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Differential Roles of the Salience Network During Prediction Error Encoding and Facial Emotion Processing Among Female Adolescent Assault Victims

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ABSTRACT

BACKGROUND: Early-life assaultive violence exposure is a potent risk factor for posttraumatic stress disorder (PTSD) and other mood and anxiety disorders. Neurocircuitry models posit that increased risk is mediated by heightened emotion processing in a salience network including the dorsal anterior cingulate cortex, anterior insula, and amygdala. However, the processes of reinforcement learning (RL) also engage the salience network and are implicated in responses to early-life trauma and PTSD. To define their relative roles in response to early-life trauma and PTSD symptoms, the current study compared engagement of the salience network during emotion processing and RL as a function of early-life assault exposure.

METHODS: Adolescent girls (n = 30 girls who had previously been physically or sexually assaulted; n = 30 healthy girls for comparison) 11 to 17 years of age completed two types of tasks during functional magnetic resonance imaging: a facial emotion processing task and an RL task using either social or nonsocial stimuli. Independent component analysis was used to identify a salience network and characterize its engagement in response to emotion processing and prediction error encoding during the RL tasks.

RESULTS: Assault was related to greater reactivity of the salience network during emotion processing. By contrast, we found lesser encoding of negative prediction errors in the salience network, particularly during the social RL task, in girls who had been assaulted. The dysfunction of salience network activity during emotion processing and prediction error encoding was not associated with PTSD symptoms.

CONCLUSIONS: These results suggest that hyper- versus hypoactivity of the salience network among trauma-exposed youths depends on the cognitive-affective domain.

Keywords: Adolescence, Early-life trauma, Emotion, Prediction errors, PTSD, Salience network

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Early-life exposure to assaultive violence, including physical, sexual, and witnessed violence, is a potent risk factor for the development of posttraumatic stress disorder (PTSD) and general psychopathology. Indeed, longitudinal studies among a nationally representative sample of adolescents have demonstrated dose-response relationships, such that prospective risk for depression, PTSD, binge drinking, cigarette smoking, and delinquent behavior increases with the severity of assaultive violence exposure (1–3). Given the potent risk for PTSD and general psychopathology associated with early-life exposure to violence, research has sought to identify the neural mechanisms by which this risk is conferred.

Dominant neurocircuitry models posit that the primary neural mechanisms mediating PTSD and related psychopathology following early-life trauma include heightened emotion processing in the amygdala, dorsal anterior cingulate cortex (dACC), and anterior insula, with concurrent decreased emotion regulation and/or inhibition in the medial prefrontal cortex and hippocampus (4–9). From a large-scale neural network perspective (10,11), the amygdala, dACC, and anterior insula are individual nodes within a larger salience network, and hyperactivity of the individual nodes among trauma-exposed persons and persons with PTSD has been conceptualized as reflecting hyperactivity of the larger salience network (7). While most research has focused on adult PTSD, emerging research among trauma-exposed pediatric samples suggests similar, though not identical, neural mechanisms (12), including heightened dACC activity during emotion processing in pediatric PTSD (13,14), dose-response relationships between childhood trauma severity and amygdala activity during emotion processing (15), altered amygdala-insula functional connectivity following treatment in pediatric PTSD (16), and altered functional connectivity of the anterior insula and dACC in trauma-exposed youths (17,18).

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Whereas much research has investigated the neurocircuitry of emotion and threat, the impact of early-life trauma on neural mechanisms of reinforcement learning (RL) has comparatively been underinvestigated (19–23). This is striking, given that traumatic stress–related psychopathology is conceptualized from a learning perspective (24–28) and that two hallmark characteristics of PTSD are dysfunctional fear learning and fear extinction (4,29,30), processes that rely on RL mechanisms (31–35). Existing data suggest that early-life maltreatment, stress, and deprivation are associated with deficits in RL performance (19,20,22) and hypoactivity of the lateral and medial prefrontal cortex (19). With respect to adolescents exposed to assaultive violence, our prior pilot study (36,37) among adolescent girls during a social learning task demonstrated a linear relationship of severity of assault exposure with both poorer learning performance and lesser activation in the anterior insula and anterior cingulate cortex in response to unexpected negative social outcomes, which we conceptualized as negative prediction errors (PEs). The hypoactivation of the salience network in that sample was interesting, given the typical finding of heightened salience network activity during negative emotion processing among trauma-exposed and PTSD samples. The anterior insula and dACC are widely implicated in encoding risk (38), PEs (39,40), and volatility (41). As such, hypoactivity during learning within these regions might be expected in trauma-exposed and PTSD samples characterized by decreased learning in response to negative PEs, such as during fear-extinction learning. Data from this study are broadly consistent with prior reports of poorer learning among early-life maltreatment samples (19,20,22) and negative correlations between stress exposure and dACC activation during learning (19). Nonetheless, it is relevant to mention that a recent study (23) found PEs for hyperactivity during punishment in a more posterior midcingulate cortex cluster among maltreated youths who displayed elevated attention and conduct problems, but not mood or anxiety symptoms, relative to those found in the comparison group. Accordingly, there is some inconsistency in prior studies, which might reflect differences in samples, tasks, and modeling approaches.

