Jodi A. Quas[1]
Ilona S. Yim[1]
Robin S. Edelstein[2]
Larry Cahill[3]
Elizabeth B. Rush[1]

[1]*Department of Psychology and Social Behavior, University of California 4201 Social and Behavioral Sciences Gateway, Irvine, CA 92697-7085 E-mail: jquas@uci.edu*

[2]*Department of Psychology, University of Michigan, Ann Arbor, MI*

[3]*Department of Neurobiology and Behavior, University of California Irvine, CA*

The Role of Cortisol Reactivity in Children's and Adults' Memory of a Prior Stressful Experience

ABSTRACT: *The purpose of this study was to identify whether cortisol reactivity to a stressful laboratory event was related to children's memory of that event and to determine whether this relation was comparable to that observed in adults. Nine- to 12-year-olds and young adults completed an impromptu speech and math task during which repeated cortisol samples and self-reported stress ratings were collected. Two weeks later, participants' memory for the tasks was examined. Greater cortisol reactivity was associated with enhanced memory, most prominently in children. Self-reported stress was unrelated to memory. Findings reveal that an important mechanism underlying the association between emotion and memory in adults, namely activation of the hypothalamic pituitary adrenal axis, appears to operate similarly in late childhood. Findings also demonstrate that positive associations between cortisol reactivity and memory are evident when the event that actually elicited that reactivity serves as the to-be-remembered event. © 2010 Wiley Periodicals, Inc.* Dev Psychobiol 53: 166–174, 2011.

Keywords: *children; HPA axis activation; memory; cortisol; reactivity; recall*

INTRODUCTION

Despite decades of research with adults demonstrating that negative emotional, often stressful, information can be remembered quite well, critical gaps remain in our understanding of children's memory for emotional information, especially in the extent to which mechanisms thought to affect memory for emotional experiences in adults also apply to children (e.g., Quas & Fivush, 2009; Reisberg & Hertel, 2004). In particular, a large body of research suggests that activation of the hypothalamic pituitary adrenal (HPA) axis is an important predictor of adults' memory for negative emotional information (McGaugh, 2004; Wolf, 2009). Very few studies; however, have examined HPA axis activation and memory in children, and the methodologies employed in studies with children and adults have varied, making comparisons across age virtually impossible. Thus, it is not known whether the links between HPA axis activation and memory differ across age.

The HPA axis is a key biological system responsive to stress exposure. When activated, the hypothalamus releases corticotropin-releasing hormone (CRH), which stimulates the release of adrenocorticotropic hormone (ACTH) from the pituitary. ACTH binding on the adrenal cortex results in the release of cortisol, the most important glucocorticoid in humans. Glucocorticoid binding on the pituitary, hypothalamus, and higher order brain sites serves as a negative feedback system that gradually down-regulates the activity of this system (Eichenbaum & Otto, 1992; Munck, Guyre, & Holbrook, 1984). High concentrations of glucocorticoid receptors are found in key regions of the brain relevant for emotional memory, including most notably the hippocampus and amygdala (Erickson, Drevets, & Schulkin, 2003; McGaugh, 2004). The hippocampus plays an important role in spatial and declarative memory and in the consolidation of information for transfer to long-term memory (e.g., Eichenbaum, Dudchenko, Wood, Shapiro, &

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Tanila, 1999). The amygdala is activated in response to personally salient events, including those that are threatening or stressful (Herman, Ostrander, Mueller, & Figueredo, 2005), and may help individuals orient toward and hence better encode those events.

A large body of research in adults has investigated the associations between HPA axis activation and memory for emotional information (see McGaugh, 2004; Roozendaal, McEwen, & Chatterji, 2009; Wolf, 2009). In this research, HPA axis activation is typically induced endogenously or pharmacologically before, during, or after exposure to emotional information. Findings fairly consistently reveal positive associations between HPA axis activation and memory (e.g., Cahill, Gorski, & Le, 2003; Putman, van Honk, Kessels, Mulder, & Koppeschaar, 2004; Rimmele, Domes, Mathiak, & Hautzinger, 2003; but see Schwabe & Wolf, 2010). However, studies have not directly assessed whether HPA axis activation affects memory for the precise event that elicited that activation in the first place, a noteworthy omission in light of the large body of research on eyewitness testimony which suggests that stress enhances memory for information directly related to the cause of the stress at the expense of memory for unrelated, peripheral details (see Christianson, 1992; Deffenbacher, Bornstein, Penrod, & McGorty, 2004; Reisberg & Hertel, 2004). One exception is a study by Smeets, Giesbrecht, Jelicic, and Merckelbach (2007) in which adults delivered a surprise speech about their personality and afterward listened to lists of words, including those about personality traits. Greater cortisol responses to the speech task were associated with enhanced memory for trait words but not other words. These results suggest that the memory enhancing effects of HPA axis activation may be strongest when there is content overlap between the stress-inducing event and to-be-remembered information.

