Comprehensive Psychoneuroendocrinology 9 (2022) 100106

Contents lists available at ScienceDirect

Comprehensive Psychoneuroendocrinology

journal homepage: www.sciencedirect.com/journal/comprehensive-psychoneuroendocrinology

Adolescents take more risks on days they have high diurnal cortisol or emotional distress

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ARTICLE INFO

Keywords:
Emotional distress
Risk-taking
Diurnal cortisol
Daily diary

ABSTRACT

This study investigates how the interplay between adolescents' daily levels of emotional distress and diurnal cortisol relates to their risk-taking behaviors. Specifically, we test competing hypotheses whether emotional distress exacerbates the link between cortisol and risk taking, or whether cortisol only predicts risk taking in the absence of emotional distress. Ethnically diverse adolescents (N = 370; ages 11–18) reported their daily levels of emotional distress and risk-taking behavior for 5 days, and provided 4 saliva samples/day for 4 days. Emotional distress was positively associated with risk taking the same day and on average across days. Moreover, emotional distress and total cortisol output interactively predicted risk taking, such that total cortisol output was positively associated with risk taking on days when adolescents felt low levels of emotional distress, but not on days when adolescents felt high levels of emotional distress. High levels of emotional distress were associated with high levels of risk taking regardless of total cortisol output. There were no direct associations between cortisol and risk taking on daily or average levels. Results suggest that cortisol is associated with risk-taking behavior on days when adolescents are not already feeling emotionally distressed enough to take risks.

1. Introduction

Adolescents are known for taking risks which could compromise their physical and emotional wellbeing. Identifying factors during adolescence which represent vulnerability or protect against risk-taking behavior is critical for informing interventions to promote adolescents' welfare [1]. Risk-taking behavior is driven in part by underlying neurodevelopmental changes which occur during adolescence, including heighted physiological and emotional responses to stress [2,3,4]. In particular, it has been hypothesized that adolescents make more risky decisions when they have elevated levels of the stress-hormone cortisol, which increases activation of neural systems that drive reward seeking behaviors [5], and when they are emotionally distressed, which depletes self-regulation and decision-making capacities [6,7,8]. Given that heightened cortisol and emotional distress each individually predict risk-taking behavior, it possible that a combination (i.e., interaction) of both heightened cortisol and emotional distress is linked to the highest levels of risk-taking behavior. Alternatively, it is possible that emotional distress only predicts risk-taking behavior in the absence of higher cortisol, or vice versa. However, these possibilities have not been empirically tested. Such knowledge is important for clarifying the conditions under which cortisol and emotional distress are precursors - or vulnerability factors - for the emergence of risk-taking behavior, and can inform efforts to reduce adolescents' health-compromising risks.

In this longitudinal daily diary study of adolescents, we test two competing hypotheses: whether emotional distress buffers or exacerbates the daily association between cortisol and risk-taking behavior. Specifically, we test whether levels of total diurnal cortisol output are positively associated with risk taking only when adolescents are experiencing emotional distress, or whether total diurnal cortisol output emerges as a second vulnerability factor for risk taking only in the absence of emotional distress. By examining how the interplay between physiological and emotional distress is linked to risk-taking behavior, this research may shed light on how and when to intervene in order to reduce adolescents' negative risk taking, and instead harness adolescents' risk-taking tendencies in order to support their positive development.

1.1. Risk-taking behavior during adolescence

Adolescents tend to take more risks than children or adults [1], in part because of underlying neurodevelopmental changes which

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https://doi.org/10.1016/j.cpnec.2021.100106
Received 13 December 2021; Accepted 13 December 2021
Available online 15 December 2021

influence decision making [8]. Adolescents' neurobiological systems are consistently vulnerable to stress [3], characterized by decreased cognitive-control, and increased physiological response to risk and reward [4]. Although some risk-taking behaviors can be positive [9,10], many risk-taking behaviors can compromise adolescents' physical, social and emotional wellbeing. For example, drug and alcohol use, risky sexual behavior, and lying or cheating can all threaten adolescents' physical safety and health, as well as their interpersonal relationships, emotional stability, and chances of life-long success [11]. As such, identifying the emotional and physiological correlates of risk taking is critical, because such knowledge can help researchers to understand how to mitigate adolescents' negative risk-taking behavior, and promote their positive adjustment across the lifespan [1].

