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Examining Factors Involved in Stress-Related Working Memory Impairments: Independent or Conditional Effects?

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A large and growing body of research demonstrates the impact of psychological stress on working memory. However, the typical study approach tests the effects of a single biological or psychological factor on changes in working memory. The current study attempted to move beyond the standard single-factor assessment by examining the impact of 2 possible factors in stress-related working memory impairments. To this end, 60 participants completed a working memory task before and after either a psychological stressor writing task or a control writing task and completed measures of both cortisol and mind wandering. We also included a measure of state anxiety to examine the direct and indirect effect on working memory. We found that mind wandering mediated the relationship between state anxiety and working memory at the baseline measurement. This indirect relationship was moderated by cortisol, such that the impact of mind wandering on working memory increased as cortisol levels increased. No overall working memory impairment was observed following the stress manipulation, but increases in state anxiety and mind wandering were observed. State anxiety and mind wandering independently mediated the relationship between change in working memory and threat perception. The indirect paths resulted in opposing effects on working memory. Combined, the findings from this study suggest that cortisol enhances the impact of mind wandering on working memory, that state anxiety may not always result in stress-related working memory impairments, and that high working memory performance can protect against mind wandering.

Keywords: stress, working memory, cortisol, mind wandering

Despite the relatively stable nature of working memory, variation in working memory occurs as a result of a number of situational factors including psychological stress (Ilkowska & Engle, 2010). Although the impact of psychological stress on working memory has been well documented, the factors involved in this impairment are not as clear. Possible factors that have been suggested to be involved include intrusive thoughts or mind wandering (Klein & Boals, 2001) and cortisol (Lupien, Gillin, & Hauger, 1999; Lupien & Lepage, 2001).

Impact of Mind Wandering on Working Memory

Mind wandering refers to a category of thoughts that are defined as shifts away from a current task or ongoing activity and toward personal concerns or goals (Antrobus, Singer, & Greenberg, 1966; McVay & Kane, 2010; Smallwood & Schooler, 2006). These task-unrelated thoughts (TUTs) could include personal relevant thoughts regarding planning future positive events, thinking about neutral events, or thinking about negative life events, as would be typical of intrusive thoughts or rumination (Nolen-Hoeksema, Parker, & Larson, 1994). Thus, mind wandering may be thought of as a larger umbrella conceptualization of TUTs that includes neutral (i.e., future meals or future planning), TUTS with a positive valence (i.e., positive rumination or positive stimuli), and TUTs with a negative valence (i.e., rumination or intrusive thoughts). The Control Failures × Personal Concerns model of mind wandering (McVay & Kane, 2010) suggests that mind wandering reflects an interaction between failure of working memory to control attention and individual personal concerns being triggered by the environment. According to the executive attention model of working memory (Kane, Conway, Hambrick, & Engle, 2007), the role of working memory is to control the contents of attention. As such, individuals with higher working memory are able to control their attention and experience a lower rate of TUTs relative to individuals with lower working memory (McVay & Kane, 2009). However, when working memory fails to prevent TUTs from occurring, subsequent cognitive performance is impaired (McVay & Kane, 2010). A recent meta-analysis provided further support for the role of working memory in controlling rates of TUTs and for subsequent impairment in working memory following instances of TUTs (Randall, Oswald, & Beier, 2014).

Although some evidence suggests a beneficial effect of mind wandering on autobiographical planning (Baird, Smallwood, &

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Schooler, 2011) and creative thinking (Baird et al., 2012), the impact of mind wandering on ongoing task performance is negative (Randall et al., 2014). Mind wandering impairs performance on a variety of tasks, including reading comprehension (McVay & Kane, 2010; Smallwood, McSpadden, Luus, & Schooler, 2008), sustained attention (McVay & Kane, 2009), self-rated performance on everyday tasks (McVay, Kane, & Kwapil, 2009), and working memory (Mrazek, Phillips, Franklin, Broadway, & Schooler, 2013).

Following from the Control Failures × Personal Concerns model of mind wandering, factors that increase personal concerns should result in increases in the likelihood of experiencing TUTs. As such, stress should result in mind wandering when the stressor triggers personal concerns and the concerns are not controlled by working memory. These personal concerns following a stressor are likely to have a negative valence. Supporting this idea, self-reported mind wandering with a negative valence (e.g., intrusive thoughts about a personal stressful life event) has been shown to predict poorer working memory performance (Klein & Boals, 2001). The impact of negative emotion on working memory appears to be mediated by increases in mind wandering with a negative valence (e.g., ruminative thoughts about negative information; Curci, Lanciano, Soleti, & Rimé, 2013). Likewise, it has been suggested that the negative impact of anxiety on working memory (Eysenck, Payne, & Derakshan, 2005; Shackman et al., 2006) is due to increases in worry-related TUTs about the stressor (Eysenck & Derakshan, 2011; Eysenck, Derakshan, Santos, & Calvo, 2007). Thus, the impact of stress or anxiety on working memory appears to be mediated by mind wandering. Specifically, the prior studies point to mind wandering with a negative valence, or intrusive thoughts and rumination, as mediators of the impact of stress on working memory.