As mentioned, very few studies have examined cortisol and memory in children, although among studies that have been conducted, children's memory was tested for the precise event that elicited the cortisol response in the first place. In two such studies, for example, Merritt, Ornstein, and Spicker (1994) and Chen, Zeltzer, Craske, and Katz (2000) compared children's cortisol levels during invasive medical procedures to their later memory of those procedures. Merritt et al. collected saliva samples from 3- to 7-year-olds shortly after a medical test and at the same time but on another day when children were at home. Cortisol difference scores were unrelated to children's memory for the test, when memory was tested shortly afterward and a month later. Chen et al. collected saliva in chronically ill 3- to 18-year-olds before and after undergoing treatment for leukemia. A week later, children's memory for the treatment was examined. Pre- to post-cortisol changes were again unrelated to memory.

Two other studies used a somewhat different approach to study the links between cortisol and memory. Quas, Bauer, and Boyce (2004) collected saliva samples before and after 4- to 6-year-olds completed mildly challenging laboratory tasks. Cortisol change scores were unrelated to children's memory of the tasks when assessed a few weeks later, although most children had exhibited no or minimal cortisol increases, making it difficult to detect associations. Eisen, Goodman, Qin, Davis, and Crayton (2007) tested maltreated children's memory for medical examinations. Cortisol was collected after the exam and a few days later at the same time of day. Larger cortisol responses to the exam were associated with enhanced memory, but only among children low in dissociative tendencies.

Given the nonnormative nature of some samples (e.g., chronically ill, maltreated), differing methodologies (medical procedures, potentially nonarousing laboratory tasks), uncontrollable nature of the to-be-remembered events, and lack of standardized collection of saliva, it is difficult to compare results across studies or infer how cortisol reactivity relates to children's memory. Theoretically, HPA axis activation should be positively related to children's memory, possibly even more robustly than in adults. That is, when exposed to stress, children lack a broad repertoire of emotion regulation strategies (e.g., diverting attention, re-interpreting an experience–strategies more easily available to adults, see Gross, 1998; Gross & Thompson, 2007) on which they can rely to reinterpret the situation. Children may thus focus exclusively on a stressor rather than diverting their attention elsewhere or reinterpreting the stressor, leading to stronger associations between cortisol and memory in children than in adults.

To test this possibility directly; however, a to-be-remembered event must reliably elicit cortisol responses that are comparable between children and adults; the event must also be objectively verifiable. In the current study, we constructed such an event. We modified an existing, well-validated psychosocial laboratory stressor, the Trier Social Stress Test (TSST, Kirschbaum, Pirke, & Hellhammer, 1993) to create a single, identical version (TSST-M) to which both children and adults similarly respond (Yim, Quas, Cahill, & Hayakawa, 2010). We exposed 9- to 12-year-olds and young adults to this procedure. After a 2-week delay, we had participants return for a memory interview regarding what happened during the TSST-M. We collected saliva samples before and repeatedly after the TSST-M and collected a self-report measure of stress. We also collected cortisol samples and self-reported stress measures during the memory interview to ensure that the interview itself did not elicit stress responses that could affect memory. Our primary hypotheses were first that larger cortisol

responses to the TSST-M would predict better memory, and second that this association would be stronger in children than adults.

MATERIALS AND METHODS

Participants

The sample included 28 9- to 12-year-olds ($M = 10.68$, 12 female) and 29 18- to 23-year-olds ($M = 19.87$, 16 female). These age groups were selected first because versions of the TSST have been used successfully in prior studies with children age 9 years and older and with adult college student populations (Dickerson & Kemeny, 2004; Kudielka, Buske-Kirschbaum, Hellhammer, & Kirschbaum, 2004). Second, both children and adults in these age ranges have ongoing experience in school, increasing the comparable relevance of the TSST-M instructions across age, which require participants imagine entering a new class and introducing themselves.

Children were recruited from a database of families interested in research. They received compensation for participating. Adults were recruited from the university subject pool and received extra course credit for participating. Most children (79%) were Caucasian, non-Hispanic (the remainder were Asian American, Pacific Islander, or multi-ethnic). Adults' ethnicity varied: 30% Caucasian, nonHispanic; 33% Asian; 20% Hispanic; and 17% multi-ethnic. Sixty-one percent of the sample (parents or adult participants) reported an annual family income of $100,000 or more; 4% reported an annual income of $35,000 or less. None of the participants was on daily medication or had a chronic medical condition. Only adult women on oral contraception were recruited to control for variations in cortisol across the menstrual cycle. None of the female child participants had experienced menarche, although some may still have begun the pubertal transition.

Three other participants (two child, one adult) began session 1, but stopped part way through. Four other participants (two child, two adult) did not return for session 2 due to illness or scheduling conflicts.

