST, participants completed a short-term memory task as well as measures of cognitive flexibility and problem solving. Cortisol reactivity was measured via four saliva samples collected throughout the laboratory session.

Based on previous research we hypothesized a main effect of age, with older adults compared with younger adults having a slower reaction time when switching cognitive sets, being better at problem solving, and no age-group differences in short-term memory. Our second hypothesis was that performance on the cognitive tasks would differ by acute stress condition such that cognitive flexibility would be enhanced in the positive feedback condition (because of a broadening of perspective and increased divergent thinking), problem solving would be enhanced in the negative feedback condition (because of an increase in deliberative thinking), and short-term memory would be impaired in the negative feedback condition (because of increases in cortisol, which interferes with hippocampal and prefrontal cortex functioning). We did not have clear directional hypotheses regarding the interaction of age and acute stress given the various literatures. On the one hand, homeostatic capacity approaches might argue that acute stress would be especially harmful to older adults who might lack the physiologic elasticity to respond efficiently, whereas affective theories might predict a more resilient response to stress among older than younger adults. We also conducted exploratory analyses to examine associations between psychological appraisals of the task and cognitive performance, as well as the influence of cortisol reactivity on cognitive performance to determine if these relationships were moderated by age.

Methods

Participants

One hundred and twenty six healthy younger ($n = 61$; mean age = 31, $SD = 5$, range = 25–40; $n = 32$ women) and older ($n = 65$; mean age = 66, $SD = 5$, range = 60–79, $n = 35$ women) community members were recruited from the Boston, Massachusetts, area. Participants were randomly assigned to one of three conditions described in detail below: negative feedback condition ($n = 42$; $n = 21$ older and $n = 21$ younger adults), positive feedback condition ($n = 40$; $n = 20$ older and $n = 20$ younger adults), and the control condition ($n = 44$; $n = 24$ older and $n = 20$ younger adults). Inclusion criteria were English speaking, normal or corrected vision and hearing, and no use of corticosterone or other medication that would affect neuroendocrine responses. All participants signed informed consent and the study was approved by the Committee on the Use of Human Subjects at Harvard University, which serves as the Institutional Review Board (study F12882). We did not conduct a formal a priori power analyses but instead based our target sample size on previous studies examining effects of stress on cognition (Shields et al., 2016). We planned to recruit 120 total participants and oversample by 5% for some expected data loss.

Procedures

Participants were scheduled in the afternoon (between the hours of 12 and 5) to control for the diurnal cycle. Upon arrival at the laboratory they read and signed a consent form. After being given 20 minutes (min) to acclimate to the lab environment, participants provided an initial saliva sample (T1). They then took the first part of the Wechsler Memory Scale Logical Memory task (Story A), which is a measure of short-term memory, and completed the Backward Digit Span task, which served as a pre-stressor measure of working memory. Participants were then randomly assigned to one of three acute stress conditions. In all conditions participants completed the TSST, during which participants gave a speech and completed serial subtraction (Kirschbaum et al., 1993). In both experimental conditions, participants were told they would be performing in front of two evaluators whereas in the control condition participants were told they would perform the task in an empty room with no operating cameras or intercom system. Based on previous research, the two experimental conditions were designed to induce different affective and physiological responses (Akinola & Mendes, 2008; Kassam et al., 2009; Koslov et al., 2011).

Participants assigned to the negative feedback condition completed the TSST in front of a panel of two evaluators (one male; one female). During the task these evaluators displayed negative nonverbal feedback cues to evoke social evaluative threat in the participants(e.g. rolling their eyes, sighing, and shaking their heads at the participant as they gave their speech). This technique has been shown to reliably increase negative affect and activate stress-related physiological systems like the hypothalamic–pituitary adrenal cortical axis (HPA) and the sympathetic nervous system (Akinola & Mendes, 2012; Kassam et al., 2009; Koslov et al., 2011). Participants assigned to the positive feedback condition completed the same TSST with evaluators who provided positive feedback, such as nodding, leaning forward, and smiling at the participant. This approach has yielded lower threat appraisals, less negative emotional reactions, faster cortisol recovery, and less cardiovascular threat responses than the negative feedback condition (Akinola & Mendes, 2008; Kassam et al., 2009; Koslov et al., 2011). Participants assigned to the control condition completed the same TSST in a room alone, with instructions delivered to participants by an experimenter who then left the room during the completion of the speech and serial subtraction task.