An intermediate group of thoughts, task-related interference (TRI; Smallwood, Riby, Heim, & Davies, 2006), must be examined along with TUTs. TRI refers to thoughts involving the evaluation of task performance. These thoughts are partially task-related, but can be harmful to performance given that focusing on performance may reduce the focus on completing the task. TRI is related to poorer performance in high-pressure situations involving cognitive tasks (Beilock, 2008; Benny & Banks, 2015) and reduced cognitive performance in older adults during situations that elicit stereotype threat (Hess, Auman, Colcombe, & Rahhal, 2003). As a result, the impact of stress on working memory may be due to increases in TRI following the stressor.

Biological Factor Involved in Stress-Related Impairments

A second possible factor, cortisol, has also been linked to impairments in working memory (Elzinga & Roelofs, 2005; Lupien et al., 1999). Stress-induced cortisol release is a good candidate as a mediator of the observed impairments in working memory after stress. Cortisol is the end product of hypothalamic–pituitary–adrenal axis activation and is released in response to physiological or psychological stress (Het & Wolf, 2007; Sapolsky, Romero, & Munck, 2000; Schwabe, Haddad, & Schachinger, 2008). Cortisol actions in the brain are mediated by mineralocorticoid receptors and glucocorticoid receptors in regions critical for cognitive processing: the hippocampus and the prefrontal cortical (PFC) structures (De Kloet, Vreugdenhil, Oitzl, & Joëls, 1998; Lupien & Lepage, 2001). Working memory performance is affected by stress-induced activation of low-affinity glucocorticoid receptors in the PFC (Lupien & Lepage, 2001). Indeed, acute hydrocortisone administration results in a dose-dependent impairment in working memory (Lupien et al., 1999; but see Oei, Tollenaar, Spinhoven, & Elzinga, 2009; Robinson, Sünram-Lea, Leach, & Owen-Lynch, 2008). Given that a critical role of the PFC is to reduce distracting or irrelevant information, it is possible that cortisol-induced impairments in PFC-mediated working memory performance are due to a glucocorticoid-mediated increase in distractibility (Chao & Knight, 1998; Gabrieli, Poldrack, & Desmond, 1998; Postle, 2006).

Increases in distractibility and mind wandering may occur because of increases in cortisol (Chao & Knight, 1998; Postle, 2006). However, these increases in distractibility can also occur independently from cortisol given that working memory impairment occurred immediately following the stressor of helicopter underwater evacuation training in a study by Robinson et al. (2008). This would have been prior to increases in cortisol because it takes a few minutes for the hypothalamic–pituitary–adrenal axis to induce the release of cortisol from the adrenal cortex and maximal cortisol concentrations are delayed by up to 30 min after a stress (reviewed in Kirschbaum & Hellhammer, 2000). An alternative explanation here is that stress-induced increases in distractibility in the helicopter underwater evacuation training resulted in increases in state anxiety, which is known to increase (stress-related) TUTs (Harrington & Blankenship, 2002; Mrazek et al., 2011). For this reason, a measure of anxiety was included in the present study.

Possible Moderator of the Impact of Stress

Appraisal of a stressor as a threat may also play a role in determining the impact of the stressor. The subjective appraisal of a situation as a threat increases state anxiety during an examination stressor (Lay, Edwards, Parker, & Endler, 1989). Similarly, threat appraisal alters cortisol responses to a stressor (Schlotz, Hammerfald, Ehlert, & Gaab, 2011). Appraisal of the stimuli as a threat may also increase the likelihood that the stress manipulation will trigger personal concerns, resulting in a greater likelihood of experiencing mind wandering. Although stress manipulations may be designed to result in the perception of the stimuli as a threat, individual differences in that perception may play a large role in the impact of that stressor on cognitive functioning.

The Current Study

The current study examined the impact of a psychological stress manipulation on working memory, mind wandering, and cortisol. To our knowledge, this is the first study to examine the possible impact of the interaction between TUTs and cortisol on working memory. To induce a psychological stress that is personally relevant, we asked participants in the stress condition to nominate a negative life event that was troubling them at that time and then engage in an expressive writing task (for a review, see Pennebaker, 1997, and Frattaroli, 2006). The goal of this task was to prime participants with personal concerns, thus increasing the likelihood of experiencing mind wandering (McVay & Kane, 2010), specifically mind wandering with a negative valence that is likely to impact working memory. Similar writing tasks have been used previously to induce TUTs in prior work (Banks, Welhaf, & Srour, 2015; Grisham, Flower, Williams, & Moulds, 2011; Watkins, 2004). Participants completed measures of state anxiety at baseline and following the stress manipulation as measures of the impact of the stress manipulation.

The first goal of the current study was to examine the role of TUTs, TRI, and cortisol as factors for understanding the relationship between state anxiety and working memory. To do this, we examined the relationship between these factors prior to the stress manipulation. We first hypothesized, based on prior work examining the impact of negative emotion on working memory (Curci et al., 2013), that the impact of state anxiety on working memory would be mediated by rates of TUTs and negative TRI at the baseline in all conditions. Second, due to the impact of cortisol on the PFC (Chao & Knight, 1998; Postle, 2006), we specifically hypothesized that cortisol would moderate the impact of TUTs but not negative TRI on working memory, such that higher levels of cortisol would result in a greater negative impact of TUTs on working memory relative to lower levels of cortisol.