Questionnaires and Procedure

Study procedures were approved by the University of California, Irvine, Institutional Review Board. Both sessions began between 13:30 and 16:30 to control for diurnal changes in circulating cortisol. Written parental and adult consent and child assent were obtained at the outset of each session.

Session 1. Session 1 began with participants completing brief questionnaires about their background and health. Children also answered puberty-related questions. Next, an initial saliva sample (pre-TSST-M) was collected (−2 min relative to the TSST-M; 33 and 24 min after children and adults, respectively, had arrived).

Participants were then escorted to a different room where a male and female adult observer were waiting. A research assistant explained the TSST-M procedure: Following a 3-min preparation period, participants would be asked to give a 6-min speech and complete a 4-min math task. For the speech task, participants imagined that they were in a new class, introduced themselves, and talked about their personality. After they stopped speaking, the male observer asked scripted questions. For the math task, participants subtracted 5 (children) or 13 (adults) from 1,027 aloud. The female observer corrected errors and had participants begin again.

Next, participants returned to the first room, provided a second saliva sample (+1 min after the TSST-M ended) and completed an 18-item questionnaire, developed for the present study, concerning their experiences during the TSST-M. Questions asked, on a 7-point scale (1 = not at all, 7 = extremely), how participants felt they had performed (e.g., how hard they tried, how difficult the tasks were). Two items asked participants about the stressfulness of the TSST, specifically how stressful and challenging the tasks were. After answering the questions, participants completed unrelated filler tasks while additional saliva samples were collected at 10, 20, 30, 45, 60, and 75 min post-TSST-M. Parents were asked not to discuss the TSST-M between sessions with their child.

Session 2. Two weeks later, $M = 14$ days, $SD = 1.14$ (range 11–20; 91% fell between 13 and 15 days), participants returned for a surprise memory test. Interviews were conducted in a different building by an unfamiliar female interviewer. The interview session started approximately 17 min later for children and 2 min later for adults than the first session did. TSST-M observers from the previous session were not present.

After a rest period, participants provided a saliva sample (−2 min before the interview began; preinterview). Then, the interviewer entered, introduced herself, and explained the task. She gave participants 3 min to prepare and then commenced the interview. It began with two free-recall questions asking what happened during the previous session (e.g., "Tell me everything that happened."). These were followed by 38 direct questions about specific details of the session. Seven of these were open-ended (e.g., "You had to talk about something negative during your speech, tell me what you said."), and 25 were closed-ended (including an approximately equal number of yes, no, and short-answer responses; e.g., "Did the observers take notes during your speech?" Did you bring your speech materials back to this room afterward?

"How many saliva samples did you take total the last time?"). The direct questions asked about details of what occurred before, during, and after the TSST-M to assess a range of aspects of participants' memory for the prior session. Six misleading questions were also included, but are not considered further because they tapped suggestibility not memory per se. All direct questions were asked in the order specified, regardless of the content of participants' free-recall responses.

After the interview, the participant completed an 18-item questionnaire concerning their experiences during the memory interview. Two items tapped participants' perceptions of the stressfulness of the interview (how challenging/stressful was the interview). Responses ranged from 1 = not at all to 7 = extremely. Additional saliva samples were collected at the following: 1, 10, 20, 30, 45, 60, and 75 min after the interviewed ended. Finally, participants were thanked, debriefed, and received their payment or course extra credit.

Cortisol Assay

Saliva samples were collected with the Salivette sampling device (Sarstedt, Nümbrecht, Germany), stored at room temperature until completion of the session, and then kept at −70°C until assayed. After thawing for analysis, samples were centrifuged for 10 min at 2,000*g* and 4°C. Levels of cortisol were determined using a commercially available enzyme immonoassay procedure (ELISA, IBL-America, Minneapolis, MN). Samples were assayed in duplicate. Interassay and intra-assay coefficients of variance were <4.9% and 4.1%, respectively. The sensitivity of the assay was .012 ng/ml.

Coding

Participants' responses to the "How challenging/stressful was the TSST-M/interview?" questions were significantly correlated within each session, $rs > .35$, $ps < .001$ and were thus averaged to reflect participants' perceived stress to the TSST-M and interview.

Memory accuracy was determined by two independent raters who achieved reliability of at least 97% agreement on 30% of the sample. Free recall was coded for unique units of factual information about subjects, actions, and objects (e.g., "I had to give a speech" = 3 units: "I," "gave," and "speech") using procedures employed in prior studies (e.g., Quas & Lench, 2007). Ambiguous, nonverifiable, and repeated statements were not coded. Correct and incorrect units were summed separately. Participants provided very little incorrect information, $M = 1.11$ units (children = .67 units, adults = 1.61 units); 2% of the total amount provided. Only correct units are considered.