Immediately following the TSST, participants completed a series of cognitive assessments with a trained research assistant they had not yet met. These assessments were the Wechsler Memory Scale delayed recall subtest, the Delis–Kaplan Executive Function System Sorting Test, and the Tower of London, in that order. Poststressor saliva samples were obtained at 20, 40, and 60 min after the start of the stress task.

Acute Stress Task Details

The task began by having participants spend 5 min preparing to give a speech. In standard TSST tasks, the speech topic is often a mock interview and people are asked to convey their qualifications for a "dream job." We modified the content given job interviews might lack self-relevance for the older participants. Thus, in this study the topic of the speech was chosen by the participant from the following list: social security reform, the cost of prescription drugs, education reform, and the rising cost of gasoline. These topics were chosen because pilot testing indicated that individuals, from both age groups viewed these topics as important and self-relevant. In the negative feedback condition, once the participant was 30 sec into their speech, the evaluators' facial expressions and body language gradually changed from neutral to negative and rejecting. Similarly, in the positive feedback condition, the evaluator's facial expression and body language changed from neutral to positive.

After the speech participants were asked to count backward in steps of 7, starting at the number 3996, as fast and as accurate as possible for 5 min. In the control condition, all instructions were the same, but there were no evaluators in the room. The three conditions were matched such that the timing, priming of task content, and metabolic demands of giving a speech were the same. The three conditions differed on the critical factor of the feedback the participants received from the evaluators. Varying the feedback can alter the type of stress, affective response, and associated psychological experience, with negative feedback inducing feelings of social evaluative threat, positive feedback inducing feelings of social acceptance, and the no social evaluation condition as a control.

Acute Stress Appraisals and Mood Questionnaires

After the TSST instructions, but before beginning the stress task, participants completed a questionnaire that assessed cognitive appraisal of how demanding the task was going to be and to what degree they had the resources needed to complete the task (Mendes et al., 2007). To assess demands, participants answered the following questions on a scale from strongly disagree (1) to strongly agree (7): The upcoming task is very demanding; the upcoming task will take a lot of effort to complete; the upcoming task is very stressful; a poor performance on this task would be very distressing for me. To assess resources, participants answered the following questions: I have the ability to perform the upcoming task successfully; it is very important to me that I perform well on this task; I'm the kind of person who does well in these types of situations. Ratings on these items were averaged within each subscale (demands α = 0.73; resources α = 0.65).

Participants also reported on their current mood using the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988). Negative mood was captured by asking participants how much of each of the following emotions they felt right now on a scale from not at all (1) to a great deal (5): distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, afraid; for positive mood, items were: proud, excited, strong, enthusiastic, interested, alert, inspired, determined, attentive, active. Ratings on these items were averaged within each subscale (negative emotion α = 0.85, positive emotion α = 0.91). Mood items were not captured after the TSST because of evidence suggesting that asking about an emotion fundamentally changes (and often reduces) the person's experience of that emotion (Kassam & Mendes, 2013; Lieberman et al., 2011), which may alter downstream cognitive outcomes of interest.

Cognitive Tasks

Working Memory

Before the acute stress task, working memory was measured with the Backward Digit Span subtest of the Wechsler Adult Intelligence Scale (Wechsler, 1955). Five series of numbers of increasing length (increasing from 3 to 7 digits) were read to each participant at the rate of one digit per second. For each of the five trials, participants had to repeat the numbers in reverse order. For each correctly repeated digit set, the number of digits was added up to create a total score. The total score range was 0–25.

Short-Term Memory

Short-term memory was assessed with the Wechsler Memory Scale delayed recall subtest (Wechsler, 1997). Before the acute stress task, participants were read a brief story (Story A) and then asked to describe the story back to the research assistant in detail. Participants were scored on how well they recalled specific story details (detail recall score) and general story themes (thematic recall), and these two scores were combined to create a total score. These three immediate recall scores measure short-term memory encoding ability. Approximately 30 min after the story was read (and after the acute stressor), participants were asked to recall the story in as much detail as possible. These delayed recall scores measure short-term memory consolidation and retrieval.