The purpose of the current study was to directly test the hypothesis, drawing from our and others' earlier results (19,37), of differential dysfunction of the salience network during emotion processing versus RL as a mechanism conferring risk following early-life assaultive violence. We directly compared activity of the salience network (SN) during a facial emotion processing (FEP) task and during RL tasks using either social or nonsocial stimuli among a sample of adolescent girls who had been exposed to varying severities of assaultive violence. We used independent component analysis (ICA) to identify a large-scale SN, and we used computational modeling of the RL tasks to characterize PE signals.

METHODS AND MATERIALS

Participants

Participants consisted of 60 adolescent girls, aged 11 to 17 years, whom we enrolled at two different sites. In all, 26 participants (n = 13 girls who were previously exposed to assault) were recruited from Little Rock, AR, and the surrounding area; 34 participants (n = 17 girls who were previously exposed to assault) were recruited from Madison, WI, and the surrounding area. This study focused on girls to reduce heterogeneity associated with sex differences in neural, hormonal, and clinical variables. An inclusion criterion for typically developing girls was the absence of mental health disorders, trauma exposure, and psychiatric treatment histories. An inclusion criterion for assaulted girls was a history of directly experienced physical or sexual assault that the girl could recall. Recruitment focused on enrolling girls who had previously experienced assault and who had a relative balance of PTSD diagnoses. Exclusion criteria for all participants included histories of psychotic symptoms, developmental disorders, neurocognitive disorders, magnetic resonance imaging (MRI) contraindications, pregnancy, history of traumatic brain injury, loss of consciousness >10 minutes, and major medical disorders. Adolescents who had previously experienced assault were not excluded based on psychotropic medication usage; however, they were required to have been stable on any medications for ≥4 weeks. Clinical and demographic characteristics are provided in Table 1. Imaging data from 1 participant was excluded because of excessive head motion, and imaging data from 2 participants were unusable because of a technical error during scanning. Behavioral analyses used all participants' data, and the imaging analyses were based on 57 participants.

Assessments

PTSD symptoms were assessed with the Clinician-Administered PTSD Scale, Child and Adolescent Version (42), and PTSD diagnoses were defined in accordance with definitions used in prior studies among youths (13,43). Other current and lifetime mental health disorders were assessed with the Mini-International Neuropsychiatric Interview for Children and Adolescents (44). Assaultive trauma histories were characterized using the trauma assessment section of the National Survey of Adolescents (1,45,46), a structured interview that uses behaviorally specific dichotomous questions to assess 17 categories of direct assaultive traumas across the domains of sexual assault, physical assault, and severe abuse from a caregiver. Participants also completed a corroborative assessment of childhood trauma via the Childhood Trauma Questionnaire (CTQ) (47), a widely used self-report measure assessing separate physical abuse, physical neglect, emotional abuse, emotional neglect, and sexual abuse domains of childhood maltreatment.

RL Tasks

Each participant completed two RL tasks, one featuring social and the other neutral (i.e., neither social nor emotional) stimuli, using a three-arm bandit (Supplemental Figure S1). During the social task, participants were directed to select among three mock people displaying neutral facial expressions in whom to invest $10, and the mock person returned either $20 or $0. The probabilities of positive returns were 80%, 50%, or 20%, and probabilities across the mock people switched every 30 trials, for a total of 90 trials. The nonsocial task was structured identically, except that participants selected between three houses with varying probabilities of being open (returning $20) or