Responses to the direct questions were coded as correct or not, with latter including incorrect, do-not-know, and unscoreable (e.g., failing to provide an answer) responses. A direct question proportion score was created to reflect the number of correct responses out of the total number of direct, including open- and closed-ended, questions asked.

Statistical Methods

In the analyses, cortisol levels were log-transformed to reduce skewness (raw scores are presented in the Figures for ease in interpretation). The final three TSST-M sampling times (+45-, +60-, and +75-min intervals) did not differ from one another, $F(2, 106) = 1.80$, n.s. Thus, only cortisol data from the first six time points (pre-TSST-M, +1, +10, +20, +30, and +45) were included. Cortisol peaked approximately 10 min after the TSST-M ended and returned to pre-TSST-M levels over the remaining four time points (this peak was comparable between children and adults). In the preliminary analyses, *t*-tests and ANOVAs were computed for simple group comparisons, and Pearson product moment correlations were calculated to test associations among potentially relevant variables.

Random effects multilevel modeling procedures (SAS 9.2 PROC MIXED) were used to test our main hypotheses, which concerned whether the trajectories of participants' cortisol responses to the TSST-M were related to children's and adults' memory. This approach allowed for concurrent examination of within- (level 1) and between- (level 2) subject variations. The within-subject variable corresponded to each participant's cortisol values at the six time points across the TSST-M (termed "time"). As mentioned, cortisol values peaked at the +10 time point. Thus, cortisol was centered on this time point, allowing us to interpret the intercept as the predicted peak cortisol values. The between-subject variables were age and the two memory variables (free-recall and direct question proportion scores), entered in separate models. Conceptually, our interest concerned whether TSST-M cortisol trajectories differentially predicted children's and adults' memory. Because the models are correlationally based, the conceptual interpretation (i.e., that trajectories "predict" memory) is consistent with the patterns of associations observed (see Davis & Sandman, 2010; Yim et al., 2009, for similar analytic approaches to understanding the relations between biological response trajectories and child and adult outcomes).

An unconditional growth curve model including a random intercept and linear slope term met convergence criteria and revealed significant unexplained within-subject variability, $\sigma_r^2 = .359$, $p < .001$, as well as between-subject variability for both the intercept,

$\sigma_0^2 = .627$, $p < .001$, and the linear effects of time, $\sigma_1^2 = .00008$, $p < .08$. Similar to other studies examining cortisol responses to the TSST, a comparison of linear and quadratic growth models suggested that a quadratic model best described the cortisol trajectory across the TSST-M (the difference between the linear and quadratic unconditional model log likelihood ratios was significant, χ^2 [1] = 53.60, $p < .001$, quadratic coefficient = −.0006; $p < .0001$). However, the model including the quadratic effect in the random statement did not meet convergence criteria, and thus the quadratic term was entered as a fixed effect (Singer & Willett, 2003). Models depicting associations between changes in cortisol over time and the two memory variables, including whether these associations varied between children and adults, were then tested. Variables were centered prior to their inclusion (cortisol was centered at +10, the peak). The models included the linear and quadratic cortisol variables (time, time^2), the level 2 variables (age, memory), and all interactions.

In a final set of analyses, two hierarchical linear regressions examined the links between participants' self-reported stress and their memory performance. Participants' self-reported stress ratings and age group were entered (Step 1) followed by the stress × age interaction (Step 2). Variables were centered on the mean prior to their inclusion (Aiken & West, 1991), and participants' free-recall and direct question proportion scores were again examined separately.

RESULTS

Preliminary Analyses

Preliminary analyses tested for potential confounds, identified age differences in memory, and determined whether stress at retrieval, indexed via cortisol and self-report, related to memory.

Regarding potential confounds, delay between sessions did not vary between children and adults, t (55) = .47, n.s., and was unrelated to participants' cortisol, rs −.17 to .04, n.s. Longer delays were associated with participants providing a greater amount of detail in free recall, r (55) = .30, p = .028, but controlling for delay did not affect any of the reported results. Delay is not considered further. Gender interacted with age to influence participants' cortisol responses (see Yim et al., 2010): Girls and boys exhibited similar increases in cortisol to the TSST-M; women exhibited a dampened cortisol response relative to men, most likely because women were taking oral contraceptives, a requirement for other aspects of the study (see Yim et al., 2010) and a point to which we return shortly.

When the memory variables were examined, participants' free-recall responses were marginally related to their direct question correct responses, r (55) = .26, p = .05. Also, children, M = 27.71 (19.15), provided less correct information in free recall than adults, M = 50.79 (24.08), t (53) = 3.93, $p < .001$, but children and adults did not differ in the proportion of correct responses provided to direct questions, Ms = .60 (.11) and .64 (.08), respectively.