The second goal of the study was to examine the impact of a psychological stress manipulation on working memory, mind wandering, cortisol, and the relationships between these factors. Our third prediction was that following the stress manipulation, participants would have lower working memory, higher rates of TUTs, higher rates of negative TRI, and higher cortisol levels compared with a control condition. Following from the Control Failure × Personal Concerns model of working memory (McVay & Kane, 2010) and recent meta-analytic support for that model (Randall et al., 2014), our fourth hypothesis was that baseline working memory would predict TUTs in the control condition following the control writing manipulation. However, in the stress condition, we hypothesized that the writing task would prime personal concerns, such that the higher level of personal concerns would result in a failure of working memory to prevent TUTs for individuals with higher and lower working memory. Participants completed a measure of threat appraisal as an indication of the degree to which they felt that the writing task was a threat. Higher levels of threat appraisal may result in increased priming of personal concerns that could trigger TUTs. We predicted that high levels of state anxiety and threat perception would result in failures of working memory to prevent TUTs from occurring; therefore, appraisal of the situation as a threat and state anxiety would predict TUTs, but baseline working memory would not.

Finally, the study examined the impact of state anxiety and threat appraisal of the stressor on working memory. Petrac, Bedwell, Renk, Orem, and Sims (2009) demonstrated a negative relationship between perceived stress and divided attention but a positive relationship between state anxiety and divided attention. Given the role of working memory in attentional control (Kane et al., 2007) and the role of working memory in divided attention (Colflesh & Conway, 2007), the current study explored this effect on working memory. Based on these findings, our fifth hypothesis was that threat appraisal of the stress manipulation would result in increases in state anxiety and TUTs in the stress condition. However, consistent with Petrac and colleagues, the increases in state anxiety and TUTs would have opposing impacts on working memory. Specifically, we predicted that greater threat appraisal would result in increases in state anxiety, which would in turn increase working memory performance. We hypothesized that threat appraisal would result in increases in TUTs, which would in turn decrease working memory performance.

Method

Participants

Sixty undergraduates (43 women; mean age = 21.07 years, *SD* = 3.30) from Nova Southeastern University participated in the current study in exchange for a gift card. All procedures were approved by the Nova Southeastern University Institutional Review Board.

Measures

Automated operation span (AOSPAN) task (Unsworth, Heitz, Schrock, & Engle, 2005). The AOSPAN task is a complex span task that was used to measure working memory. This task requires the participant to maintain a list of letters in memory while verifying an answer to a math equation. Participants are presented with a math equation (e.g., 8 + 4/2 = ?) and then presented with a digit (e.g., 6). The participant verifies the digit is either "true" or "false"; then the participant is presented with a target letter (a capital letter randomly selected among 12 options). After three to seven verification–letter pairs, participants are presented with a grid containing all 12 possible letters and are asked to indicate, via mouse click, the letters presented in serial order. In this study, 15 trials were presented, with three presentations of each set length (3–7). The task was scored by summing the number of letters recalled in the correct serial position (Conway et al., 2005). The AOSPAN task has been shown to have good internal reliability (.80) and high test–retest reliability (.83; Unsworth et al., 2005).

Thought probes. To measure the incidence of TUTs, we inserted thought probes following recall of the letters in each set of the AOSPAN task. Participants were asked "What were you just thinking about?" and given seven responses options to choose from: (a) task-related thoughts, exclusively, (b) task performance/evaluative thoughts (positive), (c) task performance/evaluative thoughts (negative), (d) everyday stuff, (e) current state of being, (f) daydreams, and (g) other TUTs. This method of capturing TUTs has been used successfully in prior research with a sustained attention task (McVay & Kane, 2009) and working memory tasks (Banks et al., 2015; McVay, Meier, Touron, & Kane, 2013). The percentage of TUTs was calculated by summing the number of probes indicated as d through g above and dividing by the number of probes presented (15). Probes b and k are task-related but are not considered on-task; rather, they contribute to TRI (Smallwood et al., 2006) and, therefore, consistent with prior work (McVay & Kane, 2009), they were not included in the percentage of TUTs. However, the percentage of TRI may be altered as a result of the stress manipulation. The percentage of positive and negative TRI was calculated separately by dividing the number of probes indicated as b (positive TRI) or c (negative TRI) by the number of probes presented (15).

State Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). The STAI State Anxiety Inventory (STAI-S) was used to measure state anxiety. The

STAI-S is a 20-item measure that assesses subjective psychological states such as nervousness, tension, restlessness, unpleasantness, and worry. Higher scores indicate higher anxiety. Internal consistency was high in the current sample for each of the STAI-S measures (αs = .90–.94).

Salivary cortisol assessment. Saliva samples were collected from each participant through passive drool into polyethylene tubes at two time points during the experiment. Immediately after collection, sample tubes were stored in a −20°C freezer. For cortisol quantification, the saliva samples were thawed, vortexed, and centrifuged at 3,000 rpm (0.9 *g*) for 15 min. Cortisol was then quantified via human enzyme immunoassay kits per the manufacturer's instructions (Salimetrics, Carlsbad, CA).

Cognitive Appraisal Scale (CAS; Skinner & Brewer, 2002). A revised version of the CAS was used to measure trait styles of cognitive appraisal. Of the five subscales in the CAS, only the Threat Appraisal subscale (CAST) was used in the current study. The CAST addresses the tendency to focus on the negative evaluation of others and concerns regarding the ability to cope with situations perceived as stressful or demanding. The CAST demonstrated satisfactory levels of internal consistency in the current sample (α = .91).

