Regulated and Unregulated Forms of Cortisol Reactivity: A Dual Vulnerability Model

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Objective: To test in a laboratory setting the hypothesis that the most problematic daily outcomes should be particular to individuals displaying higher cortisol reactivity and deficits in executive functioning as assessed in a task-switching paradigm. **Methods:** Thirty-eight volunteers completed a comprehensive assessment protocol. Individual differences in cortisol reactivity were quantified in an initial laboratory session involving a social stress speech task. Subsequently, individual differences in task-switching costs in a cognitive paradigm were assessed in a second session. Participants then reported on four problematic outcomes—error reactivity; worry; core aspects of negative emotionality; and aggression behavior frequency—for 15 consecutive days. **Results:** Levels of cortisol reactivity did not predict task-switching costs. Instead, and as hypothesized, individual differences in cortisol reactivity and task-switching costs interacted to predict the problematic daily outcomes. The highest levels of such problematic outcomes were particular to high cortisol reactors also exhibiting greater task-switching costs. **Conclusions:** The findings support the dual vulnerability model proposed and are discussed from temperamental, health risk, and daily outcome perspectives. These findings indicate that cortisol is a risk factor, particularly when combined with deficiencies in task-switching. **Key words:** cortisol reactivity, executive function, task switching, daily outcomes.

MLM = multilevel modeling; **RT** = reaction time.

INTRODUCTION

Our investigation borrows from what seems to be a particularly generative view of psychopathology among children and adolescents. Even very young infants differ in their stress reactivity (1). Stress-reactive infants and children, in turn, are unfortunately prone to many adverse outcomes later in life (2), including those of a health-related nature (3). However, the childhood temperament literature (4,5) suggested that such problematic outcomes may be particular to stress-reactive individuals who are not able to regulate their reactivity due to poor executive skills—termed "low effortful control" in this literature. Support for variants of this interactive risk model has recently been found in studies of internalizing and externalizing problems (6), biases to attend to threatening information (7,8), and extensions of the model have also proven effective in predicting alcohol and cannabis use (9,10).

In this literature, stress reactivity is typically assessed in terms of self- or parent-report, rather than in physiological terms, and effortful control is typically assessed similarly. Such reports are subjective, and there are concerns as to whether such subjective reports best tap the mechanisms of interest to psychosomatic researchers (11) or treatment providers (12,13). Pertinent to our investigation, self-reports of stress reactivity often fail to converge with biological assessments of stress reactivity (14). In addition, self-reported personality variables are notoriously insensitive to therapeutic change (15). Accordingly, a main goal of the present research was to objectively measure stress reactivity and poor executive skills among the same individuals and then to determine whether individuals displaying such dual vulnerabilities—i.e., high stress reactivity plus poor executive skills—might be most prone to a diverse array of problems in everyday living.

Stress reactivity can be assessed objectively in terms of changes in salivary cortisol levels after a stressor, most often in the context of variations of the Trier Social Stress Test (16). Stress reactivity of this type is thought be a major potential explanatory mechanism in understanding disease risks of multiple types (17). This literature has tended to focus on factors that exacerbate (social-evaluative conditions) (18) or mitigate (social support) (19) stressor reactivity in the laboratory, but it is also apparent that individuals differ dramatically in terms of such physiological stress reactions when eliciting conditions are held constant (20). In the latter connection, higher levels of cortisol reactivity have been linked to multiple problematic outcomes, such as self-reported stress (21), lower resilience (22), insecure attachment styles (23), depression (24), and overeating when stressed (25). Many of these findings fit with McEwen's (26) suggestion that unnecessary cortisol reactivity is a major biological risk factor for poor physical and mental health.