Finally, although the memory interview was designed be supportive, participants' cortisol levels and self-reported stress responses during the interview were nonetheless examined to ensure that stress at retrieval did not affect memory. Cortisol did not increase in response to the interview. Across the time period ranging from −2 min prior to the interview (pre-interview) to +30 min post-interview, children's cortisol values ranged from 1.59 to 2.57 nmol/L, and adults' cortisol values ranged from 2.02 to 4.11 nmol/L; and none significantly differed over time or between age groups. Participants' self-reported stress was substantially higher during the TSST-M than interview and did not differ across age: The TSST-M means were 5.13 (1.34) and 4.81 (1.11) for children and adults, respectively. The interview means were 2.61 (1.09) and 2.33 (1.30) for children and adults, respectively. Finally, neither the cortisol measures nor self-reported stress during the interview was related to memory, rs = −.20 to .21, n.s.

Cortisol Reactivity to the TSST-M, Age, and Memory

Main analyses examined the links between cortisol trajectories to the TSST-M and memory and evaluated whether these links differed for children and adults. First, free recall was considered. Significant interactions were observed between free-recall and the TSST-M cortisol trajectory (time^2) as well as among age (child/adult), free-recall and cortisol trajectory (time^2) (see Tab. 1). To interpret these interactions, cortisol trajectories were plotted for individuals who reported more versus less correct information in free recall. Separate plots were done for children (Fig. 1a) and adults (Fig. 1b). Overall, larger responses to the TSST-M were associated with providing more correct narrative information in free recall, with this pattern being more robust in children than in adults.

Second, participants' direct question accuracy was examined. A similar pattern emerged: The direct question × time^2 and the age group × direct question × time^2 interactions were significant (Tab. 1). When cortisol trajectories were plotted for children with lower versus higher proportion accuracy scores, results were virtually identical to those observed for free recall: Larger cortisol responses predicted children providing a greater number of accurate responses (Fig. 2a). Similar associations were not

Table 1. Results of Between-Person Effects of Age Group, Memory, and Their Interaction on Cortisol Response Trajectories Across the First Six Samples

	Memory: free recall units correct		Memory: direct question proportion accuracy	
	Coefficient	*t*	Coefficient	*t*
Intercept (peak cortisol)	.407	2.25*	.366	2.22*
Age group	.188	.73	.366	.62
Memory	.007	.87	.146	1.01
Age × memory	−.011	1.02	−2.162	−.89
Rate of change (time)	.003	1.07	.003	.95
Age group	−.001	−.73	.001	.32
Memory	−.001	.77	.022	.84
Age × memory	.000026	.13	−.002	−.52
Quadratic rate of change (time^2)	−.001	−7.18***	−.001	−6.50***
Age group	.001	1.70	.001	.73
Memory	−.001	−3.09**	−.002	−2.21*
Age × memory	.000015	2.06*	.005	2.89**
Variance components	Estimate	*Z*-value	Estimate	*Z*-value
σ_0^2 (Intercept)	.624	4.73***	.617	4.76***
σ_{01} (correlation b/w intercept and slope)	−.0002	−.12	−.0002	−.10
σ_1^2 (slope)	.00009	2.07*	.00004	1.89†
σ_e^2 (residual)	.330	10.26***	.344	10.36***

Note. Time refers to changes in cortisol across the first six sampling periods. Time^2 refers to quadratic changes in cortisol across the first six sampling periods.

***$p < .001$.

**$p < .01$.

*$p < .05$.

†$p < .10$.

uncovered among adults (Fig. 2b) whose direct question accuracy was unrelated to their cortisol trajectories.

To ensure that the gender differences in adults' TSST-M cortisol responses did not affect the results, models were reconducted excluding women, who as mentioned exhibited a dampened TSST-M cortisol response relative to men. Despite the reduced sample size, the time interactions remained significant. Larger cortisol responses predicted enhanced free-recall and direct question performance in children and enhanced free-recall performance in adult males.

Finally, associations between participants' self-reported stress during the TSST-M and memory were examined. First, participants' self-reported TSST-M stress was unrelated to their TSST-M cortisol levels across all time points, *r*s −.18 to .04, n.s. Second, regres-