Procedure

Upon arriving in the lab, participants completed an informed consent form and were randomly assigned to the control ($n = 30$) or stress condition ($n = 30$). All participants completed baseline measures of the STAI-S, provided a saliva sample, and then completed the baseline AOSPAN task with thought probes. Participants in the stress condition then completed the psychological stress manipulation. Stress condition participants were asked to nominate an "extremely negative life event that is currently troubling" them. Following the nomination of the event, participants received the following instructions:

> During today's session, I want you to let go and write about your deepest thoughts and feelings about the negative event you nominated. In your writing, you might want to explore your emotions and thoughts about the negative event. You may write about more than one aspect of the event if you choose. Some people find it best to explore your emotions and then try to come to an understanding of the event(s). Do your best to try to "tie it all together" at the end of your writing. We ask that you do not include any information that could identify you as we want this writing to remain confidential and for you to feel free to be able to write things you would not want tied to you. You will have 10 minutes to write. Only the researchers involved in this project will have access to read your essays. Therefore, your confidentiality is assured and your name will never be linked to anything you write. The important thing is that you really let go and dig down to your very deepest emotions and thoughts about the negative event and explore them in your writing.

This set of instructions is similar to those used in expressive writing studies and studies examining linguistic content of narratives about negative life events (Boals, Banks, Hathaway, & Schuettler, 2011). Thus, these instructions should result in an increase in psychological stress.

Participants in the control condition engaged in a standard control writing task in which they were asked to think about what they had done the day before. Control participants received the following instructions:

> The purpose of today's writing assignment is to get you to think about what you did yesterday. If you will, make a detailed list of everything you did yesterday. Avoid including any emotional content or feeling you may have had about your day. Your description should be as objective as possible. If you have any questions, feel free to ask the experimenter. You have 10 minutes to write.

Upon completion of the writing task, all participants completed postwriting manipulation measures of the STAI-S, AOSPAN task with thought probes, CAST, brief demographics measure, and provided a saliva sample. Participants were then thanked for their participation and debriefed.

Results

Data from two participants were excluded because they did not complete the writing task ($n = 1$) and a computer failure ($n = 1$), resulting in a final sample of 58 (control condition $n = 30$, stress condition $n = 28$). All data were screened for outliers (values more than 3 *SD* away from the mean). No outliers were detected. A variety of negative events were nominated by participants in the stress condition for the writing task, including academic stress, financial problems, relationship difficulties with parents or significant others, and fears of failures impacting future careers.

The Role of TUTs, TRI, and Cortisol at Baseline

To test the first hypothesis, that rates of TUTs or TRI would mediate the impact of state anxiety on working memory at baseline, we conducted a series of mediation analyses using the PROCESS SAS macro (Hayes, 2013) on the model shown in Figure 1a. Given the limited sample size and to alleviate concerns regarding violations of normal distribution assumptions, our analysis relied on the nonparametric bootstrapping method (1,000 samples) to provide a robust estimation of both direct and indirect effects (Preacher & Hayes, 2008). This method provides a 95% confidence interval (CI) around the indirect effect. The indirect

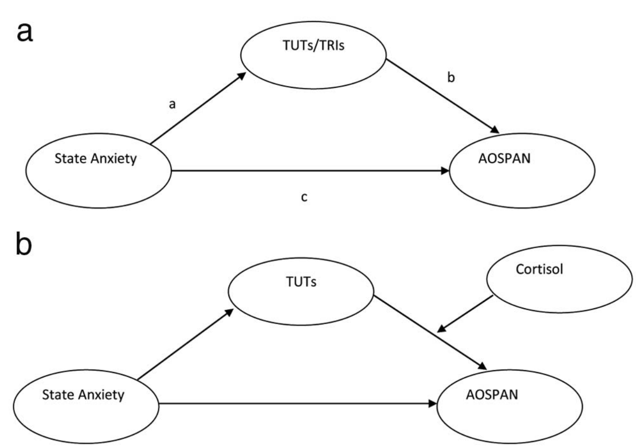

Figure 1. (a) Mediation model at baseline. (b) Mediated moderation model at baseline. TUTs = task-unrelated thoughts; TRI = task-related interference; AOSPAN = automated operation span task.

effect is considered to be significant when the CI does not contain zero, indicating that the mediation effect is different from zero (Preacher & Hayes, 2008). As seen in Table 1, a significant negative indirect effect of state anxiety on AOSPAN task performance was observed, indirect effect $= -0.17$, bootstrapped $SE = 0.11$, bootstrapped 95% CI [−0.50, −0.03], such that increased state anxiety predicted increased TUTs, $b = 0.006$, $t(57) = 2.63$, $p < .05$, which, in turn, impaired AOSPAN task performance, $b = -28.81$, $t(57) = 2.50$, $p < .05$. No significant direct effect of state anxiety on AOSPAN task performance was found after accounting for the indirect effect, direct effect $= -0.20$, $SE = 0.20$, $t(57) = -1.02$, $p > .05$, 95% CI [−0.61, 0.20]. Positive and negative TRI did not serve as significant mediators for an indirect impact of state anxiety on working memory. Although state anxiety was a significant predictor of negative TRI, $b = 0.009$, $t(57) = 3.08$, $p < .01$, and the bootstrapped 95% CI did not include zero [−0.39, −0.02], negative TRI did not predict AOSPAN task performance, $b = -17.63$, $t(57) = -1.90$, $p > .05$; therefore, we cannot consider this a significant mediation effect.