Table 1. Clinical and Demographic Characteristics of the Participants

Variable	Control Group	Assault Group, 1–2 Assaults	Assault Group, 3+ Assaults
n	30	12	18
Age, Years, Mean (SD)	14.9 (2.9)	15.6 (1.44)	15.8 (1.6)
IQ, Mean (SD)	116.8 (21.3)[a]	103.4 (16.8)	100.61 (19.01)[a]
Race and/or Ethnicity, %			
White	60.0	50.0	61.1
Black	20.0	33.3	11.1
Asian	3.3	0.0	0.0
Hispanic, Latina	3.3	8.3	16.7
Pacific Islander	0.0	0.0	0.0
Native American	0.0	0.0	0.0
Other	13.3	8.3	11.1
Number of Direct Assaults, Mean (SD)	0.00 (0.00)	1.33 (0.492)[a]	4.72 (1.447)[a]
Sexual Assault, %	0.0	66.7	88.9
Physical Assault, %	0.0	50.0	88.9
PTSD Diagnosis, %	0.0	50.0	55.6
Mood Disorder Diagnosis[b], %	0.0	50.0	50.0
Anxiety Disorder Diagnosis, %	0.0	66.7	72.2
CAPS Total Severity Score, Mean (SD)	n/a	39.42 (29.03)	45.28 (30.86)
UCLA PTSD RI Score, Mean (SD)	n/a	27.17 (19.43)	30.72 (15.18)
CBCL Anxiety Score, Mean (SD)	2.30 (2.25)[a]	5.67 (6.08)[a]	10.17 (5.97)[a]
CBCL Depression Score, Mean (SD)	1.47 (1.89)[a]	4.92 (3.90)[a]	5.33 (2.99)[a]
Psychiatric Medications, %			
SSRI	0.0	30.8	38.9
SNRI	0.0	7.7	0.0
NDRI	0.0	7.7	0.0
Mood stabilizer	0.0	7.7	16.7
Benzo	0.0	7.7	5.6
Stimulants	0.0	15.4	5.6
Other	0.0	0.0	5.6

Benzo, benzodiazepine; CAPS, Clinician-Administered PTSD Scale; CBCL, Child Behavior Checklist; IQ, intelligence quotient; NDRI, norepinephrine–dopamine reuptake inhibitor; PTSD, posttraumatic stress disorder; SNRI, serotonin and norepinephrine reuptake inhibitor; SSRI, selective serotonin reuptake inhibitor; UCLA PTSD RI, University of California–Los Angeles PTSD Reaction Index.

[a]$p < .05$.

[b]Mood disorder includes major depressive disorder and bipolar disorder.

locked (returning $0). Participants were told their study compensation would be proportional to their performance on the task. Main trial phases of interest for the RL tasks were the decision phase (when participants decided the person in whom to invest, duration determined by participant reaction time), the anticipation phase (while the participant was waiting for the reward outcome, jittered duration of 1.5–3 seconds), and the feedback phase (when the participant was delivered the outcome, 2 seconds followed by an intertrial interval of 1.5–3 seconds). Unmodeled rest phases (fixation cross) that separated trial phases served as the baseline. More details are provided in the Supplement.

Emotion Processing Task

Consistent with the methods of our prior studies (15,48), participants viewed facial stimuli and made button presses indicating decisions related to the sex of the actor. The faces contained either neutral or fearful expressions, presented either overtly (500 ms) or covertly (33 ms), in blocks of 10 faces. There was an equal number of female and male faces. The facial expression (neutral vs. fearful) × stimulus duration (overt vs. covert) factorial design constituted the primary variables of interest in this task, with rest phases (10-second blocks of fixation cross) serving as the baseline. More details are provided in the Supplement.

MRI Acquisition and Image Preprocessing

MRI acquisition parameters and preprocessing are described in the Supplement.

Data Analysis

Reinforcement Learning. We modeled behavior during the RL tasks using a modified version of the Rescorla-Wagner model (49,50). This model takes the form of $V_{t+1} = V_t + \delta \times \alpha$, where V refers to expected value of a chosen action, δ is a PE ($\text{outcome}_t - V_t$), and α is a learning rate that ranges from 0 to 1. The expected value of a chosen action changes from trial to trial based on δ. The learning rate, α, controls the speed with which value expectations are updated, with higher learning rates leading to faster changes in expected value. We used a

softmax function to transform value expectation into action probabilities through use of an exploration and/or exploitation parameter. Consistent with prior research (51,52), we tested four different Rescorla-Wagner–based models that manipulated whether the model was risk sensitive (53) and whether the model updated the expected value of the unchosen option (51) in a factorial design (more details provided in the Supplement). The value expectations and PEs of the best-fitting model for the group were carried forward to the functional MRI analyses using mean sample parameters (54).

Independent Component Analysis. We used ICA (55) with a model order of 35 components. Task data from all runs for all participants were combined in a single ICA analysis, allowing for direct comparisons of network engagement during the RL and FEP tasks. Of the 35 components, 16 were deemed functional networks (rather than artifact from head motion or cerebrospinal fluid, etc.). We identified a canonical SN consisting of peak loadings in dACC and bilateral anterior insula, on which we focused the primary analyses. Supplemental Figure S2 displays all functional networks identified.