Self-regulatory deficits can be assessed objectively in terms of poor performance on cognitive tasks requiring executive functioning (27). Such tasks typically have two conditions—an easy condition in which automatic habits of mind are sufficient and a difficult condition in which such automatic habits of mind must be overridden (28). Executive processing deficits are then defined in terms of especially slow reaction times (RTs) exhibited in such difficult (relative to easy) task conditions (29). Extensive sources of data have shown that RT costs in such tasks are especially high among frontal-lobe damaged individuals (30) and are pronounced among old-aged individuals, whose brains encounter significant frontal-lobe shrinkage (31). Of more importance, poor performance in such tasks, even among younger individuals, has been shown to predict attention-deficit/hyperactivity disorder-like symptoms (32), behavioral problems (33), and tendencies toward aggressive behavior (34). In the present investigation, poor executive function is assessed in terms of task-switching costs, following the recommendations of prominent cognitive researchers (35).

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In accordance with dual-vulnerability considerations, we hypothesized that high levels of cortisol reactivity to a laboratory stress task in combination with pronounced task-switching costs would be particularly problematic. Cortisol reactivity and task-switching costs were assessed in different sessions to guard against order-of-measurement effects (36). Following such independent assessments, we assessed problematic outcomes in a daily experience-sampling protocol, procedures thought to capture "life as it is lived" (37) at the same time minimizing retrospective biases (38). Multiple problematic, although decidedly "proximal," health-relevant daily outcomes were assessed—error reactivity, worry, negative emotionality, and aggression. Respectively, these outcomes can be viewed in terms of cognition (error reactivity and worry), emotion (negatively emotionality), and behavior (aggression), thereby representing a broad conceptual range. The outcomes are likely to overlap, and convergence across them should be viewed in terms of what is shared among them—problems in daily living—rather than what is unique to each outcome measure.

METHODS

Participants

Forty-two (n = 20 females) North Dakota State University undergraduates completed a laboratory stress task and provided usable cortisol samples at both baseline and post-stressor time points. All 42 of these individuals provided usable data during the cognitive assessment portion of the study, but four of them were deleted for completing <55% of the daily surveys in the experience-sampling protocol. Analyses are, therefore, based on the 38 participants for whom complete data sets were available.

General Procedures

Participants initially completed a laboratory stressor assessment under the guidance of Dr. Hilmert (December 2006–April 2007). They received course credit for this portion of the study. Several weeks after the conclusion of the initial assessment, participants were recruited to Dr. Robinson's laboratory to complete a cognitive assessment, during which time deficits in task-switching abilities were measured (April 2007). After this second assessment, participants were asked to complete a 15-day Internet-based experience-sampling protocol (April 2007–May 2007). They received monetary compensation ($30 for full compliance) for these second and third portions of the study.

The study protocol was approved by our Institutional Review Board.

Individual Differences in Cortisol Reactivity

Laboratory Stressor Task

Participants initially volunteered for a study described as involving physiological responses to challenge. To control for diurnal variation in cortisol levels, all sessions were conducted between 1 PM and 5 PM. After arriving at the laboratory, informed consent was obtained. Subsequently, participants were fitted with electrodes for electrocardiogram assessment and a blood pressure cuff. Such measurements were not of interest to the present report and will be reported at a later time. After electrode placement, a 10-minute resting baseline ensued, during which time the participants were encouraged to relax.

After the 10-minute baseline, participants were informed that they would be asked to give a 5-minute speech on the topic of euthanasia to an undergraduate audience member (39). They were given 5 minutes to prepare their speech immediately before giving it. Participants were told to stand up while giving the speech and to be as convincing as possible in supporting a particular position (pro or con) on euthanasia.

To enhance the social-evaluative nature of this stressor task, several advocated procedures were used (16). An audience member was present during the speech. The audience member was described as a fellow undergraduate volunteer, but was actually a research confederate. This confederate was seated directly in front of the participant and was instructed to make extensive notes during the speech while expressing disapproving facial expressions and/or evaluative comments approximately every 30 seconds. In addition, the experimenter stood behind the participant's left shoulder during the speech. Finally, a prominent video camera was pointed at the participant during the speech, and it was stated that the speech would be evaluated by communication experts and professors at a later time.