To examine the second hypothesis, that cortisol would moderate the relationship between TUTs and working memory, we conducted a regression analysis. Given that TRI was not related to working memory, it was not included in this analysis. Baseline rates of TUTs, cortisol, and an interaction between TUTs and cortisol were entered as predictors of baseline AOSPAN task performance. A significant model was found, $R^2 = 22.93$, $F(3, 54) = 5.35$, $p < .01$, with only the interaction between cortisol and TUTs serving as a significant predictor of AOSPAN task performance, $\beta = -.68$, $t(57) = 2.20$, $p < .05$, 95% CI [−325.13, −14.91]. To examine the interaction, we plotted the relationship between TUTs and AOSPAN task performance for hypothetical cortisol values at the mean and ±1 standard deviation from the mean. In addition, simple slopes analyses were conducted. As seen in Figure 2, TUTs did not affect AOSPAN task performance at low levels of cortisol, $p > .05$, but TUTs had a negative impact on AOSPAN task performance at mean levels of cortisol, $b = -25.64$, $SE = 10.86$, $p < .05$, 95% CI [−47.41, −3.86], and at higher levels of cortisol, $b = -51.54$, $SE = 14.12$, $p < .001$, 95% CI [−79.85, −23.24].

To determine whether the indirect effect of state anxiety on working memory through TUTs was moderated by cortisol, we conducted a moderated mediation analysis using the PROCESS macro (Hayes, 2013). Replicating the initial model tested in Figure 1a, with the addition of cortisol as a moderator (see Figure 1b), the indirect effect of state anxiety on working memory through TUTs was moderated by cortisol, such that a significant conditional indirect effect of state anxiety on working memory through TUTs was observed at higher levels of cortisol, $b = -0.26$, bootstrapped $SE = 0.13$, bootstrapped 95% CI [−4.65, −0.09], but not at lower, $b = 0.03$, bootstrapped $SE = 0.14$, bootstrapped 95% CI [−0.31, 0.28], or mean levels of cortisol, $b = -0.11$, bootstrapped $SE = 0.10$, bootstrapped 95% CI [−0.47, 0.01]. No significant direct effect of state anxiety on AOSPAN task performance was found after accounting for the indirect effect, $b = -0.29$, $SE = 0.20$, $t(57) = -1.43$, $p > .05$, 95% CI [−0.69, 0.11]. This suggests that cortisol plays an important role in determining the impact of mind wandering and state anxiety on working memory, such that mind wandering is most harmful and, sometimes only harmful, when cortisol is elevated.

Impact of Stress Manipulation

To test the third hypothesis, that the psychological stress manipulation would result in a decrease in working memory and increases in cortisol, TUTs, TRIs, and state anxiety compared with the control condition, we conducted a series of analyses of variance. No effect of time, condition, or time by condition interaction was observed on the AOSPAN task, positive TRI, or negative TRI, *p*s > .05. The TUTs reveled an effect of time, $F(1, 56) = 8.77$, $p < .01$, partial $\eta^2 = .16$, and an interaction between time and condition that approached significance, $F(1, 56) = 2.97$, $p = .09$, partial $\eta^2 = .05$, but no effect of condition, $p > .05$. Because the interaction approached significance, we conducted paired samples *t* tests to examine change in TUTs in each condition. As seen in Table 2, a significant increase in TUTs was observed in the stress condition, $t(27) = 2.70$, $p < .05$, $d = 0.55$, from baseline to poststressor, but not in the control condition, $p > .05$. A significant effect of time, $F(1, 56) = 27.11$, $p < .0001$, partial $\eta^2 = .48$, and interaction between time and condition, $F(1, 56) = 4.19$, $p < .05$, partial $\eta^2 = .07$, but no effect of condition, $p > .05$, was found for state anxiety. Paired samples *t* tests indicated that a significant increase in state anxiety occurred in the stress condition, $t(27) = 8.11$, $p < .001$, $d = 0.69$, and in the control condition, $t(29) = 3.53$, $p < .01$, $d = 0.30$. However, analysis of change scores

Table 1
Mediation Analysis Results Examining Mediators for the Impact of State Anxiety on AOSPAN Performance at Baseline

Mediator	Path a	Path b	Path c	Path c′	Indirect effect	95% CI for indirect effect
TUTs	0.006*	−28.81*	−0.37	−0.20	−0.17	[−0.48, −0.03]
Negative TRI	0.009**	−17.63	−0.37	−0.22	−0.15	[−0.39, −0.02]
Positive TRI	−0.002	7.53	−0.37	−0.35	−0.02	[−0.12, 0.02]

Note. Values represent unstandardized path coefficients. a = path from state anxiety to the mediator; b = path from the mediator to automated operation span task (AOSPAN) performance; c = path from state anxiety to AOSPAN performance; c′ = path from state anxiety to AOSPAN performance controlling for the indirect effect through the mediator; TUT = percentage of task-unrelated thoughts; TRI = percentage of task-related interference.
* $p < .05$. ** $p < .01$.

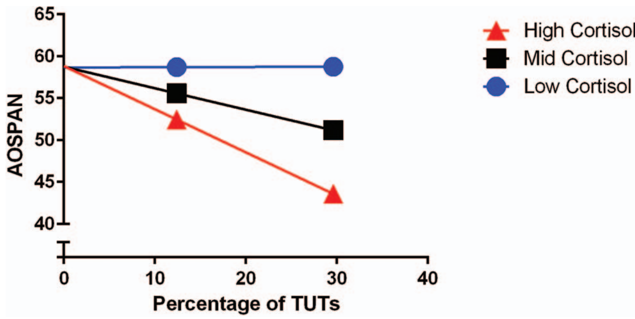

Figure 2. Moderation effect of cortisol on the impact of task-unrelated thoughts (TUTs) on automated operation span (AOSPAN) task performance at baseline. See the online article for the color version of this figure.