Cognitive Flexibility

Cognitive flexibility was measured with the Delis–Kaplan Executive Function System Sorting Test (Delis et al., 2004; Latzman & Markon, 2010). This sorting task consists of a set of six stimulus cards, each has a different shape with a single word printed in its center. The cards have eight pairs of distinct arrangement options, or "sorts," five perceptual concept sorts, and three verbal concept sorts. We administered the free sorting component of this test in which participants were asked to sort the cards into two equal groups of three cards each and to describe the common feature of each group and then to sort them again. The participant is given four minutes and the number of sorts completed is recorded. The outcomes measured are: how long each attempted sort takes (in seconds; then averaged across all attempts), number of attempted sorts (both correct and incorrect), number of correct sorts (maximum is 8), and number of incorrect sorts.

Problem Solving

Problem solving was measured with the Tower of London task (Shallice, 1982). In the Tower of London task, participants transfer three colored balls located on three rods from a set state to a goal state. There are a minimum number of moves the participant is allowed to use and the rods can each only hold a certain number of balls, which adds to the complexity. The problems get increasingly difficult each round. The outcomes of interest are: the number of problems solved correctly, the number of extra moves made across all problems over and above the minimum number required to complete each problem, the time in seconds it takes the participant to execute all moves summed across each problem (aka problem time; slower indicates worse performance), and the time in seconds it takes the participte to make the first move (aka planning time; slower indicates worse performance). Participants completed this using tangible, in-lab resources (not computer based).

Cortisol

Saliva was obtained with four IBL SaliCap sampling tubes (Hamburg, Germany) using the passive drool collection method, which captures 1 mL of saliva via a plastic straw. Four samples were taken throughout the laboratory session. The first sample was provided after participants completed initial study questionnaires and completed the first part of the short-term memory task but before they were told about the upcoming speech task. The second sample was timed to be provided 20 min after the research assistant began reading the directions for the upcoming speech task. Sample three was provided 40 min after the start of the speech task, and sample four was provided 60 min after the start of the speech. The timing of the samples was in an effort to capture the arc of the expected rise and fall of salivary cortisol over the course of the laboratory visit (Dickerson & Kemeny, 2004). Saliva samples were stored at −80°C until they were shipped overnight on dry ice to a laboratory in Dresden, Germany, where they were assayed for salivary free cortisol using commercial immunoassay kits (IBL, Hamburg, Germany). Intra- and inter-assay coefficients of variance were less than 10%.

Results

Manipulation Checks

We first conducted a 2 × 2 analyses of variance (ANOVAs) with age group (older vs. younger adults) and evaluation condition (evaluation vs. no evaluation) as independent factors, and pretask appraisals and emotion ratings as the dependent variables. The two feedback conditions were combined given that participants in these conditions received the same set of instructions, and, at that point in the protocol, had not received differential feedback from the evaluators. As expected, participants in the two evaluative conditions differed in their psychological appraisal of the task *prior* to it beginning compared to those in the control condition; participants in the evaluative conditions reported greater perceived demands $F(1, 121) = 6.84$, $p = .01$, fewer resources $F(1, 121) = 4.17$, $p = .043$, and greater negative emotions, $F(1, 121) = 14.89$, $p < .001$. There was no main effect of condition on positive emotions, $F(1, 121) = 0.21$, $p = .651$, and no main effect of age on pretask demands, $F(1, 121) = 0.74$, $p = .393$, resources, $F(1, 121) = 1.74$, $p = .19$, negative emotions, $F(1, 121) = 1.17$, $p = .282$, or positive emotions, $F(1, 121) = 2.4$, $p = .124$. Age by condition interactions was also not significant.

