Early stressful experiences are associated with reduced neural responses to naturalistic emotional and social content in children

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ARTICLE INFO

ABSTRACT

How do children's experiences relate to their naturalistic emotional and social processing? Because children can struggle with tasks in the scanner, we collected fMRI data while 4-to-11-year-olds watched a short film with positive and negative emotional events, and rich parent-child interactions (*n* = 70). We captured broad, normative stressful experiences by examining socioeconomic status (SES) and stressful life events, as well as children's more proximal experiences with their parents. For a sub-sample (*n* = 30), parenting behaviors were measured during a parent-child interaction, consisting of a picture book, a challenging puzzle, and free play with novel toys. We characterized positive parenting behaviors (e.g., warmth, praise) and negative parenting behaviors (e.g., harsh tone, physical control). We found that higher SES was related to greater activity in medial orbitofrontal cortex during parent-child interaction movie events. Negative parenting behaviors were associated with less activation of the ventral tegmental area and cerebellum during positive emotional events. In a region-of-interest analysis, we found that stressful life events and negative parenting behaviors were associated with less activation of the amygdala during positive emotional events. These exploratory results demonstrate the promise of using movie fMRI to study how early experiences may shape emotional, social, and motivational processes.

1. Introduction

Children's early experiences play an outsized role in building their understanding of other people: how others think, what they feel, and how they interact with each other. Supportive social relationships can have a positive effect on long-term socioemotional development (Smith and Pollak, 2021). In contrast, early life stress introduces vulnerability in the development of emotional and social processes (Hanson et al., 2021; Herzberg and Gunnar, 2020; Milojevich et al., 2021). Areas of the brain that construct emotions, including medial prefrontal cortex, anterior insula, and amygdala (Lindquist et al., 2012; Park et al., 2018), and areas involved in motivational processes, including nucleus accumbens and ventral tegmental area (Cromwell et al., 2020; Park

et al., 2021), are particularly sensitive to stress. A common normative source of stress is low socioeconomic status (SES), which is associated with a constellation of negative experiences like reduced access to resources, increased chaos in the home, and greater exposure to violence (Evans, 2004; McLaughlin and Sheridan, 2016). In animal models, when early life stress is experimentally induced, rodents are more likely to show blunted affect and reduced social exploration later in life, via cascading changes in the development of affective and reward neurocircuitry (Birnie et al., 2020; Glynn and Baram, 2019; Peña et al., 2017). Severe forms of adversity (abuse, neglect, and parental separation) also impact socioemotional development in humans (Callaghan and Tottenham, 2016; Cohodes et al., 2021; McLaughlin and Lambert, 2017): children exposed to adversity show more intense emotional responses to

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negative stimuli (Lavi et al., 2019; Weissman et al., 2019) and alterations to corticolimbic functional connectivity (Gee et al., 2013). However, little is known about the effects of early normative stressors, especially observed parenting behaviors, on neural responses to naturalistic emotional and social content in early childhood.

Parents play a central role in their child's early emotional maturation (Atzil et al., 2018; Callaghan and Tottenham, 2016; Tan et al., 2020), influencing social adjustment later in development (Perry et al., 2020; Yaniv et al., 2021). Children who are securely attached experience more positive affect and improved emotion regulation (Cooke et al., 2019). Parental positive affect and control directed towards the child (i.e., "positive parenting") includes behaviors like emotional expressions of warmth, affection, and behaviors that address the child's needs while fostering security and growth. Studies on relationships between positive parenting and children's brain activity, using functional magnetic resonance imaging (fMRI), have generated mixed results, perhaps due to differences in general study design like sample size, population demographics, and fMRI scan parameters and analysis pipelines, as well as due to the use of different age ranges, behavioral tasks, and operationalization of parenting behaviors (Farber et al., 2020; Kujawa et al., 2020; Tan et al., 2020). For instance, one study of 13–16-year-olds found that greater maternal warmth and support related to lower amygdala reactivity to negative faces (Romund et al., 2016), whereas another study of 11–15-year-olds found that greater family-wide warmth related to higher amygdala reactivity to negative faces (Farber et al., 2019). In a different study, during a parent-adolescent interaction task designed to elicit anxiety, greater use of reframing and problem solving by the parent (almost always the mother) with their 9–14-year-old related to lower anterior insula and perigenual cingulate activation in response to threatening stimuli (Butterfield et al., 2019). Importantly, self-reported and observed maternal warmth was also found to have a protective effect in children exposed to violence at home, consistent with a normalizing effect on amygdala sensitization to threats (Stevens et al., 2021). One longitudinal study in 8–10-year-olds found that positive maternal behaviors observed during a parent-child interaction task at age 8 was associated with decreased connectivity at the 18-month follow-up between the superior parietal lobule and the executive control network, which includes medial frontal regions (Pozzi et al., 2021).