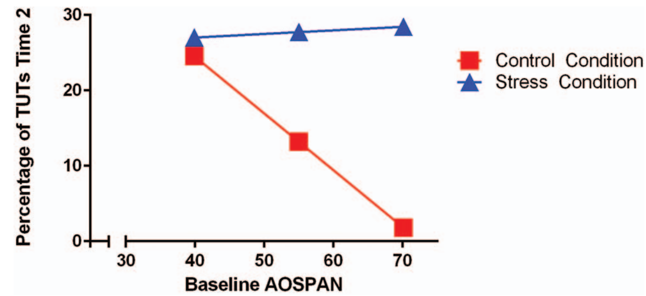

Figure 3. Impact of baseline automated operation span (AOSPAN) task performance on task-unrelated thoughts (TUTs) at Time 2 by condition. See the online article for the color version of this figure.

indicated a greater increase in state anxiety in the stress condition than control condition, $t(56) = 2.05$, $p < .05$, $d = 0.36$. Finally, an effect of time on cortisol was found, $F(1, 56) = 10.46$, $p < .01$, partial $\eta^2 = .19$, such that cortisol levels decreased following the writing task. Based on the lack of a significant effect of either positive or negative TRI on AOSPAN task performance and the lack of change in TRI over time, only TUTs were examined in subsequent analyses.

To test the fourth hypothesis, that baseline working memory would predict TUTs in the control condition but that threat appraisal and state anxiety would predict TUTs in the stress condition, we conducted separate regression analyses for each condition. Baseline AOSPAN task performance, poststress manipulation state anxiety, and CAST scores were entered as predictors of poststress TUTs. As hypothesized, in the stress condition, CAST scores predicted TUTs, $\beta = .42$, $t(1) = 2.24$, $p < .05$, but neither state anxiety nor baseline AOSPAN task performance was a significant predictor. In the control condition, baseline AOSPAN task performance scores predicted TUTs, $\beta = -.43$, $t(1) = -2.33$, $p < .05$, but neither state anxiety nor CAST scores were significant predictors. Figure 3 shows the relationship between baseline AOSPAN scores and postwriting TUTs by condition.

These results suggest that the predictors of TUTs were altered by the writing manipulation, despite a lack of changes in AOSPAN task performance. Specifically, it appears that factors that predicted baseline AOSPAN scores, state anxiety and TUTs, increased following the stress manipulation. However, in contrast to the baseline mediation model, state anxiety did not predict poststress manipulation TUTs in the stress condition. As such, we were interested in examining a mediation model predicting postwriting task AOSPAN scores, controlling for baseline AOSPAN scores. Controlling for baseline AOSPAN scores allowed for an examination of the impact of factors on changes in AOSPAN task performance as a result of the stress manipulation.

Impact of Treat Appraisal

As seen in Figure 4, to test our fifth hypothesis, that threat appraisal would increase state anxiety and TUTs but that these factors would have opposing effects on working memory, we examined the impact of CAST scores on postwriting task AOSPAN scores mediated by state anxiety and TUTs, controlling for baseline AOSPAN scores. To test this mediation model, we used the PROCESS macro (Hayes, 2013) and relied on the bootstrapped CIs to indicate significant indirect effects. The mediation analysis in the control group did not produce any significant direct or indirect effects. No direct effect from CAST to postwriting task AOSPAN scores was found following the mediation in the stress condition, direct effect = 0.23, $SE = 0.15$, $t(27) = 1.51$, $p > .05$, bootstrapped 95% CI [−0.07, 0.53], or the control condition, direct effect = 0.21, $SE = 0.25$, $t(29) = 0.86$, $p > .05$, bootstrapped 95% CI [−0.30, 0.72]. The mediation analysis conducted with the stress condition revealed two significant mediation pathways. The first significant indirect effect of CAST on AOSPAN task performance was through state anxiety (Path AB in Figure 4). CAST led to

Table 2
Effect of Time and Condition on Working Memory, Mind Wandering, and Stress

Variable	Stress condition Time 1 mean (*SD*)	Stress condition Time 2 mean (*SD*)	Control condition Time 1 mean (*SD*)	Control condition Time 2 mean (*SD*)
AOSPAN	57.75 (17.10)	56.93 (15.09)	52.43 (12.71)	51.00 (15.06)
TUTs	13.57 (17.82)	27.86 (32.36)	11.33 (16.81)	15.30 (20.93)
Negative TRI	20.00 (20.61)	18.57 (25.03)	21.11 (24.07)	24.44 (29.68)
Positive TRI	19.05 (24.26)	13.57 (26.26)	16.00 (23.13)	13.56 (20.82)
State anxiety	36.36 (9.57)	44.46 (13.52)	37.30 (10.30)	40.83 (13.52)
Cortisol (μg/dl)	0.28 (0.13)	0.25 (0.10)	0.27 (0.17)	0.19 (0.09)

Note. AOSPAN = automated operation span task; TUTs = task-unrelated thoughts; TRI = task-related interference.