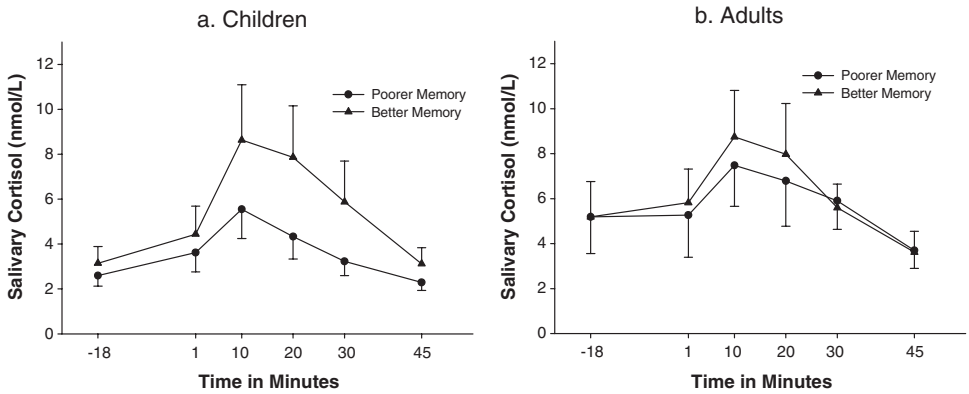

FIGURE 1 Free-recall performance based on the trajectories of cortisol (Nmol/L) across the TSST-M in children (a) and adults (b). Lines created using a median split per age for the amount of information provided in free-recall.

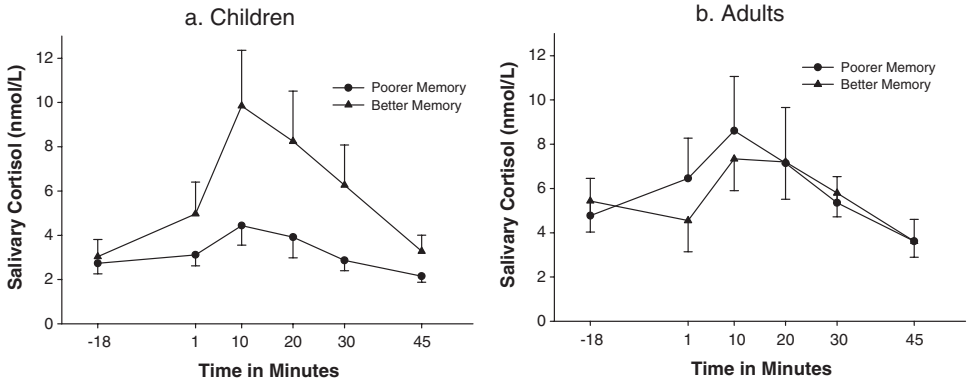

FIGURE 2 Direct question performance based on the trajectories of cortisol (Nmol/L) across the TSST-M in children (a) and adults (b). Lines created using a median split per age for proportion of direct questions answered correctly.

sions were conducted predicting participants' free-recall and direct question accuracy from their age and self-reported TSST-M stress responses. Although age significantly predicted the amount of information provided in free recall (consistent with the preliminary analyses), participants' self-reported stress was unrelated to memory, directly or in conjunction with age.

DISCUSSION

Although a sizeable body of research has been devoted to understanding the links between cortisol and memory for emotional information in adults, much less attention has focused on such links in children. Nor has research with adults investigated how cortisol responses during a stressful event relate to memory for the event that elicited those cortisol responses in the first place. In the current study, we relied on a well-controlled laboratory procedure, the TSST-M, as the to-be-remembered event. The procedure reliably elicited comparable cortisol responses across age. We then developed a comprehensive, structured memory interview that tapped memory for the complex features of the entire TSST-M experience. We collected multiple measures of cortisol before and after the to-be-remembered event occurred. Finally, we included children and adult so that the relations between cortisol and memory could be compared across age. Findings provide much-needed knowledge about the potentially important role of cortisol reactivity in children's as well as adults' memory for personally meaningful, stressful experiences.

Our findings are consistent with studies that have revealed similar positive associations between stress as measured autonomically and children's memory for emotional information (e.g., Quas & Lench, 2007), and with studies that have reported beneficial effects of HPA axis activation during or shortly after exposure to emotional information on adults' memory (e.g., Cahill et al., 2003; Putman et al., 2004; Smeets et al., 2009). Studies of cortisol and memory in children have not, however, revealed similar relations, although as mentioned, methodological limitations, atypical samples, or lack of cortisol responses may have accounted for former studies' findings. With the current study's rigorous methodology, greater cortisol responses were related to enhanced memory in children, perhaps due to cortisol's well-established effects on amygdala-based emotional memory circuitry (McGaugh, 2004; Roozendaal et al., 2009).

Few associations emerged between cortisol reactivity and memory in adults. Because the adults and children reacted comparably to the TSST-M (see also Yim et al., 2010), it is not simply the case that the TSST-M was not as salient to adults. Nor did adults perform at ceiling on the memory test. Instead, the lack of relations may have been due to other factors. First, the college student sample may have well-established general knowledge about completing studies for course credit. As such, regardless of the magnitude of their cortisol responses at encoding, their general knowledge (e.g., going to a research laboratory, answering questions posed from research assistants) may have helped them better encode or perhaps later retrieve information. Second, extant studies with adults have not investigated how HPA axis activation affects their memory for the precise event that elicited the activation. Instead, studies have examined how that activation relates to memory for simpler and often unrelated information (e.g., emotionally laden words or pictures). We assessed memory for a complex personal experience that caused the HPA axis activation. Numerous factors (e.g., memory strategy use, attentional capacity, and inferential abilities) in addition to cortisol likely affected how well the adults recounted what occurred. Perhaps, had the experience been more distressing, stronger associations between

cortisol and memory in adults may have emerged. Of note, however, Het, Ramlow, and Wolf (2005) reported that, across studies examining effects of exogenously induced HPA axis activation at encoding, findings with adults often vary, just as did ours.