Subsequent to the speech, participants were again told to relax. The video camera was pointed at the ceiling, the research confederate left the room, the participant was seated again, and a series of relatively mundane tasks were administered. The laboratory stressor was, thus, a discrete occurrence relative to the less stressful tasks occurring before and after it.

Cortisol Measurement

A Salivette (Sarstedt, Numbrecht, Germany) collection device was used for each of two salivary cortisol measurements. For each, participants chewed on the Salivette cotton dental roll for 3 minutes before replacing the dental roll back in the collection device. Samples were placed in a freezer (−20°C) immediately after the relevant participant-specific laboratory session. Salivary samples were sent to Salimetrics, LLC (State College, Pennsylvania). Cortisol levels were assayed from 25-μL samples, using the HS-cortisol High Sensitivity Salivary Cortisol Immunoassay Kit (Salimetrics, LLC, State College, Pennsylvania). Assays were performed in duplicate, and analyses were done using the average of these assay results (μg/dL).

The baseline measure assessed cortisol levels 10 minutes into the protocol, after a resting period. Studies (18) have shown that salivary cortisol levels associated with acute stress peak 21 minutes to 40 minutes after the onset of the stressor. Accordingly, a post-stressor cortisol measure was obtained 35 minutes after the speech task began. Baseline and post-stressor assessments of cortisol were not significantly correlated, although there was some degree of overlapping variance, $r = .17$, $p > .30$. To remove the modest overlapping variance observed, residual reactivity scores for post-stressor cortisol levels were computed such that they were necessarily uncorrelated with baseline levels of cortisol. Irrespective of individual differences, there was an increase in cortisol levels from baseline to post stressor, but one that was not significant, $F < 1$. In addition, such changes did not vary by sex, $F < 1$.

Individual Differences in Task-Switching Costs

Task

In task-switching paradigms, the interest is in the extent to which processing speed is slowed by requiring a switch (versus repeat) of a prior processing rule on the previous trial (29). There are two typical procedures used to examine such task-switching costs: one involves predictable trial-to-trial switches and the other involves unpredictable trial-to-trial switches. Altmann (40) reviewed relevant sources of data and suggested that unpredictable switches are more likely to tap the executive functions of interest. Accordingly, we used a paradigm of the latter type in the present investigation.

We modeled our cognitive task after that of Meiran, Chorev, and Sapir (41). Participants were asked to categorize simple numeric stimuli (1, 2, 3, 4, 6, 7, 8, and 9) according to one of two processing rules. Such stimuli were presented in one of two clearly outlined boxes. Participants were asked to categorize stimuli as odd (f key) versus even (j key) if presented in the higher of the two boxes, but to categorize stimuli as <5 (f key) versus >5 (j key) if presented in the lower of the two boxes.

Stimuli were randomly selected and randomly assigned to one of the two boxes. Thus, there was no predictability concerning the trial-specific stimulus, which box it would be presented in, and the stimulus-processing rules would produce orthogonal responses (e.g., if the digit "2" was presented, an f key response would be required if it was presented within the higher box, but a j key response would be required if it was presented within the lower box). When stimuli are presented in randomized locations, spatial attention processes contribute to performance, although such effects are typically as small as 15 milliseconds (42). Nevertheless, to reduce such spatial scanning contributions to performance, we presented a prominent arrow before each trial stimulus at least 300 milliseconds preceding it. Thus, the presented arrow would guide spatial attention in a manner that reduces such spatial contributions to performance. Therefore, task-switching costs of the type assessed can be primarily understood in terms of difficulties in overriding a prior task-set in favor of the current task-set (41).

To preclude possible speed-accuracy tradeoffs (43), a substantial 1200-millisecond error message was presented after inaccurate responses. Such procedures should produce a high accuracy rate and, therefore, render RTs the more sensitive measure. The task administered 160 consecutive trials.