Within-Subject ICA Network Time-Course Analyses. We characterized within-subject network encoding during the FEP and RL tasks with general linear models in which network time courses were regressed onto task-specific design matrices that were created in the AFNI software suite (Medical College of Wisconsin, Milwaukee, WI) (56). For the FEP, the design matrix consisted of four regressors for each of the task conditions (i.e., fear vs. neutral × overt vs. covert factorial design). For the RL tasks, the design matrices consisted of regressors for the outcome, anticipation, and decision phases for the tasks. The outcome phase was parametrically modulated by signed PEs, and the anticipation and decision phases were parametrically modulated by V (52,54,57,58). Using MATLAB (The MathWorks, Inc., Natick, MA), we regressed the network time courses onto these design matrices to estimate β coefficients that were carried forward into second-level analyses. Given that reward outcomes are highly collinear with signed PEs (59) (i.e., negative PEs occur only on loss trials), we used a model-comparison approach to demonstrate that SN activity better reflects PE encoding rather than reward outcome processing (Supplement).

Between-Subject ICA Network Analyses. The primary analyses focused on testing associations with assault-exposure severity and component encoding during the FEP and RL tasks using linear mixed-effects models (MATLAB's fitlme.m). We hypothesized that there would be a positive association between assault severity and SN activity during FEP tasks and a negative association between assault severity and SN encoding of negative PEs. In an approach that was consistent with a dose-response relationship between assault-exposure severity and risk for psychopathology (1,60) and as we did in our prior study of a separate sample (37), we tested a linear effect of assault exposure by coding an ordinal variable with three levels: typically developing (code = 0; n = 30), girls exposed to one or two categories of assaults (code = 1; n = 12), and girls exposed to three or more categories of assaults (code = 2; n = 18). This resulted in assault groups that were matched in PTSD diagnoses, caregiver-rated anxiety and depression, and psychotropic medication use (Table 1). An identical linear mixed-effects model was then conducted with the CTQ. Secondary analyses focused on testing the impact of current PTSD symptom severity (Clinician-Administered PTSD Scale total severity scores) on variables of interest among the girls who had experiences assault (n = 30). All models included fixed effects of ordinal assault-exposure severity (or PTSD symptom severity), age, verbal IQ, and scanning site, and random effects for task contrast and head motion (framewise displacement) nested within a subject factor. We controlled for alpha inflation due to multiple comparisons across the 16 identified ICA networks with Bonferroni correction.

RESULTS

Behavioral Performance on RL Tasks

The risk-sensitive anticorrelated Rescorla-Wagner model (Supplement) provided best fit to the behavioral data in both groups (Figure 1A), and choice behavior was well described by this model (Figure 1B). There was no overall difference in performance between the social and nonsocial tasks (p = .20) (Supplemental Figure S2). Mixed-effect models were nonsignificant for relationships between correct responses (p = .09) and softmax betas (p = .068) as a function of assault-exposure severity (Figure 1C).

Differential SN Activity as a Function of Assault-Exposure Severity

We first tested the higher-order assault-exposure severity × task (RL vs. FEP task) interaction and initially compared PE encoding during both RL tasks to FEP collapsed across stimulus category and observed a significant assault × task interaction, t_{327} = 3.56, p < .001 (Bonferroni-corrected p = .007). This higher-order interaction was then decomposed by testing separate models for the RL and FEP tasks.

For the RL tasks, we observed a main effect of assault-exposure severity indicating weakened SN encoding of negative PEs, t_{99} = −3.50, p < .001, that was not moderated by social versus nonsocial RL task, t_{99} = 1.16, p = .25. However, the relationship with assault-exposure severity was more robust during the social RL task, t_{48} = −3.86, p < .001, compared with the nonsocial RL task, t_{47} = −1.74, p = .09 (Figure 2A). The relationship between weakened SN encoding of negative PEs and assault-exposure severity remained when PTSD symptom severity was included as a covariate, t_{98} = −3.11, p = .002.

For the FEP task, while the overall main effect of assault-exposure severity on FEP was not significant, t_{216} = 1.87, p = .063, there was a group × facial expression (neutral vs. fear) x duration (covert vs. overt) interaction, t_{212} = 2.57, p = .011. This interaction was attributed to greater SN responses to overt fear faces in the highly severe assault group compared with those of both other groups, t_{106} = 2.09, p = .039 (Figure 2B). The group × facial expression × duration interaction remained significant when controlling for Clinician-Administered PTSD Scale symptom severity,