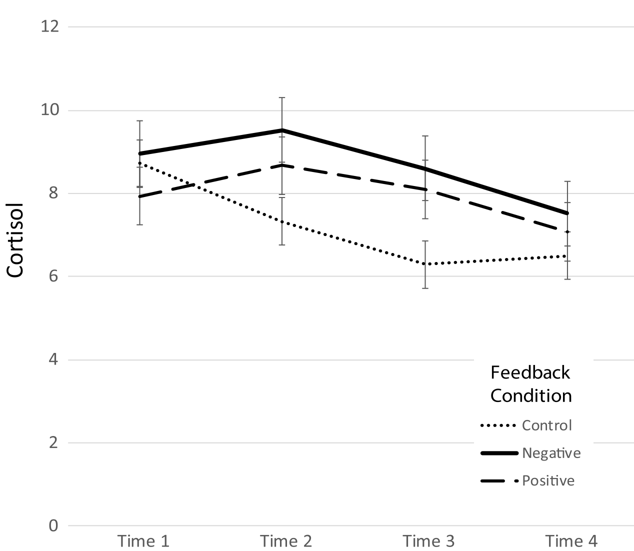
Cortisol Responses

We examined the extent to which our conditions engendered cortisol changes as intended. We ran a mixed model with time as a repeated factor and age (young or old) and condition (three levels of feedback) as between subjects. We observed a time effect, $F(3, 117) = 10.60$, $p < .0001$; a time by condition effect, $F(6, 234) = 2.89$, $p < .0099$; and no other significant main effects or interactions. There were no differences at time 1 (baseline cortisol) by condition, but at time 2 (cortisol reactivity to stressor) and time 3 (40 min after the start of the stressor), the control condition was significantly lower than the positive and negative feedback (see Figure 1). The positive and negative feedback conditions did not significantly differ from each other. By time 4 (60 min after the start of the stressor) there were no observed cortisol differences across conditions.

Baseline Short-Term Memory-Encoding Capacity and Working Memory Capacity

To examine effects of age before the stress manipulation on short-term and working memory, we conducted one-way ANOVAs with age as the group variable and the immediate recall and digit span scores as the dependent variables. No difference between older and younger adults emerged for the immediate recall task: for detail recall, $F(1, 124) = 0$, $p = .969$; for thematic recall, $F(1, 124) = 0.01$, $p = .94$; for total score, $F(1, 124) = 0$, $p = .99$. There were also no differences between older and younger adults for the digit span task, $F(1, 124) = 2.25$, $p = .136$. These results suggest that older and younger individuals in this sample possessed a similar short-term memory-encoding and working memory capacity.

Figure 1
Mean Cortisol Levels Over Time by Feedback Condition. Error Bars Represent Standard Error of the Condition Mean



Effect of Age and Condition on Poststressor Cognitive Performance

We examined the impact of age and condition on post-stress cognitive performance with 3 × 2 ANOVAs with age group, acute stress condition, and their interaction, as independent factors, and each cognitive performance outcome as a dependent variable. These results are presented in Table 1. Significant main effects and interactions from these ANOVAs were followed up using contrasts to examine the simple effects. Effect sizes for the significant effects are reported as partial eta squared in Table 1.

Cognitive Flexibility

For the Card Sort task there was a main effect of age for all measures. Older adults took longer to complete the sorts ($p < .001$), attempted fewer sorts ($p < .001$), completed fewer correct sorts ($p < .001$), and fewer incorrect sorts ($p = .005$). There was no main effect of condition on these measures (all p's $> .05$). There was a significant age by condition interaction on time per attempted sort, $F(2, 119) = 3.81$, $p = .025$ (Figure 2); older adults took longer than younger adults to complete the sorts in the positive feedback condition only, $F(1, 119) = 17.74$, $p < .001$. Older adults in the positive feedback condition also took significantly longer than older adults in the negative feedback condition, $F(1, 119) = 12.64$, $p < .001$, and in the no-feedback condition, $F(1, 119) = 5.31$, $p = .023$. No other significant age by condition interactions emerged (for number of attempted sorts, $p = .158$, for correct sorts, $p = .134$, and for incorrect sorts, $p = .367$).

Problem Solving

For the Tower of London task there was a main effect of age on number of extra moves used across all problems, $F(1, 125) = 5.95$, $p = .016$, and time to complete problems, $F(1, 125) = 23.55$, $p < .001$. After the acute stressor, older adults used a greater number of extra moves and took more time to complete the problem. Age did not influence the number of problems solved correctly ($p = .284$) or time before initiating action ($p = .09$). There was no main effect of feedback condition and no significant age by feedback interaction for any problem solving outcome.