Quantification

We heavily penalized errors and, thus, accuracy rates in the task should be very high. This proved to be the case, mean = 96.43%. In quantifying RT, several routine procedures were used (44). We deleted inaccurate responses, log-transformed millisecond RT values to reduce positive skew, and then replaced log latencies that were especially fast (<2.5 standard deviation [SD] below the mean) or slow (>2.5 SD above the mean) with such 2.5 SD cutoff scores. By such procedures, all accurate responses contributed to the computation of task-switching costs, but in a manner that reduced the undue impact of especially fast or slow responses (44).

Such transformed log-latency means were then quantified as a function of whether the same versus a switched response-mapping rule was required across consecutive trials (41). As is typically observed, there was a large normative switching cost, such that responses were quite a bit faster if the previous response mapping was repeated (mean = 751 ms) relative to switched (mean = 853 ms), $F(1,37) = 162$, $p < .01$. Of interest, though, was whether individual differences in task-switching costs would predict daily functioning. To examine this question, we computed a task-switching cost for each participant by subtracting the individual's log latency mean within the repeated condition from the individual's log latency mean within the switched condition. Higher scores, thus, reflect higher task-switching costs.

We also sought to estimate the reliability of individual differences in task-switching costs. To do this, one task-switching cost estimate was computed for odd target trials, and another was computed for even target trials. These two independent estimates were correlated at $r = .73$, $p < .01$, indicating a high degree of reliability.

Daily Outcome Measures

Procedures

The hypothesis of our dual-vulnerability model was that the most problematic outcomes should be observed among individuals a) who are high in cortisol reactivity and b) who exhibit large task-switching costs. To examine predictions from this model, we designed an experience-sampling protocol. For each of 15 consecutive days, individuals were asked to report on four outcomes reflective of problematic reactivity and functioning.

E-mails were sent each morning to remind study participants to complete the relevant survey later in the day. They did so each evening (after 8 PM) by logging into a secure Web site and completing the relevant daily survey. Surveys were removed at 9 AM the next day to minimize retrospective biases. We deleted the data of four participants who completed <55% of the daily reports. Among the remaining group of participants, compliance with the protocol was excellent, as the average participant completed 13.2 of the 15 surveys (mean = 88%; minimum number = 9 of 15).

Daily Outcomes

Broadbent et al. (45) suggested that stress reactivity renders individuals more prone to errors in everyday life. In addition, a brain region—the anterior cingulate cortex—that exhibits reactivity to errors has been implicated in disorders characterized by anxiety and worry (46). Accordingly, we first sought to assess the extent to which individuals noticed and reacted to errors on a daily basis. This daily error reactivity measure consisted of two items ("I noticed little errors I was making today" and "I was annoyed by mistakes today") responded to along a 1 (strongly disagree) to 5 (strongly agree) scale (mean = 2.68). The reliability of the scale, assessed across the 502 daily reports, was reasonably high ($\alpha = 0.70$).

Borkovec and Sharpless (47) reviewed several sources of data in support of the idea that worry is stress reactive but is also likely to be facilitated to the extent that cognitive control is weak (48). For example, higher levels of worry can be linked to the construct of rumination—i.e., difficulties in "moving on" after a problematic occurrence (49). Accordingly, we next sought to assess the extent to which individuals exhibited higher levels of daily worry ("I worried about a lot of things today" and "My worries interfered with other activities today"; 1 = strongly disagree; 5 strongly agree). This daily measure, too, exhibited reasonable levels of reliability ($\alpha = 0.71$).

Individual differences in negative emotionality are marked by stress-reactivity (3) and tendencies to be self-conscious and, in turn, criticize the self (50). There are also some sources of data (51,52) to suggest that such relations are particularly true of individuals exhibiting poor executive functioning. Accordingly, the daily survey next sought to assess several core attributes of negative emotionality ("criticized myself," "felt overwhelmed," and "worried about something"). A frequency scale (0 = not a single time; 3 = more than two times) was used. The α for this daily outcome scale was 0.71.