1.2. Diurnal cortisol and risk-taking behavior

Researchers in developmental neuroscience have long recognized that adolescents' physiological arousal plays a key role in their risk-taking behavior, in part by influencing underlying cognitive functioning and decision-making capacities [12,13,14]. One key physiological marker that influences cognitive functioning and behavior is cortisol, a stress-hormone which is the end product of hypothalamic-pituitary adrenal axis (HPAA) activation [15]. Elevated levels of cortisol are proposed to increase risk-taking behavior, in part by increasing activation of the neural systems which drive reward seeking [7]. Specifically, according to the Stress Triggers Additional Reward Salience model [7], heightened cortisol is associated with dopamine release in the ventral striatum, a key component of brain circuitry for decision making and reward-related behavior [16,17]. In turn, dopamine and glucocorticoid exposure increase striatal activation, which enhance the salience of potential rewards [7], and predisposes individuals to risky behavior.

Consistent with this theory, empirical evidence from animal and human models provides some evidence that cortisol is positively associated with risk-taking behavior [5,18]. In rodents, experimental administration of cortisol increased reward drive by facilitating dopamine release in the ventral striatum [5]. In human models, three double-blinded experiments found that medical administration of cortisol increased risk-taking behavior [19,20,18], although one other experiment found the opposite effect [21]. In another study, higher levels of diurnal cortisol measured in saliva were linked to greater risk-taking behavior [19]. Further, acute cortisol reactivity to laboratory challenges has been positively associated with risk-taking behavior in several studies, although there been mixed and inconclusive results (for a review, see Ref. [22]. However, most prior work has focused on acute cortisol reactivity in response to laboratory stressors or risk-taking tasks (e.g., Daughters et al., 2013; Pabst et al., 2013; van den Bos et al., 2014), rather than diurnal cortisol levels which occur naturally throughout the day. Measuring diurnal cortisol is more ecologically valid because diurnal cortisol reflects naturally occurring fluctuations in cortisol in real-life settings outside of the laboratory. Accordingly, daily measurement of diurnal cortisol can shed light on the role that cortisol plays in risk-taking behavior in real world environments that adolescents' experience.

A few studies have examined the link between diurnal cortisol and risk taking in adults [23,24]. In one study of young adults, baseline levels of salivary cortisol were positively correlated with self-reports of risk-taking behavior [25] and observed risk-taking behavior during financial investments [19] In addition, one study of young adolescents found that elevated levels of morning cortisol were associated with higher effortful control, although the authors did not measure risk taking explicitly [26]. To extend this work, more research is needed to clarify whether heightened daily levels of diurnal cortisol represent vulnerability for risk taking behavior in adolescents' daily lives. For instance, measuring total diurnal cortisol output and risk-taking behavior repeatedly across days could illuminate whether adolescents take more risks on days that they display higher total cortisol output. This would support the hypothesis that elevated cortisol that occurs naturally across the day is linked to greater risk-taking behavior.

1.3. Emotional distress and risk-taking behavior

Beyond physiological arousal, adolescents' emotional distress is one of the strongest predictors of their risk-taking behavior [27,28,29]. Youth who experience more depressive symptoms tend to engage in more substance use and other physical health risk behaviors [30,31]. Increased risk taking may in part serve as a coping mechanism for distressing emotions (Boals, vanDellen, & Banks, 2011). Further, emotional distress decreases adolescents' ability to inhibit natural responses, which makes it difficult to resist risky impulses [8]. Indeed, one study used ecological momentary assessments (EMAs) and revealed that more stressful experiences from daily life were linked to lower impulse control on a laboratory task [8]. Further, laboratory studies have illustrated that adolescents make more risky decisions when they are experiencing high levels of emotional stress [32,6]. However, similar to research on cortisol, it is unclear whether adolescents' naturally occurring, daily levels of emotional distress are associated with their risk-taking behavior [8]. Such research can clarify the association between natural variations in emotional distress and risk-taking behavior in real world environments.