The current results highlight the need for continued research in this domain. For one, the child participants ranged in age from 9 to 12 years. It will be important to examine whether similar links between cortisol and memory emerge in younger children, who may react differently physiologically and behaviorally to the TSST-M (Gunnar, Wewerka, Frenn, Long, & Griggs, 2009). It will also be important to examine adults across a wide age range, given that the adults in our sample were largely from early adulthood, and cortisol responses may also change in late adulthood (Kudielka et al., 2004). Second, menarche, as well as the use of oral contraceptives, can affect cortisol responses (Kirschbaum, Kudielka, Gaab, Schommer, & Hellhammer, 1999). Although findings remained identical when the women were removed, future research will need to evaluate the consistency of findings across varying ages of females, including those on versus not on oral contraceptives and those at varying stages across pubertal transition. Third, because we did not experimentally manipulate stress levels, we cannot infer causality from our research. It will be important, in the future, to develop a high and low stress but still objectively identical to-be-remembered event. With random assignment to conditions, clearer insight into the effects of heightened cortisol on children's memory can be gleaned. And fourth, although we are confident that the associations we observed between cortisol and memory were not due to age differences in reactions to the TSST-M, to variations in self-reported stress, or to stress at retrieval, we still only considered how activation of one physiological system—the HPA axis—related to memory, and we did not include a true baseline measure of cortisol. Our approach is consistent with research with adults examining how HPA axis activation measured exclusively at encoding relates to memory for emotional information. How other physiological indices of arousal (e.g., sympathetic), in conjunction with HPA axis activation, relate to children's memory needs to be investigated (see Smeets, Otgaar, Candel, & Wolf, 2008, for related research with adults). It is only with continued research that further insight can be gleaned into how stress, especially as indexed via activation of the HPA axis, affects memory across development.

NOTES

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REFERENCES

Aiken, L. S., & West, S. G. (1991). Multiple regression: Testing and interpreting interactions. Newberry Park, CA: Sage Publications.

Cahill, L., Gorski, L., & Le, K. (2003). Enhanced human memory consolidation with post-learning stress: Interaction with degree of arousal at encoding. Learning and Memory, 10, 270–274.

Chen, E., Zeltzer, L. K., Craske, M. G., & Katz, E. R. (2000). Children's memories for painful cancer treatment procedures: Implications for distress. Child Development, 71, 933–947.

Christianson, S. (1992). Emotional stress and eyewitness memory: A critical review. Psychological Bulletin, 112, 284–309.

Davis, E. P., & Sandman, C. A. (2010). The timing of prenatal exposure to maternal cortisol and psychosocial stress is associated with human infant cognitive development. Child Development, 81, 131–148.

Deffenbacher, K. A., Bornstein, B. H., Penrod, S. D., & McGorty, E. K. (2004). A meta-analytic review of the effects of high stress on eyewitness memory. Law and Human Behavior, 28, 687–706.

Dickerson, S., & Kemeny, M. (2004). Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. Psychological Bulletin, 130, 355–391.

Eichenbaum, H., Dudchenko, P., Wood, E., Shapiro, M., & Tanila, H. (1999). The hippocampus, memory, and place cells: Is it spatial memory or a memory space? Neuron, 23, 209–226.

Eichenbaum, H., & Otto, T. (1992). The hippocampus—What does it do? Behavioral Neural Biology, 57, 2–36.

Eisen, M. L., Goodman, G. S., Qin, J., Davis, S., & Crayton, J. (2007). Maltreated children's memory: Accuracy, suggestibility, & psychopathology. Developmental Psychology, 43, 1275–1294.

Erickson, K., Drevets, W., & Schulkin, J. (2003). Glucocorticoid regulation of diverse cognitive functions in normal and pathological emotional states. Neuroscience and Biobehavioral Reviews, 27, 233–246.

Gross, J. J. (1998). The emerging field of emotion regulation: An integrative review. Review of General Psychology, 2, 271–299.

Gross, J. J., & Thompson, R. (2007). Emotion regulation: Conceptual foundations. In: J. Gross, & R. Thompson (Eds.),

Handbook of emotion regulation. (pp. 3–24). New York: Oxford University Press.

Gunnar, M. R., Wewerka, S., Frenn, K., Long, J. D., & Griggs, C. (2009). Developmental changes in hypothalamic-pituitary-adrenal activity over the transition to adolescence: Normative changes and associations with puberty. Development and Psychopathology, 21, 69–85.