Wilkowski and Robinson (53) reviewed results consistent with the idea that the highest levels of aggression (e.g., arguing) seem to reflect both higher levels of emotional reactivity and lower levels of executive functioning. Although relevant experience-sampling data have not been reported, it is possible that cortisol reactivity may interact with task-switching costs to predict such behaviors. Accordingly, we sought to assess aggressive behaviors of this type in the daily survey ("argued with someone," "criticized someone," and "insulted someone"), again in relation to a 0 (not a single time) to 3 (more than two times) response scale ($\alpha = 0.72$).

Summary

We sought to understand the daily life correlates of cortisol reactivity and task-switching costs. We hypothesized that both higher levels of cortisol reactivity and higher task-switching costs would predict problematic daily outcomes, but particularly so in an interactive manner. Four problematic daily outcomes were selected on the basis of theoretical considerations, previous studies, and their presumed sensitivity to emotional reactivity processes—error reactivity, worry, daily negative emotionality, and aggressive behaviors. Convergence across these daily problematic outcomes would be particularly compelling.

RESULTS

Correlations Among Measures

The cortisol reactivity measure did not predict task-switching costs, $r = -.13$, $p > .40$. These two individual difference predictors, thus, assess different vulnerability factors. The daily outcomes all converged on individual differences in purported dysfunction, as all correlations were significantly positive, with correlations ranging from $r = .55$ (error and aggression) to $r = .82$ (error and worry), all $p < .01$. This was not unexpected, but the outcomes were conceptually distinct; we, therefore, report findings concerning each outcome separately.

Multilevel Modeling Results

On the outcome side, daily reports were nested, meaning that they were particular to a given individual. Such data are best analyzed by multilevel modeling (MLM) procedures (54). Analysis procedures of this type handle, in an unbiased manner, different rates of compliance (55), partition between—versus within—sources of variance appropriately (56), and are recommended in examining interactive hypotheses of the present type (55). MLM procedures were, therefore, used to analyze daily outcome patterns, specifically so in relation to Singer's (57) SAS PROC MIXED procedural recommendations.

Level 2 (individual difference) predictors of the daily outcomes were cortisol reactivity and task-switching costs. These were Z scored before analyses (54). Then, we performed four

MLM analyses, one for each of the daily outcomes. Results from these analyses are reported in Table 1. An important result that emerged was that higher levels of cortisol reactivity predicted higher levels of error reactivity, worry, daily negative emotionality, and aggressive behaviors with the other variables controlled. Such results encourage future studies seeking to link laboratory-assessed levels of cortisol reactivity to daily outcomes of a problematic type. In addition, higher task-switching costs significantly predicted higher levels of aggressive behavior, a result that comports with executive processing views of aggression (34,53).

Of more importance, there was robust evidence for an interactive relationship between the individual difference predictors. Specifically, as shown in Table 1, cortisol reactivity and task-switching costs interacted significantly to predict error reactivity, worry, daily negative emotionality, and daily aggressive behaviors. Such interactions remained significant when controlling for participant sex, all $p < .05$. To better understand the nature of the interactions, we estimated means for each outcome as a function of low (−1 SD) versus high (+1 SD) levels of cortisol reactivity in combination with low (−1 SD) versus high (+1 SD) levels of task-switching costs (58). These estimated means are displayed in Figure 1.

TABLE 1. Multilevel Results

	Cortisol Reactivity		Switching Costs		Interaction	
	t	*b*	*t*	*b*	*t*	*b*
Daily error reactivity	2.37*	0.33	1.17	0.14	2.28*	0.45
Daily worry	2.43*	0.34	1.17	0.14	2.16*	0.43
Daily negative emotionality	2.64*	0.27	1.33	0.12	3.11*	0.46
Daily aggressive behaviors	2.44*	0.28	2.12*	0.21	2.09*	0.34

* $p<.05$.