In addition, it is possible that the *interplay* between diurnal cortisol and emotional distress predicts risk-taking behavior. By measuring emotional distress, diurnal cortisol and risk taking repeatedly across days, researchers could identify days when adolescents are particularly susceptible to risk taking in the context of both diurnal cortisol and emotional distress. For instance, adolescents may take the most risks on days that they have high levels of both diurnal and emotional distress, because these would serve as dual emotional and physiological risk factors and exacerbate one another. Alternatively, it is possible that the effect of emotional distress on risk taking is so robust that emotional distress outweighs cortisol as a risk factor. If this were the case, adolescents would engage in high levels of risk-taking behavior when they are emotionally distressed, regardless of their cortisol levels. Heightened cortisol may only emerge as a second vulnerability factor when emotional distress is not already high, if emotional distress is overwhelmingly predictive of greater risk-taking behavior. Such research could inform interventions to redirect adolescents' risk-taking propensity towards positive outlets.

1.4. Current study

This longitudinal daily diary study investigated (1) How adolescents' daily levels of total diurnal cortisol output and emotional distress are uniquely associated with risk-taking behavior; and (2) Whether total diurnal cortisol output and emotional distress interactively predict risk-taking behavior on a daily level. We operationalized total cortisol output per day as the *Area Under the Curve* (AUC) which is optimal when moderate or low [33]. For direct associations, we hypothesized that adolescents would take more risks on days that they exhibited higher levels of total cortisol output and felt higher levels of emotional distress. For interactive associations, we had two competing hypotheses: (1) adolescents would take the most risks on days that they had higher levels of total cortisol output and emotional distress, because these dual risk factors would exacerbate one another; or alternatively, (2) total cortisol output would positively predict risk taking only on days that adolescents were not emotionally distressed, because emotional distress would "overpower" any potential vulnerability to risk taking that eleveated diurnal cortisol levels represent.

2. Methods

2.1. Sample and procedure

Participants were 370 adolescents (57.3% female; M_{age} = 14.63 years, *SD* = 1.39 years; Range 11–18). The sample was racially diverse: 39.46% were Non-Latinx White (N = 146), 25.4% Asian (N = 94), 17.8% Latinx (N = 66), 10.8% African American (N = 40), and 6.5% other race (N = 24). Approximately 10% of mothers had less than an eighth-grade education, 13% did not complete high school, 24% completed high school, 27% completed postsecondary education, and 23% completed graduate school (3% declined to answer). Participants were recruited from the community using convenience sampling (e.g., posting flyers at schools and on listservs). Participants were compensated $10 in total for completing daily diaries and $10 for completing saliva samples, and received a $20 bonus if inspection of the data indicated that they had completed all the diaries and saliva samples correctly and on time (94.24% of samples were on time).

Participants were recruited as part of seven sub-studies in the U.S. Midwest and West. These sub-studies were all combined for the current sample. Because of this methodology, participants in some studies completed slightly different protocols (described further below). Differences were due to limitations of time and resources, and the protocol being improved over the course of the full study with slight alterations. All participants were provided with diary checklists. In the full project, most participants (80%) were provided 14 days of diaries, whereas 22% of participants (N = 83) were only provided with 7 days of diaries. Participants were also provided a saliva collection kit to complete on days 2 through 5. In the study, our analyses only include days 1–5, for which all participants had data, which include the days during which cortisol was collected (days 2–5), as well as the day before the first day that cortisol was collected (since we control for risk-taking behavior the prior day). The maximum number of days used in any statistical model in this study is 5.

Most participants (90.43%) completed all days of their dairies across the 6 days used for analysis (*M* = 97.65% of days, *SD* = 35.19% of days, Range = 25%–100%). There were 1,710 total person-day (i.e., Level 1) observations. Diaries included both weekdays and weekends. The order of days differed between participants depending on the day of the week that they started, but all participants had the same proportion of weekday to weekend data if they completed all of the diaries. Participants were instructed to complete their diary in the evening before bedtime. Participants chose to complete the diaries either on paper (63.20%) or via a secure website (36.80%). Participants who responded with paper and pencil were given 14 manila envelopes and an electronic time stamper (Dymo Corporation, Stamford, CT), which verified the time that checklists were completed. The time stamper is a small device that imprints the current date and time and is programmed with a security code so that the correct date and time cannot be changed. Participants were instructed to place their completed checklists into a sealed envelope each night and to stamp the seal of the envelope with the time stamper. Participants who completed surveys online were sent an email with the link to each daily diary survey, and the time and date of completion were recorded via the website. The daily diary checklists were 3 pages long and each took approximately 5–10 min to complete. All procedures were approved by the Ethical Review Board at the sponsoring institution. Data and syntax are available upon request.