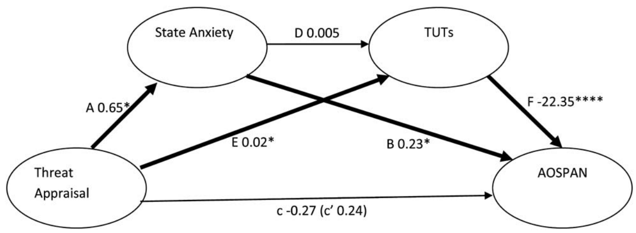

Figure 4. Mediated mediation model following the stress manipulation controlling for baseline automated operation span (AOSPAN) task performance in the stress condition. Values represent unstandardized path coefficients. * $p < .05$. **** $p = .0001$. Bold lines represent significant indirect effects. TUTs = task-unrelated thoughts.

increased state anxiety, which in turn led to increased AOSPAN task performance, indirect effect = 0.15, bootstrapped $SE = 0.09$, bootstrapped 95% CI [0.02, 0.41]. The second significant indirect effect of CAST on AOSPAN task performance was through TUTs (Path EF), such that CAST led to increases in TUTs, which in turn led to decreases in AOSPAN task performance, indirect effect = −0.35, bootstrapped $SE = 0.20$, bootstrapped 95% CI [−0.85, −0.05]. We tested a full mediation model with CAST leading to increases in state anxiety, which resulted in changes in TUTs, finally impacting AOSPAN task performance. This full model did not suggest that the two mediators operated sequentially (Path ADF), indirect effect = −0.07, bootstrapped $SE = 0.07$, bootstrapped 95% CI [−0.33, 0.002]. Based on the moderating effects of cortisol on the impact of TUTs on AOSPAN task performance at baseline, we added cortisol to the model as a possible moderator for the impact of TUTs on AOSPAN task performance. The interaction between cortisol and TUTs was not statistically significant for predicting AOSPAN task performance, controlling baseline AOSPAN task performance, $p = .09$. Significant indirect effects of CAST on AOSPAN task performance mediated by TUTs occurred at all levels of cortisol; however, higher levels of cortisol resulted in a stronger effect, indirect effect = −0.82, bootstrapped $SE = 0.44$, bootstrapped 95% CI [−1.94, −0.13], than lower levels of cortisol, indirect effect = −0.35, bootstrapped $SE = -0.35$, bootstrapped 95% CI [−0.85, −0.06]. No direct effect of CAST on AOSPAN task performance was found in this model, direct effect = 0.24, $SE = 0.18$, $t(27) = 1.31$, $p > .05$, bootstrapped 95% CI [−0.14, 0.62]. This suggests that, similar to the baseline model, cortisol influences the impact of TUTs on changes in working memory. Furthermore, although the effect of TUTs on changes in AOSPAN task performance is moderated by cortisol, TUTs may not be driven by cortisol levels. To test this, we examined correlations between cortisol and TUTs. No significant relationship was detected at the baseline collapsing across conditions, $r(56) = .13$, $p = .33$, or following the writing in the stress condition, $r(26) = -.30$, $p = .13$, or control condition, $r(28) = .12$, $p = .54$. Thus, TUTs and cortisol appear to be independent factors that interact to impact working memory.

Discussion

The purpose of the current study was to examine two possible factors involved in the impact of psychological stress on working memory. We first hypothesized that the stress manipulation would result in increased mind wandering and decreased working memory. Following the stress manipulation, a greater increase in state anxiety was observed in the stress condition than the control condition, suggesting that the manipulation was indeed stressful. An increase in mind wandering was observed in the stress condition but not the control condition. However, working memory did not decrease in the stress condition. The writing task was successful at increasing stress and producing mind wandering, but despite these effects, it did not alter working memory.

Mind Wandering, State Anxiety, and Working Memory in the Absence of Stress

Examination of the baseline data supports the second hypothesis that the impact of state anxiety on working memory would be mediated by mind wandering. This finding adds to the literature by suggesting that the impact of negative emotion (Curci et al., 2013) on working memory is due to increases in mind wandering. The interaction between mind wandering and cortisol provides a novel and critical addition to the literature on the impact of stress on working memory. Although prior work has examined the impact of mind wandering (Klein & Boals, 2001; Randall et al., 2014) and cortisol (Elzinga & Roelofs, 2005; Lupien et al., 1999) on working memory in separate studies, to our knowledge, this is the first study to demonstrate the effect of the interaction of these factors on working memory. Prior work suggests that cortisol-induced impairments in PFC working memory performance are due to glucocorticoid-mediated increases in distractibility (Chao & Knight, 1998; Postle, 2006). Our results support this idea by showing that high levels of cortisol can influence working memory indirectly through an increase in mind wandering. This effect was seen in all participants at baseline (possibly related to anticipatory increases in cortisol in some people) and was maintained at a 90% probability level in the stress group following stress exposure (when the effective sample size was reduced by half).