Simple Slopes Results

The graphs shown in Figure 1 support our dual-vulnerability model in that cortisol reactivity appeared problematic particularly among individuals with high task-switching costs. Simple slopes analyses (58) sought to support this interpretation of the results. When task-switching costs were high (+1 SD), cortisol reactivity predicted greater error reactivity ($t = 2.64$, $p < .05$, $b = 0.78$), greater levels of worry ($t = 2.58$, $p < .05$, $b = 0.77$), higher levels of daily negative emotionality ($t = 3.32$, $p < .01$, $b = 0.72$), and more frequent aggressive behaviors ($t = 2.54$, $p < .05$, $b = 0.62$). Such results indicate that cortisol reactivity is problematic among individuals exhibiting poor executive functioning.

On the other hand, a very different picture emerged in a second set of simple slopes analyses. When task-switching

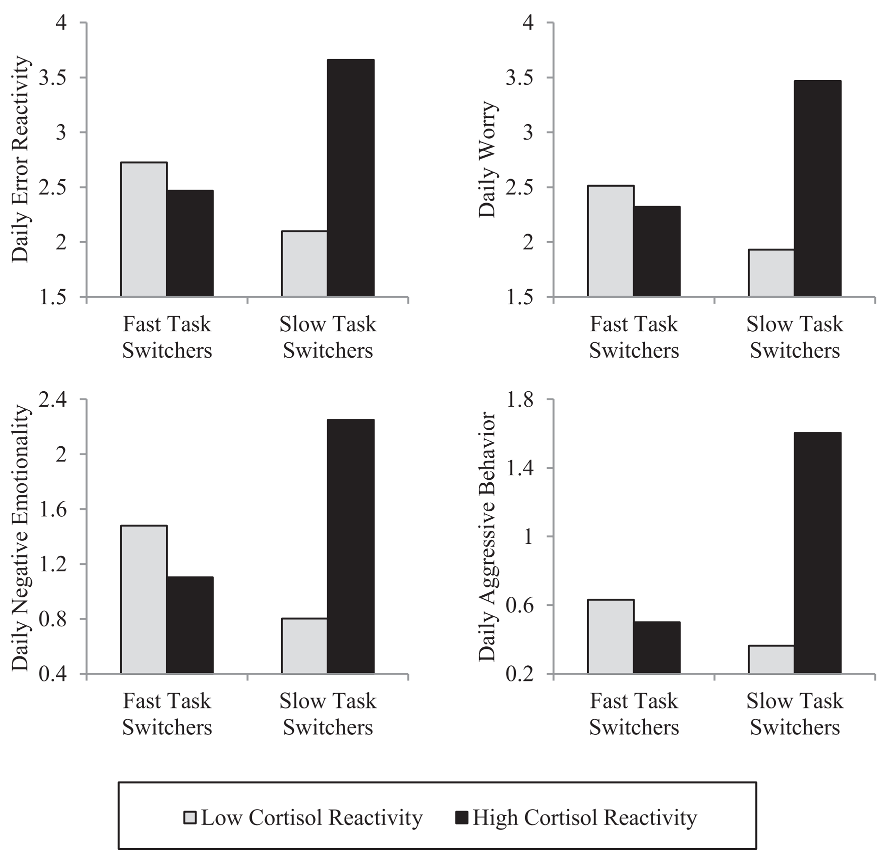

Figure 1. Interactions of cortisol reactivity and task-switching costs in the prediction of error reactivity (*top left panel*), worry (*top right panel*), negative emotionality (*bottom left panel*), and aggressive behavior (*bottom right panel*).

costs were low (−1 SD), cortisol reactivity did not predict error reactivity ($t = 0.74$, $p > .45$, $b = 0.13$), worry ($t = 0.55$, $p > .55$, $b = -0.10$), daily negative emotionality ($t = -1.48$, $p > .10$, $b = 0.19$), or more frequently exhibited aggressive behaviors ($t = -0.47$, $p > .60$, $b = -0.07$). The results, thus, support the idea that the combination of high cortisol reactivity and high task-switching costs is particularly problematic to daily functioning.