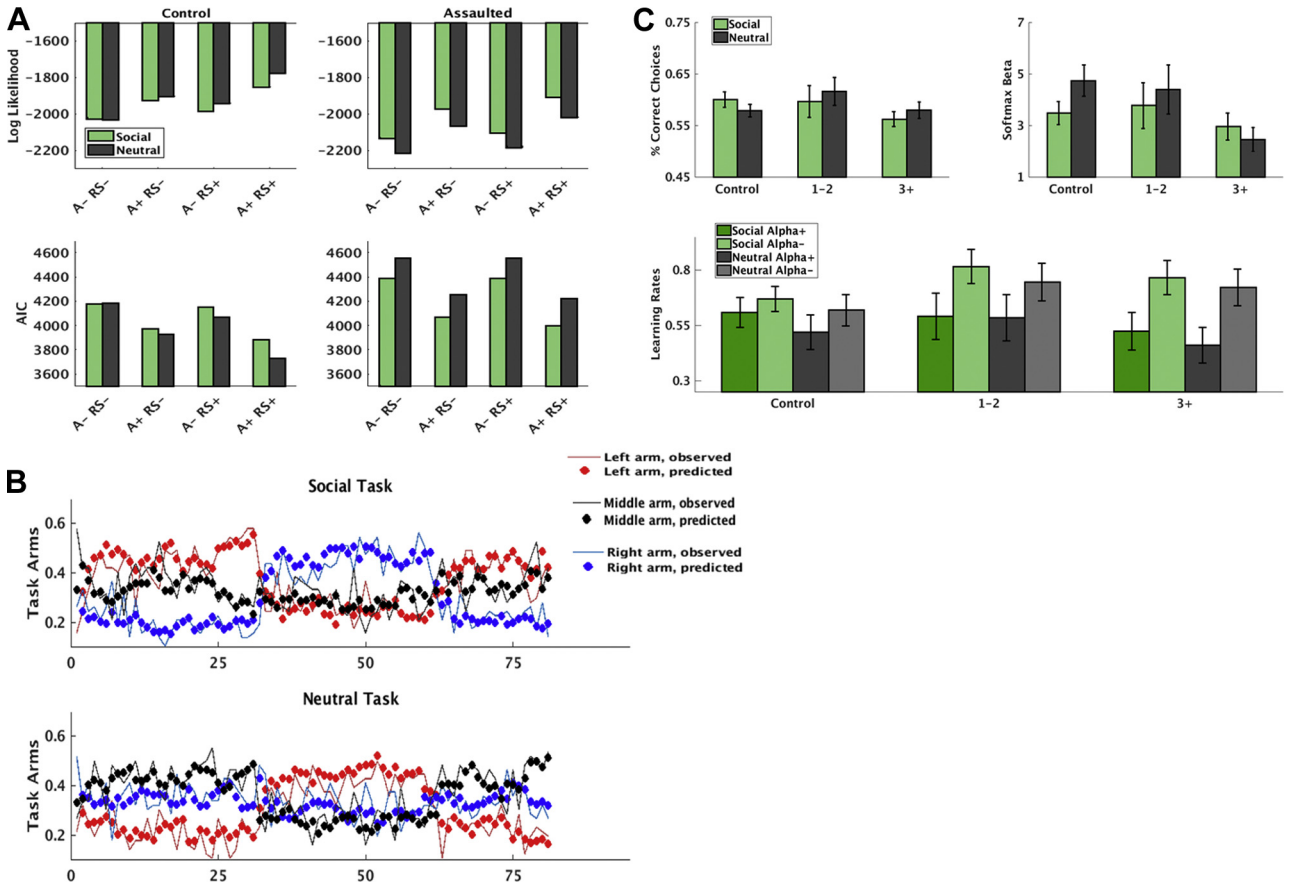

Figure 1. Modeling of the reinforcement learning tasks. **(A)** Four variations of the Rescorla-Wagner model were tested: not anticorrelated or risk sensitive (A− RS−), not anticorrelated and risk sensitive (A− RS+), anticorrelated and not risk sensitive (A+ RS−), and anticorrelated and risk sensitive (A+ RS+). The A+ RS+ variation was the best-fitting model in both groups according to both log-likelihood and Akaike information criterion (AIC). **(B)** Mean proportion of model-predicted choices and observed choices across participants for each of the three arms of the social and nonsocial reinforcement learning tasks. The change in reward structure every 30 trials is also evident. **(C)** Comparison of correct responses (percent of reinforced trials), softmax exploration and/or exploitation parameters, and learning rates (learning rates for both positive prediction errors and negative prediction errors, in accordance with the A+ RS+ model) as a function of the severity of exposure to early-life assaultive violence. "1–2" indicates girls exposed to one to two categories of assault exposure (n = 12); "3+" indicates girls exposed to three or more categories of assault exposure (n = 18).

t_{211} = 2.57, p = .011. There was no relationship between SN encoding of negative PEs during the RL tasks and SN activity during FEP, nor an interaction with assault-exposure severity (all p values $>$ .34), supporting the two processes as dissociable responses of the SN to adolescent assault exposure.