Independent and Combined Effects of Mind Wandering and Cortisol With Stress

The current findings also provide support for, and a possible addition to, the Control Failures × Personal Concerns model of working memory (McVay & Kane, 2010), which suggests that mind wandering reflects an interaction between failures of working memory to control attention and personal concerns being triggered by the environment. Mind wandering following the writing task in the control condition was predicted by working memory, such that individuals with higher working memory experienced fewer instances of mind wandering than individuals with lower working memory. This is consistent with the view that working memory should prevent mind wandering from occurring and is consistent with recent meta-analytic findings (Randall et al., 2014). However, in the stress condition, baseline working memory did not predict postwriting mind wandering. The writing stressor appears to have been sufficient to remind the participants of personal concerns, and this reminder appears to have been strong enough so that they were not controlled by working memory and resulted in an increase in mind wandering during the subsequent AOSPAN task. Prior work that successfully manipulated mind wandering has relied on manipulations that oriented the individual's attention to future plans or unresolved goals (Antrobus et al., 1966; Klos & Singer, 1981). Priming individuals with personal goals and concerns appears to increase mind wandering (McVay & Kane, 2013). Personal concerns regarding a negative life event appear to result in a greater increase in mind wandering (14%) than general personal concerns or goals (3–4%; McVay & Kane, 2013) or thoughts of the prior day (4% in the control condition). One possible reason for the increased rate of mind wandering in the current study compared with prior work is that the negative emotional valence of the event increases the impact of any subsequent TUTs and may then increase the likelihood for working memory to fail to control attention.

Alternative models of mind wandering suggest that mind wandering requires working memory resources to support the existence of TUTs (Smallwood & Schooler, 2006). This view is supported by work that found that mind wandering decreases as task difficulty increases (Forster & Lavie, 2009; Teasdale, Lloyd, Proctor, & Baddeley, 1993). The current results do not support this alternative model because of the relationship between working memory and TUTs at baseline and following the writing tasks. If mind wandering were dependent on working memory to support TUTs, then working memory at baseline would predict TUT rates in both conditions following the writing manipulation. However, although baseline working memory did predict rates of TUTs in the control condition, as would be predicted from both models of mind wandering, it did not predict TUTs in the stress condition. The stress writing manipulation resulted in an increase in TUTs that was not related to baseline working memory. Rather, the existence of TUTs following the stress writing task was predicted by threat perception, likely indicating a higher level of personal concern.

Stress and Working Memory: Multiple Paths to Impairment

Despite a lack of a significant decrease in AOSPAN task performance following the stress manipulation, examination of the predictors of AOSPAN task performance suggests a possible reason for the lack of a decrease. The mediation analysis of the stress condition showed that the impact of threat appraisal on AOSPAN task performance resulted in two opposing indirect effects. Threat appraisal increased state anxiety, but state anxiety had a positive effect on AOSPAN task performance. Although this appears counterintuitive based on the baseline mediation analysis, the positive relationship between state anxiety and AOSPAN task performance may be due to a number of factors. Given that the poststressor AOSPAN task was the second time that participants had completed the task, it is possible that motivation to engage in the task sufficiently enough to perform well had declined. In this case, increases in state anxiety would be beneficial as they could increase arousal to an optimal level, resulting in higher AOSPAN task performance. This would be consistent with an inverse U relationship between arousal and cognitive performance (Sorg & Whitney, 1992).

The second indirect effect of threat appraisal on AOSPAN task performance was negative and mediated by mind wandering. Threat appraisal increased mind wandering, which led to a decrease in AOSPAN task performance. This finding is consistent with work examining the impact of negative emotion (Curci et al., 2013) on working memory. The opposing indirect effects of state anxiety and mind wandering on the relationship between threat appraisal and AOSPAN task performance may explain the lack of a significant effect of the stress manipulation on working memory. It is important to note that these poststress manipulation mediation models were not significant for the control group, suggesting that the indirect effects of threat appraisal on working memory were due to the stress manipulation.

Limitations

Several important limitations in the current study are worth noting. The lack of a significant impairment in working memory following the stress manipulation prevented us from making a strong conclusion regarding the factors that predict stress-related working memory decrements. Based on the positive effects of state anxiety on working memory, it is possible that to see working memory impairments, the stress manipulation must produce greater increases in mind wandering. In addition, given the moderating role of cortisol, it is possible that stress manipulations that lead to greater increase in cortisol and mind wandering would result in significant impairments in working memory. Second, the lack of an increase in cortisol following the stress manipulation is concerning because of the homotypic nature of the stressor. We expected to observed increases in cortisol following the psychological stressor (Oei, Everaerd, Elzinga, van Well, & Bermond, 2006); however, it is possible that some participants experienced elevated levels of cortisol at baseline because of anticipatory stress that could result from anxiety regarding participating in psychological research. Indeed, previous research has shown that the anticipation of being in a stress task can influence cognitive and physiological processes prior to stress induction (Preston, Buchanan, Stansfield, & Bechara, 2007; Starcke, Wolf, Markowitsch, & Brand, 2008).

Conclusion

The findings in the current study offer two important additions to our current understanding of the impact of psychological stress on working memory. First, the results clarify the role of mind wandering and cortisol, such that cortisol does not directly result in working memory impairments but does increase the impact of mind wandering on working memory. This finding is in line with the idea that low-affinity glucocorticoid-receptor activation in the PFC (with high levels of cortisol) can lead to mind wandering through a disruption in deliberate, or task-related, attention processes (Chao & Knight, 1998; Gabrieli et al., 1998; Postle, 2006). Second, the results identified a possible explanation for a lack of impairment in working memory following a mild psychological stressor. The opposing indirect effect of threat perception on state anxiety may serve to protect working memory against stress-related impairments. Finally, the current study provides additional support for the Control Failures × Personal Concerns of mind wandering (McVay & Kane, 2010) such that working memory protects against mind wandering until the situation primes personal concerns that trigger mind wandering. These findings increase our understanding of the interplay between mind wandering and cortisol following stressors and the resulting impact on working memory.

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