2.2. Measures

Daily Emotional Distress. To index emotional distress, we used nine items on the daily diary checklist: sad, hopeless, discouraged, on edge, unable to concentrate, uneasy, nervous, stressed, and worried; daily *alphas* = .86–0.94, and overall Cronbach's *alpha* = .92. Specifically, we calculated two variables for emotional distress: one at the daily level (i.e., within-subjects), and one at the average level (i.e., between-subjects). At the daily level, we calculated the average of the emotional distress items each day. At the average level, we calculated the person-mean value of emotional distress as the average across all days for each individual. Missing data for AUC was 22.10% of days. Measurements each day were correlated 0.68 within the same individual (ICC = 0.68).

Daily Total Cortisol Output. Participants provided saliva at four time-points each of 4 days, for a total of 16 samples: (a) immediately upon waking up, (b) 30 min after waking up, (c) 5 p.m. (or before dinner), and (d) 8 p.m. (or before bed). Participants were instructed to take their samples before or >30 min after brushing teeth, drinking, eating, or using tobacco. In addition, raw cortisol values exceeding 60 nmol/L were flagged as outliers and excluded from analyses.

Participants recorded the timing of each sample using a log-card and stamped with the electronic time stamper, which printed the current, unalterable, date and time. Participants stamped the card beside the heading for each sample and immediately placed the sample in their fridge. At the end of the saliva collection days, the samples were transferred to the research laboratory and stored in a −80 °C freezer. At the end of the data collection period, the samples were shipped to the Laboratory of Biological Psychology at the Technical University of Dresden, Germany where they were assayed using high-sensitivity chemiluminescence-immunoassays (IBL International, Hamburg, Germany). The inter-assay coefficient of variation was <8%.

To index total daily cortisol output, we computed *Area Under the Curve (AUC)*. Specifically, we computed AUC using the trapezoid method from the first, third, and fourth cortisol measures (i.e., excluding the second sample, [34]. Specifically, we calculated two variables for AUC: one at the daily level (i.e., within-subjects), and one at the average level (i.e., between-subjects). At the daily level, we calculated AUC each day as described above. At the average level, we calculated the person-mean value of AUC as the average across all days for each individual. Missing data for AUC was 16.78% of days. Measurements each day were correlated 0.39 within the same individual (ICC = 0.39).

Daily Risk-Taking Behavior. Participants indicated via diary checklists whether they had engaged in 16 different risk taking behaviors each day: Lied or misled your parents; Threatened or insulted a family member; Threated, insulted, or made fun of a peer; Engaged in sexual activities not included intercourse (kissing, sexual touching, oral sex); Sexted; Had sexual intercourse; Drank alcohol; Used nicotine; Used cannabis; Used other drugs; Hit or hurt someone; Stole something; Lied to someone; Cheated on something; Snuck out of your house without your parents knowing; Went somewhere your parents would disapprove of. To create these risk-taking items, we used items adapted from the Youth Risk Behavior Surveillance System (CDC, 2004). Consistent with this survey, we considered these activities risk-taking behaviors because they have the possibility of compromising adolescent health when not done in safe and developmentally-appropriate ways. Similar daily diary items have been used to assess risk-taking behavior in prior published studies (e.g., Armstrong-Carter et al., 2021). The composite variable was continuous, with higher values reflecting more risk-taking behavior (Cronbach alpha = .56). The low Cronbach alpha is likely because these risk-taking items reflect divergent aspects of risk-taking behavior because we used a checklist approach. For instance, adolescents might have sexual intercourse on days that they did not use drugs, and vice versa. These behaviors do not necessarily co-occur but each reflect a unique aspect of general risk taking. There was no missing data for this variable. Measurements each day were correlated 0.40 within the same individual (ICC = 0.40).

Demographic Characteristics. We report demographic characteristics only for descriptive purposes. Because our analyses approach is within-subjects, characteristics which vary between subjects do not need to be included as covariates. Mothers reported their *Maternal Education* level, which ranged from 0 (<8th grade completed) to 6 (completed graduate school), *Family income*, which ranged from less than $14,999 to more than $90,000 (Median = $60,000 - $74,999). Missing data was

4.01% for maternal education and 5.46% for family income. Adolescents self-reported their age, gender, and race/ethnicity. Race/ethnicity was dummy coded within each race (i.e., Latinx = 1, not Latinx = 0) and categorized into five groups: African American, Asian, Latinx, White non-Latinx, and Other or Mixed Race.