Herman, J. P., Ostrander, M. M., Mueller, N. K., & Figueredo, H. (2005). Limbic system mechanisms of stress regulation: Hypothalamic-pituitary-adrenal axis. Progress in Neuro-Psychopharmacology & Biological Psychiatry, 29, 1201–1213.

Het, S., Ramlow, G., & Wolf, O. T. (2005). A meta-analytic review of the effects of acute cortisol administration on human memory. Psychoneuroendocrinology, 30, 771–784.

Kirschbaum, C., Kudielka, B. M., Gaab, J., Schommer, N. C., & Hellhammer, D. H. (1999). Impact of gender, menstrual cycle phase, and oral contraceptives on the activity of the hypothalamic-pituitary-adrenal axis. Psychosomatic Medicine, 61, 154–162.

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The 'Trier Social Stress Test.' A tool for investigating psychobiological stress responses in a laboratory setting. Neuropsychobiology, 28, 76–81.

Kudielka, B. M., Buske-Kirschbaum, A., Hellhammer, D. H., & Kirschbaum, C. (2004). HPA axis responses to laboratory psychosocial stress in healthy elderly adults, younger adults, and children: Impact of age and gender. Psychoneuroendocrinology, 29, 83–98.

McGaugh, J. L. (2004). The amygdale modulates the consolidation of memories of emotionally arousing experiences. Annual Review of Neuroscience, 27, 1–28.

Merritt, K. A., Ornstein, P. A., & Spicker, B. (1994). Children's memory for a salient medical procedure: Implications for testimony. Pediatrics, 94, 17–23.

Munck, A., Guyre, P. M., & Holbrook, N. J. (1984). Physiological function of glucocorticoids in stress and their relation to pharmacological actions. Endocrine Review, 5, 25–44.

Putman, P., van Honk, J., Kessels, R. P. C., Mulder, M., & Koppeschaar, H. P. F. (2004). Salivary cortisol and short-term and long-term memory for emotional faces in healthy young women. Psychoneuroendocrinology, 29, 953–960.

Quas, J. A., Bauer, A., & Boyce, W. T. (2004). Physiological reactivity, social support, and memory in early childhood. Child Development, 75, 797–814.

J. A. Quas, & R. Fivush (Eds.), (2009). Emotion and memory in development: Biological, cognitive, and social considerations. New York: Oxford University Press.

Quas, J. A., & Lench, H. C. (2007). Arousal at encoding, arousal at retrieval, interviewer support, and children's memory for a mild stressor. Applied Cognitive Psychology, 21, 289–305.

D. Reisberg, P. Hertel (Eds.), (2004). Memory and emotion. New York: Oxford University Press.

Roozendaal, B., McEwen, B. S., & Chatterji, S. (2009). Stress, memory, and the amygdala. Nature Reviews Neuroscience 10, 423–433.

Rimmele, U., Domes, G., Mathiak, K., & Hautzinger, M. (2003). Cortisol has different effects on human memory for emotional and neutral stimuli. Neuroreport, 14, 2485–2488.

Schwabe, L., & Wolf, O. T. (2010). Learning under stress impairs memory formation. Neurobiology, Learning, and Memory, 93, 183–188.

Singer, J. D., & Willett, J. B. (2003). Applied longitudinal data analysis. New York: Oxford.

Smeets, T., Giesbrecht, T., Jelicic, M., & Merckelbach, H. (2007). Context-dependent enhancement of declarative memory performance following acute psychosocial stress. Biological Psychology, 76, 116–123.

Smeets, T., Otgaar, H., Candel, H., & Wolf, O. T. (2008). True or false? Memory is differentially affected by stress-induced cortisol elevations and sympathetic activity at consolidation and retrieval. Psychoneuroendocrinology, 33, 1378–1386.

Smeets, T., Wolf, O. T., Giesbrecht, T., Sijstermans, K., Telgen, S., & Joels, M. (2009). Stress selectively and lastingly promotes learning of context-related high arousing information. Psychoneuroendocrinology, 34, 1152–1161.

Wolf, O. T. (2009). Stress and memory in humans: Twelve years of progress. Brain Research, 1293, 142–154.

Yim, I. S., Glynn, L. M., Dunkel-Shetter, C., Hobel, C. J., Chicz-DeMet, A., & Sandman, C. A. (2009). Risk of postpartum depressive symptoms with elevated corticotrophin-releasing hormone in human pregnancy. Archives of General Psychiatry, 66, 162–169.

Yim, I. S., Quas, J. A., Cahill, L., & Hayakawa, C. (2010). Children's and adults' salivary cortisol responses to an identical psychosocial laboratory stressor. Psychoneuroendocrinology, 35, 241–248.