Differential SN Activity With a Corroborative Measure of Early-Life Trauma

We repeated analyses of SN task engagement using the CTQ total score as a corroborative measure of early-life maltreatment severity. These analyses also demonstrated weakened SN encoding of negative PEs as a function of greater CTQ total scores, t_{99} = −2.27, p = .026 (Figure 3A), and no interaction with social versus nonsocial RL task, t_{99} = 1.08, p = .28. For the FEP task, this analysis supported a main effect of greater CTQ total scores on SN responses during FEP, t_{216} = 2.18, p = .03 (Figure 3B), and a nonsignificant CTQ × task interaction, t_{216} = −1.87, p = .06.

Exploratory Analyses of Network Engagement During FEP

Given that we observed primarily SN deactivation in the control group during the FEP task, we hypothesized that perhaps the decreased SN engagement in the control group compared with relative increase in SN engagement in girls who had experienced severe assault was due to differences in alternative network engagement patterns between the groups. Other than a motor network, which was robustly activated in each group because of the considerable motor demands of the block design task (Supplemental Tables S1 and S2), the network that was most strongly activated in the control group, t_{27} = 9.06, p < .001 (Bonferroni-corrected p < .001), was a network with dominant loadings in the bilateral fusiform gyrus, caudate, and nucleus accumbens (Figure 4), subsequently referred to as a fusiform-striatum (FS) network and attributed to object and reward processing (61–63). Further demonstrating the functional relevance of the FS network, this was also the most robustly engaged

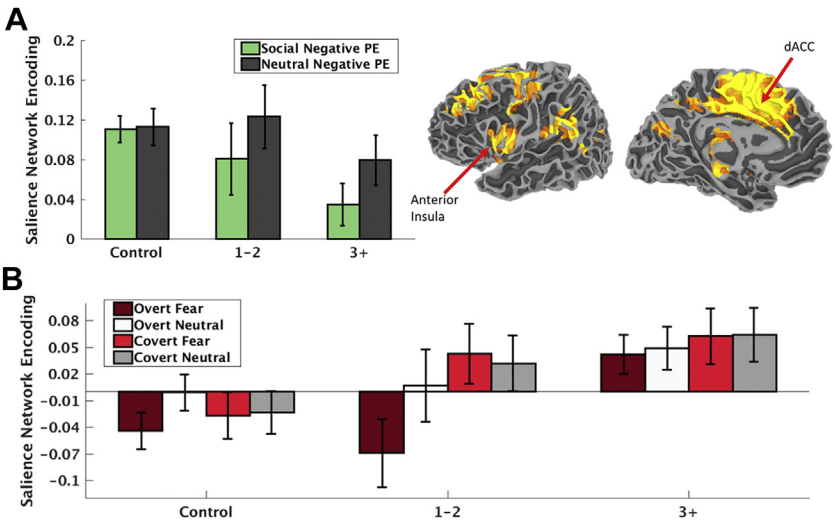

Figure 2. **(A)** Salience network (top right panel, radiological convention) encoding (regression coefficients from the first-level independent component analysis time-course modeling) of negative prediction errors (PEs) during the reinforcement learning task decreases with the severity of exposure to early-life assaultive violence. **(B)** Salience network activity (regression coefficients from the first-level independent component analysis time-course modeling) during facial emotion processing increases with the severity of exposure to early-life assaultive violence. "1–2" indicates girls exposed to one to two categories of assault exposure (n = 12); "3+" indicates girls exposed to three or more categories of assault exposure (n = 18). dACC, dorsal anterior cingulate cortex.

network during positive PE encoding in the control group, t_{27} = 10.21, $p < .001$ (Bonferroni-corrected $p < .001$; Supplemental Tables S1 and S2). Given the robust engagement of the FS network during FEP in the control group, we then tested the hypothesis of opposing patterns of network engagement during FEP between the control and assaulted groups and observed a significant assault-exposure severity × network (SN vs. FS) interaction, t_{436} = 2.81, p = .005, such that SN activity during FEP increased linearly across assault exposures (Figure 2B), while FS network activity decreased linearly across assault exposure, t_{216} = −2.13, p = .034 (Figure 4A). Functionally opposing responses of the SN and FS during FEP across participants was further supported by a model result demonstrating a strong negative relationship between SN and FS recruitment during FEP, t_{225} = −4.53, $p < .001$ (Figure 4B).

Network Response to PE and FEP as a Function of PTSD Symptom Severity

When examining the effect of PTSD symptom severity among the girls who had experienced assault, the higher-order group × task interaction comparing both RL tasks to FEP collapsed across stimulus category did not reveal any significant interaction or main effects of PTSD (all p values > .6).

Ruling Out Confounds Related to Medication Usage and Scanning Site

In the Supplement, we describe additional analyses demonstrating that the above results are not confounded by psychotropic medication use or differences in scanning sites.