2.3. Statistical analyses

Linear mixed effect models nested days (Level 1) within participants (Level 2). We person-centered all Level 1 predictors, and we included on the intercept person-mean values for each of our daily predictors [35]. This approach helps to isolate within-subject daily associations from between-subject average associations. Accordingly, in the tables, "Daily" variables reflect daily-level values which fluctuated within individual participants (e.g., did adolescents engage in more risk-taking behavior on days they experienced more emotional distress than usual?). In contrast, "Average" variables reflect levels of values averaged across days within each individual participant (e.g., do adolescents who experience more emotional distress on average across days display greater risk-taking behavior on average across days?). To increase the robustness of our findings, we additionally controlled for prior day levels of the outcome (i.e., risk-taking), to test if emotional distress and cortisol were associated with risk taking over and above the previous day.

Model 1 tested emotional distress and cortisol (i.e., AUC) as simultaneous Level 1 predictors of risk taking the same day. Model 2 additionally included daily-level and average-level interaction terms between emotional distress and cortisol (i.e., AUC). Specifically, we created two daily-level interaction terms (i.e., daily levels of emotional distress multiplied by daily levels of each cortisol marker) and two average-level interaction terms (i.e., person-average levels of emotional distress multiplied by person-average levels of each cortisol marker) and included these interaction terms as predictors. In addition, as described further in the results, we tested two exploratory findings: first to examine whether cortisol awakening response (CAR) and diurnal cortisol slope were related to risk taking, and second to examine whether our primary results were consistent for girls and boys. To probe significant interactions, we used the simple slopes technique at 1SD above and below the mean value of the moderator [36]. We managed missing data using full information maximum likelihood (FIML). All analyses were conducted using Stata Software (StataSE, Version 17).

3. Results

3.1. Descriptive statistics and bivariate correlations

Table 1 displays descriptive statistics for the full sample, and for boys and girls. Values were averaged across all days within individuals. On average, girls reported higher levels of risk taking and higher levels of emotional distress. There were no gender differences in cortisol. Table 1 also displays bivariate correlations using variables averaged across all days within individuals. On average, risk taking was positively correlated with emotional distress. AUC was positively correlated with family income. There were no other significant correlations.

3.2. Multilevel regression results

Table 2 displays multilevel regression models. Model 1 tested how emotional distress and cortisol each directly predicted risk taking on daily and average levels. As shown in Model 1, emotional distress was positively associated with risk taking the same day (i.e., on the daily level) and across days (i.e., on the average level). There were no direct associations between cortisol and risk taking on daily or average levels.

Model 2 tested how emotional distress and cortisol interactively predicted risk taking on daily and average levels. As shown in Model 2, the interaction between daily emotional distress and daily AUC was significantly associated with risk taking the same day. Specifically, as displayed in Fig. 1, AUC was positively associated with risk taking on days when adolescents felt low levels of emotional distress, but not on days when adolescents felt high levels of emotional distress. High levels of emotional distress were associated with high levels of risk taking regardless of AUC. There were no other significant direct or interactive associations.

3.3. Exploratory analyses

In addition, we conducted two sets of exploratory analyses. First, we explored whether CAR or diurnal cortisol slope was directly or interactively (with emotional distress) related to risk taking, by replacing CAR and diurnal cortisol slope as predictors in the model instead of AUC. CAR is the rise in cortisol shortly after awakening, and diurnal cortisol slope is the decline in cortisol across the day. Both CAR and slope are typically correlated on a daily level with AUC because they are drawn from some of the same cortisol measurements throughout the day, so it is useful to understand whether our findings reflect AUC specifically or more general patterns in diurnal cortisol fluctuations throughout the day. We found that neither CAR nor diurnal cortisol slope were directly or interactively related to risk taking on a daily level ($p > 0.05$).

Table 2
Daily total cortisol output (AUC) interacts with daily emotional distress to predict risk-taking behavior.