Short-Term Memory

For the Wechsler Memory Scale delayed recall (controlling for immediate recall scores), there was no main effect of age (for detail recall, $p = .724$, for thematic recall, $p = .965$, for total score, $p = .783$). There was a main effect of condition for detail recall ($p = .007$), thematic recall ($p = .023$), and total score ($p = .006$), where individuals in the negative feedback condition performed worse on all three performance outcomes when compared with both positive and no-feedback conditions (all ps $< .05$). There was no significant interaction of age and evaluation condition for any outcome (for detail recall, $p = .354$, for thematic recall, $p = .18$, for total score, $p = .157$).

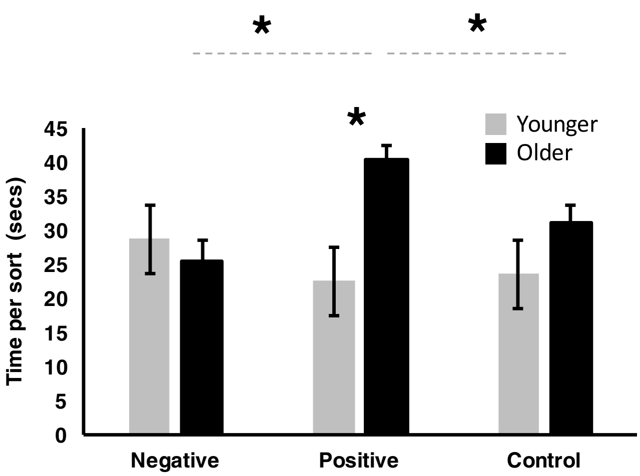
Table 1
Cognitive Task Performance Post-TSST by Age and Stress Condition

Neurocognitive process	Negative feedback condition		Positive feedback condition		Control condition		Main effect of age F	ηp^2	Main effect of condition F	ηp^2	Interaction F	ηp^2
	Younger	Older	Younger	Older	Younger	Older						
	$n = 21$	$n = 21$	$n = 20$	$n = 20$	$n = 20$	$n = 24$						
	Mean (*SE*)	Mean (*SE*)	Mean (*SE*)	Mean (*SE*)	Mean (*SE*)	Mean (*SE*)						
Cognitive flexibility												
Time per attempted sort (s)	23.83 (2.9)	25.61 (2.9)	22.65 (3)	40.46 (2.0)	23.68 (3)	31.12 (2.7)	**14.48*****	.11	2.74	.04	**3.81***	.06
Number of attempted sorts	6.62 (.45)	5.09 (.45)	7.55 (.46)	4.36 (.48)	7.35 (.46)	5.58 (.42)	**33.72*****	.22	1.06	.02	1.87	.03
Number of correct sorts	5.33 (.33)	4.38 (.33)	6.15 (.38)	3.84 (.35)	5.95 (.33)	4.42 (.31)	**34.79*****	.23	0.5	.01	2.04	.03
Number of incorrect sorts	1.38 (.26)	.57 (.26)	1.15 (.26)	.36 (.27)	.9 (.26)	.71 (.24)	**8.37****	.07	0.46	.01	1.01	.02
Problem solving												
Number of correct problems	4 (.52)	3.7 (.52)	4.8 (.53)	4.15 (.53)	4.35 (.53)	3.96 (.49)	1.16	.01	0.74	.01	0.05	0
Number of extra moves used	32.9 (4.9)	42.1 (4.9)	26.1 (5.1)	39.7 (5.1)	30.5 (5.1)	37.25 (4.6)	**5.95***	.05	0.48	.01	0.25	0
Time to complete problem (s)	196.7 (32.8)	331.38 (32.8)	169.5 (33.6)	341.7 (33.6)	217.3 (33.6)	283.8 (30.7)	**21.49*****	.16	0.09	0	1.34	.03
Time to initiate first move (s)	54.62 (11.8)	95.3 (11.8)	77.7 (12.1)	86.1 (12.1)	74.25 (12.1)	74.95 (11)	2.98	.02	0.24	0	1.64	.03
Short-term memory												
Delayed detail recall score	12.45 (.53)	13.07 (.54)	14.10 (.56)	14.68 (.54)	14.52 (.56)	13.78 (.49)	.13	0	**5.29****	.09	1.05	.02
Delayed thematic recall score	5.04 (.20)	5.42 (.22)	5.82 (.22)	5.82 (.22)	5.88 (.22)	5.46 (.20)	0	0	**3.89***	.06	1.74	.03
Delayed total score	17.17 (.75)	18.53 (.76)	19.91 (.75)	20.48 (.76)	20.69 (.75)	19.29 (.67)	.08	0	**5.43****	.10	1.88	.04

* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 2

Card Sort Task Time Per Sort Outcome in Younger and Older Adults by Experimental Condition. Error Bars Represent Standard Error of the Mean



Cortisol Trajectory and Association With Cognitive Functioning

Bivariate correlations between cortisol output in response to the acute stress task and cognitive performance are presented in Supplemental Table S1. Using a Bonferroni correction, accounting for 44 tests of correlation, a significance criterion of $p < .001$ was applied. There were no significant associations between post-stressor cognitive scores and baseline cortisol, cortisol reactivity, or cortisol recovery speed.

Exploratory Analyses: Prestressor Appraisals and Poststressor Cognitive Functioning

We tested the association between pre-stressor psychological appraisals (demands, resources, negative emotions, positive emotions) and cognitive performance using linear regression with cognitive performance as the outcome, and age, pre-stressor appraisals, and the interaction of age and appraisals as the predictors.

We found a significant interaction of age and perceived resources in predicting short-term memory, $F(3, 121) = 3.42$, $p = .019$, for the total score full model, with $b = 1.88$, $p = .023$ for the interaction term. As demonstrated visually in Figure 3, older adults who reported higher perceived resources prior to the TSST had better post-TSST short-term memory, $b = 1.79$, $p = .002$, while the relationship for younger adults was not significant, and $b = -.095$, $p = .873$. Matching these findings, we also found a significant interaction of age and positive affect in predicting short-term memory, $F(3, 121) = 3.44$, $p = .019$ for the total score full model, with $b = 2.91$, $p = .008$ for the interaction term. Older adults who reported higher positive affect prior to the TSST had better post-TSST short-term memory, $b = 2.41$, $p = .002$, while the relationship for younger adults was not significant, and $b = -0.5$, $p = .511$. Psychological appraisals were not associated with problem solving or cognitive flexibility scores for older or younger adults.