DISCUSSION

Consistent with dominant models (5,7), the results showed that SN activity during emotion processing increased with the severity of exposure to assaultive violence. By contrast, SN encoding of negative PEs decreased with the severity of assault exposure, a finding that was consistent with those of our pilot study (37) and previous reports of altered RL mechanisms among maltreated youths (19,20,23). We observed these effects both when examining the severity of assaultive violence exposure and when examining severity of early-life maltreatment as measured by the CTQ. This differential response of the SN has implications for our understanding of the neural mechanisms by which early-life trauma confers risk for PTSD and other mood and anxiety disorders.

The consistent observation of SN hyperactivity toward threat provides a powerful explanation for many clinical symptoms among victims of early trauma who develop PTSD and other mood and anxiety disorders, including attentional

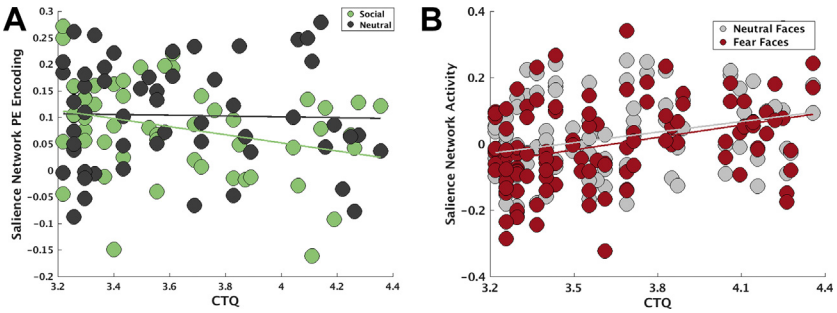

Figure 3. **(A)** Salience network encoding (regression coefficients from the first-level independent component analysis time-course modeling) of negative prediction errors (PEs) during the reinforcement learning task also decreased with the severity of early-life trauma as measured by the (log-transformed) total score of the Childhood Trauma Questionnaire (CTQ), particularly for social stimuli. **(B)** Salience network activity (regression coefficients from the first-level independent component analysis time-course modeling) during facial emotion processing increased as a function of early-life trauma on the (log-transformed) total score of the CTQ.

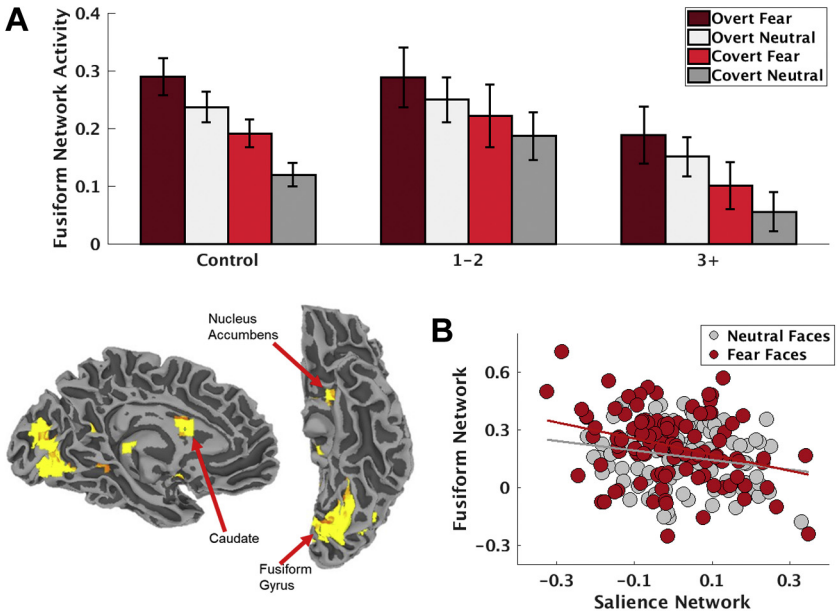

Figure 4. **(A)** A fusiform-striatum network (depicted bottom left, radiological convention) was robustly engaged during facial emotion processing in the control girls, and engagement of this network decreased with the severity of exposure to early-life assaultive violence. **(B)** There was a strong negative relationship between activation (regression coefficients from the first-level independent component analysis time-course modeling) of the fusiform-striatum and salience networks during facial emotion processing, particularly for fear faces.