	Risk-Taking Behavior			
	Model 1		Model 2	
	B	*SE*	*B*	*SE*
Risk Taking Prior Day	−0.059+	(0.033)	−0.057+	(0.033)
Daily Emotional Distress	0.157***	(0.039)	0.179***	(0.040)
Average Emotional Distress	0.282***	(0.047)	0.470***	(0.136)
Daily AUC	0.000	(0.000)	0.000	(0.000)
Average AUC	−0.001	(0.000)	0.001	(0.001)
Daily AUC X Daily Distress			−0.001*	(0.001)
Av. AUC X Average Distress			−0.001	(0.001)
Constant	−0.083	(0.118)	−0.406	(0.252)

Note: Standard errors in parentheses. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, +$p < 0.1$. Results remain the same with or without prior day risk taking in the model.

Table 1
Descriptive statistics for full sample, for boys and girls, and bivariate correlations between study constructs averaged across days within individuals.

		Boys		Girls		Full Sample				*Bivariate Correlations*			
		M	*SD*	*M*	*SD*	*M*	*SD*	*Min*	*Max*	*1*	*2*	*3*	*4*
1	Risk Taking	0.14[1]	0.29	0.28[2]	0.44	0.23	0.40	0.00	2.93	1			
2	Emotional distress	1.53[1]	0.55	1.75[2]	0.72	1.65	0.66	1.00	4.57	0.32***	1		
3	AUC	153.29[1]	57.14	165.73[1]	75.66	160.64	68.37	−185.58	492.92	−0.02	−0.02	1	
4	Maternal Education	3.63[1]	2.10	3.79[1]	1.78	3.73	1.92	0.00	6.00	0.08	−0.03	0.07	1
5	Family Income	4.16[1]	2.15	3.72[1]	2.09	3.91	2.13	0.00	6.00	−0.03	−0.06	0.26***	0.58***

Note. The differences between boys and girls are significant for mean values which have a different numerical superscript, but not for mean values which have the same numerical superscript. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, +$p < 0.1$.

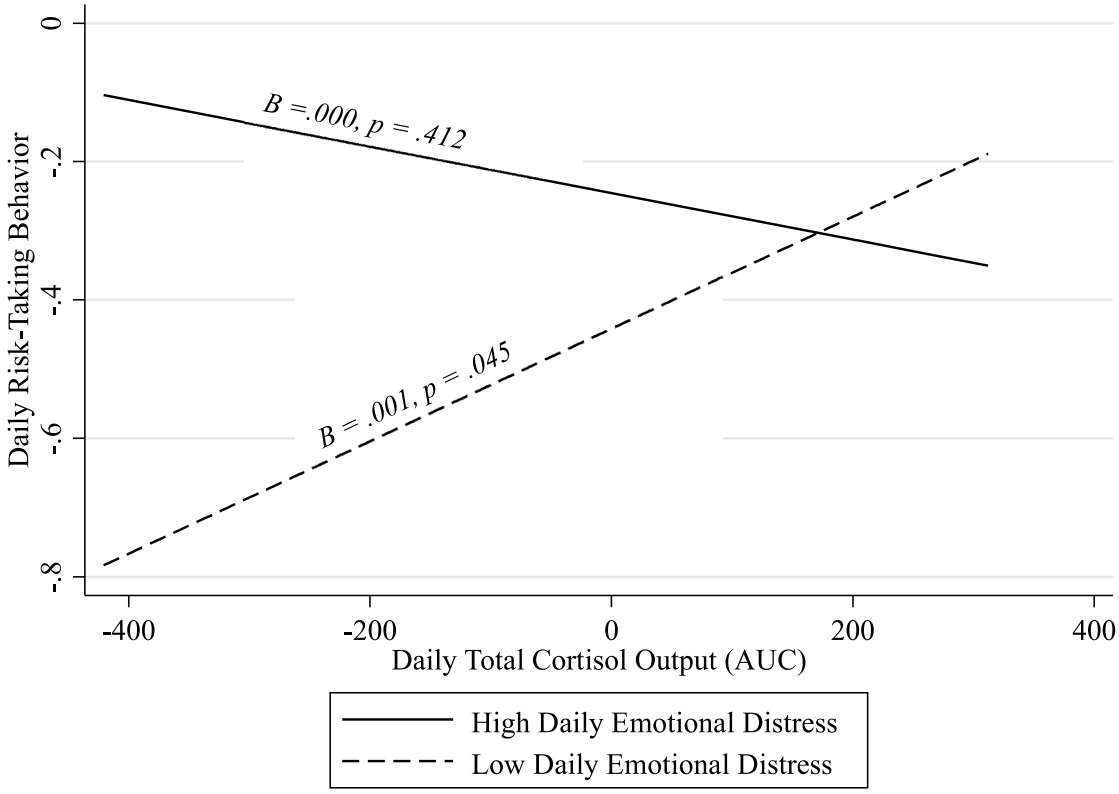

Fig. 1. High total cortisol output (AUC) is a risk factor for risk-taking behavior only on days when adolescents are not emotionally distressed. Both AUC and emotional distress are person-mean centered.