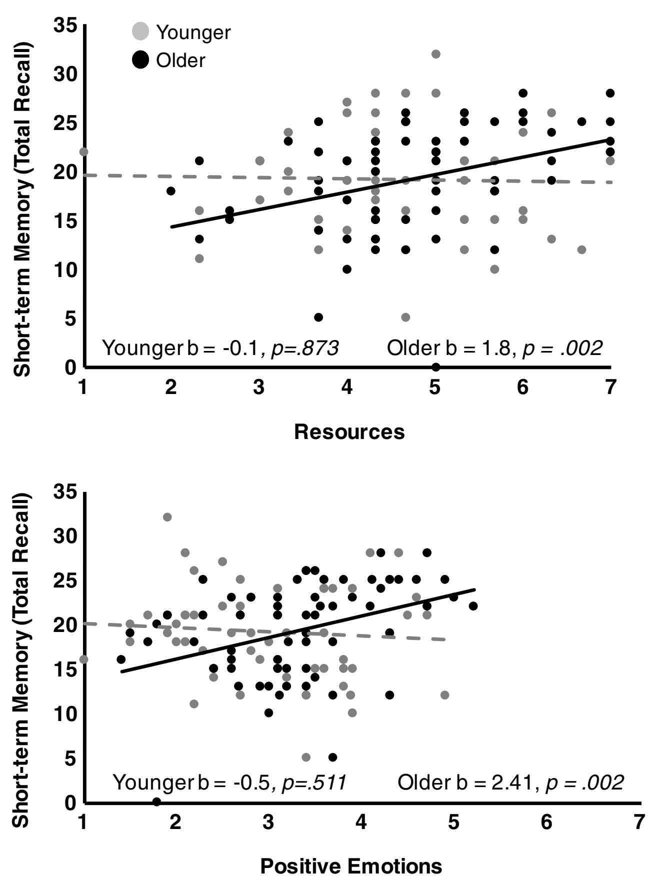
Discussion

We explored whether acute stress differentially affected cognitive flexibility, problem solving, and short-term memory after an acute stressor in older versus younger adults. We hypothesized that the influence of acute stress on cognitive functioning would vary by age group, the direction (either better or worse performance) depending on the specific cognitive domain being tested. We also examined whether the type of acute stress task (receiving negative feedback, positive feedback, or no feedback during an impromptu stress task) differentially changed post-stressor cognitive functioning and whether age influenced these effects. As hypothesized, we found that older adults performed worse on all aspects of cognitive flexibility compared with younger adults after an acute stress task, and the two age groups did not differ on short-term memory performance. Contrary to our hypotheses, older adults solved the same number of problems in a problem solving task as younger adults (though they used more moves and it took them more time to get to the correct answer), and there were no interactive effects of age and stress task type.

The reduction in cognitive flexibility and problem solving skills in the older compared to the younger adults aligns with previous research suggesting that tasks largely dependent on the prefrontal cortex (Miller & Cohen, 2001) are altered as a result of

Figure 3

Pre-stress Perceived Resources and Positive Affect Moderate the Effect of Age on Short-Term Memory Performance



normal aging processes (Mikels et al., 2005; Paxton et al., 2008; Podell et al., 2012; Reuter-Lorenz & Jantz, 2016; West, 1996). These changes, in part, are a result of shifts in the physical anatomy of the prefrontal cortex that occur in older age. These physical changes may contribute to a global slowing of responses throughout the prefrontal cortex (Salthouse, 1990; Salthouse et al., 2003). Here, we found that older adults reached the same accuracy as the younger adults in the problem-solving task, it just took them more time. Likewise, we might predict that for the flexibility task, had older adults been given more time, they may also have been able to reach the same number of correct sorts. The age-group differences did not appear to be related to cortisol secretion in our data, given that there was no relationship between cortisol and any of the cognitive performance outcomes. This is surprising, given the previous literature suggesting that the neurobiological response to acute stress, including increased cortisol concentrations in the hippocampus and prefrontal cortex, may be detrimental to complex cognitive functions (Arnsten, 2009).

While we found no age-group differences for short-term memory poststress, we did find that for older adults, there were significant positive associations between prestressor resources and positive emotions and improved short-term memory. This implies that older adults may receive a memory retrieval benefit when they perceive they have sufficient resources to navigate acute stress and/or they begin with more positive affect. These affective results align with previous work suggesting older adults report experiencing positive mood states more often than younger adults (Carstensen et al., 2000) and that this emotion bias may benefit cognitive outcomes (Mather & Carstensen, 2005). Results from our study suggest that this benefit may not extend to cognitive domains of cognitive flexibility or problem solving, supporting previous work that suggests that positivity bias in aging is domain specific (Mikels et al., 2005).

Additionally, there was a main effect of condition on short-term memory performance, with participants in the negative feedback condition having the lowest scores. This is in alignment with a significant body of past work showing that threat states (high arousal states coupled with a negative emotional valence) are associated with memory impairment (Gagnon & Wagner, 2016). This may be because low-affinity receptors in the hippocampus are activated at higher levels of cortisol production, and this directly impairs memory (Het et al., 2005). This, and future studies, would benefit from capturing other physiological systems in similar research paradigms. Capturing pre-ejection period, or other sympathetically-mediated indicators for example, would help unpack the initial triggers in the neurobiological cascade that are important for memory processes. Short-term memory may have also been reduced in the negative feedback condition because that condition induced a high-arousal negative affective state (Akinola & Mendes, 2012; Kassam et al., 2009), which led to an influx of resources toward the narrowing of attention (Lang et al., 1990), a state that is incompatible with the broad cognitive skills necessary to interpret a complex story (Fredrickson, 2001).