DISCUSSION

Cortisol reactivity and task-switching costs are best assessed under controlled laboratory conditions. Variations in such conditions have resulted in an impressive understanding of psychological and methodological factors that influence the magnitude of cortisol reactivity to stressors (18), as well as the magnitude of task-switching costs (35). At the same time, broader theorizing has suggested that individual differences in cortisol reactivity (17), on the one hand, and cognitive inflexibility (28), on the other hand, should be of value in understanding individual differences in dysfunction outside of the laboratory.

We sought to capitalize on such potential insights by a) assessing cortisol reactivity to a laboratory stress task; b) assessing difficulties in task-switching in a subsequent laboratory session; and c) using a daily experience-sampling protocol to bridge the lab-to-life interface (59), all among the same individuals. The results were informative: The most problematic daily outcomes occurred to the extent that the individual was higher in cortisol reactivity and lower in executive functioning (i.e., higher in task-switching costs). Such results are consistent with interactive models of temperament (4,5,60) and our dual-vulnerability predictions. They are discussed in relation to additional questions, implications, and future directions.

The frontal cortex is rich in receptors for cortisol and this has led to a search for relationships between cortisol release and tasks sensitive to frontal or executive functioning (61). Oei and colleagues (62) found that high levels of cortisol impaired working memory performance in a high-load condition, but not in a low-load condition. McCormick and colleagues (63) found that higher levels of cortisol led to more errors in the Wisconsin Card Sorting Test of executive functioning among women, but fewer such errors among men. Other findings could be cited, some linking cortisol reactivity to better—rather than worse—executive cognitive performance (64). It is difficult to make sense of this literature, other than to suggest that relationships between cortisol reactivity and executive functions are complex, subtle, and as yet not well understood (65). Given the complications of this literature, it was not surprising that there was no correlation between cortisol reactivity and task-switching costs in the present investigation.

Higher levels of cortisol reactivity are generally viewed as pathogenic and our findings, in part, support this idea. In an MLM model, we found that individuals exhibiting greater cortisol reactivity to our laboratory stressor task were more concerned with errors, more worried, higher in negative emotionality, and more aggressive in their everyday lives. Such results support the idea that individual differences in cortisol reactivity can be viewed in terms of threat appraisals (66) or stress-reactivity processes (16,17). In future studies of the present type, however, it would be useful to assess threat appraisals (67) and stress-reactivity processes (68) more directly than we did in the present experience-sampling protocol.

Importantly so, however, problematic daily outcomes were specific to cortisol reactive individuals exhibiting greater deficits in task-switching. This dual-vulnerability model should be extended to other outcomes that have been implicated in the cortisol reactivity literature, such as insecure attachment styles (23), depression (24), and overeating when stressed (25). If our model and its assumptions are more generally correct, these outcomes too should be particular to individuals who are cortisol-reactive and undercontrolled in executive processing terms.

Caveats and Final Considerations

The sample size was fairly small, but the research protocol was extensive. In addition, the daily outcome measures were assessed repeatedly, and doing so presumably increases their reliability and sensitivity to individual differences (69). In any case, the results were significant and robust. Thus, the interactions observed here can be considered fairly pronounced in effect size (β for the interactions ranged from 0.38 to 0.55) and consequential for this reason.

Individuals exhibit heterogeneous changes in cortisol levels in response to laboratory stress tasks (24), even under conditions in which there is no normative (mean) increase in salivary cortisol among the sample as a whole (20). This was the case in the present investigation and, accordingly, some of our sample actually exhibited cortisol decreases after the laboratory stressor. Why some individuals display decreases in cortisol release following laboratory stressors remains a relatively unexplored phenomenon, but a recent study (70) found that such decreases were associated positively with experienced fear during the baseline (pre-stressor) period. Such findings, although interesting, cannot account for the present findings as higher levels of cortisol reactivity predicted daily outcomes consistent with both fear (e.g., negative emotionality) and anger (behavioral aggression). Thus, our findings are more consistent with the idea that higher levels of cortisol reactivity reflect a general, rather than emotion-specific, propensity toward outcomes of a negative emotional type (65).

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