Second, we examined whether the interaction between emotional distress and cortisol predicting risk taking differed for girls compared to boys. Specifically, we added two three-way interaction terms as simultaneous predictors to the model, one on the daily level (i.e., daily emotional distress X daily AUC X gender) and one on the average level (i.e., person-average emotional distress X person-average AUC X gender). Neither of the interaction terms were significant, suggesting that the results remained consistent for boys and girls.

4. Discussion

The goal of this study was to understand how adolescents' daily levels of emotional distress and diurnal cortisol relate to their risk-taking behaviors within and across days. We drew on a large sample of ethnically and socio-economically diverse adolescents and used within- and between-subject analyses. We found that adolescents engaged in more risk-taking behavior on days that they felt high levels of emotional distress, over and above their cortisol levels. However, on days when adolescents felt low levels of emotional distress, high total cortisol output emerged as a second vulnerability factor for risk-taking behavior, and low total cortisol output emerged as a protective factor. The lowest levels of risk-taking behavior occurred on days when adolescents had low levels of both emotional distress and total cortisol output. In contrast to prior related research which focused on laboratory tasks [22], our study extends our understanding of the interplay between emotional distress, cortisol and risk-taking behavior to adolescents' real world, daily environments.

4.1. Adolescents take more risks on days they feel greater emotional distress

We found that adolescents took more risks (e.g., drug use, risky sexual activity, cheating) on days when they were experiencing high emotional distress (e.g., feeling sad, hopeless, discouraged). This association persisted when accounting for adolescents' average levels of emotional distress across days, and their levels of total diurnal cortisol output. Emotional distress may be linked to greater risk taking via several mechanisms. First, emotional distress may interfere with adolescents' ability to inhibit their natural responses, self-regulate, and resist risky impulses [8]. In particular, adolescents may be less able to engage in effective cognitive control by recruiting the prefrontal cortex, which is important for inhibiting impulsive decisions under conditions of emotional stress [8]. Second, when adolescents are trying to cope with emotional distress, they may tax and deplete their self-regulatory skills, which otherwise could have been used to inhibit risky behaviors or resist peer pressures [37]. Third, risk taking may serve as a coping mechanism when adolescents are trying to manage difficult and distressing emotions [38]. Our finding is consistent with prior studies that youth who experience more emotional distress and depressive symptoms tend to engage in more substance use and other physical health risk behaviors [30,31]. Our study also converges with prior laboratory studies showing that adolescents make more risky decisions and show lower impulse control when they are experiencing high levels of emotional stress [32,6,8]. In contrast to prior studies which used between-person analyses and measured risk taking via laboratory-based computer tasks [32,6,8], we demonstrate that adolescents' daily levels of emotional distress are associated with their risk-taking behavior in their real-world, daily environments such as school, home, and social settings with peers.

4.2. Cortisol output predicts greater risk taking only on days without emotional distress

Only on days that adolescents experienced low levels of emotional distress did cortisol emerge as a significant predictor of risk-taking behavior. Specifically, on days that adolescents were not distressed, high total cortisol output was associated with higher levels of risk taking, whereas low total cortisol output was associated with lower levels of risk taking. In other words, high total cortisol output appeared to be a vulnerability factor, and low total cortisol output appeared to be protective for risk taking, but only in the context of low emotional distress. Heightened total cortisol output may serve as a vulnerability factor for risk taking only when emotional distress is low because emotional distress is highly predictive of risk-taking behavior and "outweighs" any physiological vulnerability factors. Specifically, emotional distress may result in ceiling levels of risk taking, and therefore outweigh any potential vulnerability to risk taking that cortisol represents, such that cortisol only emerges as a vulnerability factor in the absence of emotional distress. This finding highlights the importance of examining both emotional and physiological correlates of risk taking simultaneously, rather than in separate statistical models or studies.