We also found that older adults in the positive feedback condition performed significantly worse on the cognitive flexibility task compared with younger adults in the same condition and compared with older adults in either the negative or no-feedback conditions. This pattern of results does not have a clear explanation, though we can speculate reasons for this pattern. It may be that receiving positive feedback was particularly surprising to older versus younger adults as it contradicted their assumption that they would not perform well on a novel task. The additional cognitive load this cognitive dissonance caused may have, in turn, slowed their ability to shift between mental sets. Alternatively, the positive feedback may have encouraged the older adults to try harder which then led to increased effort and longer card sort times. We also acknowledge that the effect we document here could have been spurious and encourage future research to investigate the relationship between various types of acute stressors, affect, and cognition in aging populations.

There are limitations to the interpretation of these findings. First, the older adults in the current study were on average 66 years old, which may be too young to begin seeing significant age-related changes in executive function, as has been suggested previously (Bryan & Luszcz, 2000). Future studies may consider recruiting a wider age range of older adults to adequately assess if stress-related cognitive vulnerabilities are revealed in older samples. Also, the sample size was modest and increasing sample size, especially given cognitive performance differences tend to yield small effect sizes, would be important for future studies; specific sample size estimates are offered in Shields et al. (2016). Another potential limitation is that the cognitive tasks that we utilized in this project were based on traditional laboratory measures. While using traditional neuropsychological assessments provides a level of reliability and validity, among other positive attributes, these tasks also have limitations. For example, they may not be sensitive to the effects of psychological state alterations in cognitively healthy adults, they may not be relevant for how stress interacts with cognition in daily life, and they may not be related to aspects of health or general well-being. A recent study (Gagnon & Wagner, 2016) suggests that the effects of acute stress on cognition may last up to 90 min for some domains (e.g. episodic memory retrieval), and thus future studies may also want to examine other tasks relevant to aging and sensitive to stress neurobiology. Additionally, the working memory task (Backward Digit Span) we employed was limited in that we capped difficulty at seven items. Considering our healthy sample and the limited age range of our older adults, examining only up to seven items may not be challenging enough for a participant's working memory capacities, inducing ceiling effects in the current data, likely limiting our ability to see differences between younger and older adults on working memory.

Another limitation of the study is that the cognitive measures were always performed in the same order. Thus, the impact of the stress task on cognitive task performance could actually be dependent on the timing of when the task was performed as the trajectory of cortisol secretion peaks and then diminishes over time. It is also possible that the last task in the series of tasks completed would have the worse performance as cognitive fatigue sets in, potentially coupled with peak cortisol. Future studies should carefully characterize timing effects (a suggestion that has been noted by others, e.g., Shields et al., 2015) in order to disentangle which parts of cognitive performance poststress are due to cortisol secretion directly versus other psychological aspects of acute stress.

Finally, an important limitation is that after the speech task participants were not asked to evaluate their perception of resources, demands, mood, or perceived stress. Thus, whether participants felt stressed afterward is inferred but not known directly. Cortisol changes by condition suggest the effectiveness of manipulations, but knowing how participants perceived the stress and negative affect after the stressor would have provided additional insight. We designed the study without a postspeech stress appraisal measure for two reasons. First, research on emotion labeling shows that when individuals label emotions this can reduce their impact (Lieberman et al., 2011). Indeed, in one paper using a similar approach to the methodology of this current paper, researchers found that simply self-reporting on emotions changed the physiologic profile compared with a comparison condition that had participants complete the same stressor but did not have them complete emotion self-reports (Kassam & Mendes, 2013). Second, we designed the procedure to transition from the acute stress speech to the cognitive tasks as seamlessly as possible. By eliminating postspeech questionnaires and having participants immediately start the cognitive tasks we were able to examine the influence of stress physiology on cognition with less than a minute of time between ending the stress task and beginning the cognitive tasks. This procedural approach has both advantages and disadvantages, the major limitation of this approach is that we do not have postspeech emotions or appraisals.

In sum, these findings further our understanding of the complexity of the relationship between aging, stress, and cognition, demonstrating that age-related cognitive differences are domain specific and not exaggerated by acute stress exposure. Notably, older adults were not more or less vulnerable to the effects of stress on cognition than younger adults as we had hypothesized. Our results do however point to the importance of future studies examining associations between old adults' perceived resources and mood and cognitive performance, a potential place to intervene to boost old adults' cognitive functioning.

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