biases toward threat (64,65), increased fear learning (66,67), and increased startle responses (68,69). Here, we observed increased SN activity for both neutral and fearful faces in the highly severe assault group, which was consistent with other reports among trauma-exposed individuals (70–72) and suggests that there is either heightened salience processing of facial stimuli per se or generalized threat responses toward neutral facial expressions. While these results are consistent with prior neurocircuitry models of early-life trauma, prior models and data have not suggested clear hypotheses regarding SN encoding of negative PEs among trauma-exposed youths. One possibility would have been to expect SN hyperactivity among trauma-exposed youths across all cognitive domains. The currents results are incompatible with this possibility and instead suggest that altered SN responses among early-life trauma victims depend on the specific cognitive-affective domain. In our control sample, we observed robust negative PE encoding in the SN, suggesting that negative PEs normatively function as salient signals. Nonetheless, early-life trauma was associated with weakened SN encoding of negative PEs. By contrast, during FEP, the control group did not reliably recruit the SN, and an exploratory analysis suggested that FEP was instead most strongly associated with engagement of a separate FS network consistent with object recognition and reward processing (61–63). Among girls who had been exposed to assault, there was evidence for strengthened engagement of the SN, particularly for overt fear faces, and weakened engagement of the FS network in an exploratory analysis. Consistent with opposing recruitment of the SN versus FS network during FEP, we observed a strong negative relationship between SN activity and FS network activity during this task. These data suggest qualitatively different network activation profiles to facial emotion versus negative PE signals among typically developing and assault-exposed youths, with possible reciprocal roles for the SN and FS networks in normative FEP.

One explanation of the opposing roles of the SN among trauma-exposed youths depending on cognitive domain might be that prolonged SN hyperactivity to threat results in subsequent blunting of SN response to other signals. If this were the case, then one would expect that SN hyperactivity to threat would be negatively related to SN hypoactivity to negative PEs. The current data are incompatible with this possibility, since analyses failed to identify a significant relationship between SN activation during FEP and SN encoding of negative PEs. Instead, the data suggest that SN hyperactivity in a particular cognitive-affective domain (e.g., FEP) among victims of early-life trauma should not necessarily be expected to generalize to other cognitive-affective domains (e.g., negative PE encoding), which is consistent with dissociable mechanisms in the SN and distinct patterns of SN alterations among trauma-exposed youths. This pattern of data suggests that the utility of SN models of early-life trauma exposure may come from further careful delineation of the SN activity across clinically relevant cognitive domains.

In much the same way that SN hyperactivity toward threat cues among trauma victims implies an adaptive response following trauma exposure, it may be the case that SN hypoactivity to negative PEs similarly serves an adaptive purpose. Whereas the SN and its primary nodes, the dACC and anterior insula, are widely implicated in attention, awareness, and cognitive control (10,11,73–75), the dACC and anterior insula are also widely implicated in encoding computational mechanisms of RL, including risk, PEs, uncertainty, and exploration and/or foraging (38–40,49,76–78). Indeed, negative PEs (e.g., omission of an expected outcome) are primary teaching signals for extinction, and PTSD is widely characterized by poorer fear-extinction learning (79) and recall (29,30). Accordingly, weakened SN encoding of negative PEs might reflect a compensatory mechanism that promotes retention of learned associations, which might have an adaptive purpose in dangerous environments (e.g., abusive early social environments).

Relatedly, a recent study found hyperactive encoding of stimulus associability [i.e., similar to a dynamic learning rate (35,80)], but not PEs, in the anterior insula and amygdala among combat veterans with PTSD (81), a finding that was consistent with a dissociation in SN hyperactivity for maintaining attentional vigilance versus computing discrepancies with prior expectations. Additionally, while we did not observe specificity for weakened encoding of social versus nonsocial negative PEs, the overall pattern of results suggested more robust impairments of PE encoding for social stimuli. In this sample of youths who directly experienced violence inflicted on them by another person, weakened SN responsivity toward unexpectedly negative social behavior could reflect learned blunted responding that develops as an adaption following toxic early social environments and helps maintain learned social associations. Weakened anterior insula has also been linked to decreased detection of untrustworthiness (82) and thereby possibly suggests a mechanism explaining heightened risk of revictimization among youths exposed to early-life trauma (2,83). Finally, the relationships observed between SN encoding of negative PEs and FEP were most strongly related to early-life trauma severity (i.e., both severity of assault exposure and the CTQ score); they remained when we controlled for PTSD symptom severity; and they did not scale with PTSD symptom severity among the adolescents who had experienced assault. This pattern of results suggests that altered SN responses best reflect a risk factor for PTSD and are not a marker of PTSD itself.

The current study is not without limitations. First, the study is limited to adolescent girls, and generalization to boys is not warranted. Second, while effects remained consistent at both sites, it is possible that heterogeneity due to site differences obscured detection of other prominent effects. Third, the sample was heterogenous with respect to comorbidity and medication use, which reflects real-world clinical samples but may limit the specificity of inferences. Fourth, the current sample was selected based on interpersonal traumas, and it is not clear whether similar results would be expected among samples exposed to noninterpersonal traumas. Fifth, the analyses regarding the FS network and alternative network engagement in a control group versus assault group were exploratory, and future research is needed to continue investigating patterns of alternative and opposing network activation among healthy and trauma-exposed youths.

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