Prior research suggests that elevated cortisol increases risk-taking behavior [20,18], in part by reducing underlying cognitive functioning and decision-making capacities [12,13,14]. Specifically, elevated cortisol is thought to increase activation of neural systems underlying reward seeking, by releasing dopamine in the ventral striatum [7,16,17]. Glucocorticoids and dopamine exposure then increase striatal activation and enhance reward salience [7], which in turn may predispose individuals to risky behavior. These neural pathways may be one mechanism to explain our findings that higher total cortisol output is related to higher risk taking, and lower total cortisol output is related to lower risk taking on a daily level. Future research should combine daily diary and neuroimaging methods to investigate which neural pathways serve as mechanisms and underlie these daily associations.

4.3. Future directions

By identifying emotional and physiological factors which co-occur with risk taking, our study highlights days on which risk taking is most likely to occur. In the future, this work may inform the design of interventions to mitigate adolescents' negative risk taking, and promote positive or prosocial risk taking via redirecting risk-taking tendencies to positive contexts. For instance, future research could track adolescents' emotional distress via app or cell-phone based technology, and their cortisol, for example, through a new skin patch that continuously records levels of cortisol in sweat [39,40]. This methodology could clarify whether emotional distress and heightened cortisol temporally precede risk taking behavior, and identify specific moments, or periods of the day, when adolescents are most likely to take risks. Interventions could then be designed to intervene in those moments. Specifically, interventions could aim to reduce adolescents' distress (e.g., via mindfulness or distraction-based techniques), reduce their opportunities for taking negative risks, and redirect their risk-taking tendencies towards more constructive outlets that serve individual goals or help peers. However, it will first be necessary to replicate our findings in other samples and contexts, and conduct further descriptive research.

4.4. Limitations

We acknowledge limitations. First, we were unfortunately unable to control for smoking or alcohol use which could impact cortisol [41]. We were also unable to control completely for medication use as we only collected this information from a subset of participants. Future research should control for these variables. Second, due to the rich nature of our daily diary and cortisol assessments, there was also a level of missing data. In particular, days that adolescents did not respond to the diaries or did not provide cortisol samples might represent the most difficult days with the highest emotional distress or cortisol. Third, our study measured emotional distress and risk taking both via daily diaries at the end of the day, and cortisol throughout the day, so the precise temporal order of emotions and events cannot be determined. As we discussed above, future research may clarify whether emotional distress and cortisol temporally precede risk-taking behavior by incorporating ecological momentary assessments (EMAs) throughout the day. Although we focused on a general measure of risk-taking behavior, future research should also differentiate between different types of assessments of risk-taking behavior (e.g., substance use compared to risky sexual activity) to clarify whether our findings are consistent across different specific risk-taking domains.

In addition, our exploratory analyses revealed there were no significant gender differences in how emotional distress and cortisol output related to risk taking. Future work may further explore potential gender differences in other samples and differentiate between the type of risk taking. For instance, two studies found that cortisol was more strongly linked to risk taking behavior among young men compared to young women [20,25], and adolescent boys take more risks in social settings with peers, whereas young girls take more risks related to their parents [42]. Given this prior research, it is feasible that the interaction between emotional distress and cortisol is more strongly linked to social risks among boys, but more strongly linked to family-related risks among girls.

4.5. Conclusion

Our study sought to identify the emotional and physiological correlates of adolescents' risk-taking behavior on a daily level. Our results suggest that emotional distress is linked to greater risk-taking behavior the same day. Further, greater total cortisol output is associated with greater risk-taking behavior, but only on days when adolescents are not already feeling emotionally distressed enough to take risks. By identifying days when adolescents are particularly vulnerable to risk taking behavior — in the context of both their emotional and physiological states — this study may help researchers in the future to understand when and how to mitigate adolescents' negative risk-taking behavior, and redirect adolescents' risk-taking tendencies towards positive or prosocial outlets.

Conflict of interest

The authors have no conflict of interest to declare. Data and syntax are available upon request.

Acknowledgements

This manuscript was prepared with support from (1) the Institute of Education Sciences (R305B140009) to Stanford University, awarded to Emma Armstrong-Carter, and the Stanford Data Science Fellowship, awarded to Emma Armstrong-Carter, (2) National Institutes of Health Grant R01DA039923 and National Science Foundation Grant SES 1459719 provided to EHT, the Department of Psychology at the University of Illinois, and the Department of Psychology and Neuroscience at the University of North Carolina at Chapel Hill. This study was not preregistered.

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