Research on parental negative affect and control directed towards the child (i.e., "negative parenting") and children's fMRI responses are similarly mixed. Negative parenting includes expressions of negative emotions (e.g., frustration or anger, disappointment) and behaviors aimed to punitively extinguish or redirect the child's behavior towards compliance. One study found that observers' ratings of negative maternal emotion and harsh verbal and physical discipline at 2 years (in a sample of only boys) was related to reduced amygdala activity to emotional faces at 20 years (Gard et al., 2017). In another study, negative maternal affect observed during a parent-child problem solving task was associated with greater response of the amygdala to negative emotional faces among 10–11-year-olds (Pozzi et al., 2020). In a study with 11–17-year-olds, observed negative maternal affect during a parent-child supportive discussion task was also associated with blunted response to positive social rewards in the amygdala, anterior insula, anterior cingulate, and nucleus accumbens (Tan et al., 2014). Thus, maternal negative affect and controlling behaviors may sensitize the child or adolescent brain to negative information, and increase risk for the development of blunted emotional responses to positive experiences. A few studies examining associations between negative parenting behaviors and functional connectivity have also found patterns consistent with more "mature" frontolimbic connectivity (e.g., more negative connectivity between the amygdala and frontal regions) (Kopala-Sibley et al., 2020; Thijssen et al., 2017), suggesting that negative caregiving experiences could also be related to accelerated development of emotion regulation abilities (Gee, 2020).

Previous studies on parenting behaviors and brain function have frequently relied on traditional task fMRI approaches, using isolated stimuli like emotional faces. Although traditional paradigms allow for rigorous experimental control, they run the risk of stripping out the broader social and motivational features of children's environments that are critical for their real-life learning and behavior (Cantlon, 2020). For this reason, it may be fruitful to turn to movie fMRI, which can be specifically leveraged to richly engage emotional and social processes of interest, since movies are intentionally designed to evoke certain nuanced responses in their viewers (Grall and Finn, 2022; Sonkusare et al., 2019). Movie fMRI allows for more dynamic analysis of complex emotional responses (Gruskin et al., 2020), improves prediction of behavior (Finn and Bandettini, 2021), and can be combined with analytical techniques that boost signal-to-noise for individual differences (Finn et al., 2020; Simony and Chang, 2019). Movie fMRI is also especially useful for improving data quality in developmental populations, as the more engaging scan experience results in greater participant compliance and reduces head motion (Vanderwal et al., 2019). Thus, movies show great promise for tapping into individual differences in multifaceted emotional and social experiences early in development.

In the current exploratory study, we examined brain responses to emotional and parent-child interaction events during a short film, in seventy 4–11-year-old children. We specifically selected a movie that has core themes related to a parent-child interaction and includes a range of positive and negative events. We also made sure to choose a movie without language or humans with racial or gender identities to limit processing differences due to language exposure or demographics. We related children's brain responses to parent-report measures of early life stress (SES and stressful life events), as well as to positive and negative parenting behaviors observed during a laboratory parent-child interaction task collected in a subset of children ($n = 30$). We broadly expected that early stressful experiences would be related to greater reactivity to negative information, and to blunted reactivity to positive information.

2. Methods

2.1. Participants

Participants were recruited from Philadelphia and the surrounding regions as part of two larger studies. One study focused on examining environmental influences on brain development in typically developing children. For this study, recruitment occurred through local schools, outreach programs, community family events, and advertisements on public transportation and social media. The Institutional Review Board at the University of Pennsylvania approved this study. The other study focused on examining brain development in children with and without autism spectrum disorder (ASD). Only the typically developing children were included in the current study. The Institutional Review Board at the Children's Hospital of Philadelphia (CHOP) approved this study. Recruitment for this study occurred through CHOP's internal recruitment infrastructure. All parents provided informed, written consent, and children provided assent. Data were collected from June 2018 to March 2020 (data collection stopped in March 2020 due to the onset of the COVID-19 pandemic).

Movie fMRI scans were acquired for 82 participants. Seventy participants were included in the final sample. Participants were excluded for the following reasons: not completing the movie fMRI scan (e.g., due to falling asleep or wanting to end the scan early, $n = 4$); incorrect registration of the participant at the scanner ($n = 1$); technical problems that resulted in an incomplete movie scan (less than 5 min of usable movie data, $n = 5$); or parent-reported diagnosis of Attention-Deficit/Hyperactivity Disorder during the visit, despite not reporting a diagnosis during screening ($n = 2$). In the final sample, children were between the ages of 4 and 11 ($M = 8.36$, $SD = 1.74$, range = 4.27–11.85). Information on racial and ethnic makeup was as follows: 57% White, 20% Black, 6% Asian, 1% Other, 16% Multiracial, and 1% Hispanic/

Latino. In the sub-sample that participated in the parent-child interaction task ($n = 30$), children were between the ages of 4 and 10 ($M = 7.58$, $SD = 1.78$, range = 4.27–10.93). Descriptive statistics of demographics and parent-report questionnaire variables are summarized in Table 1.

2.2. Questionnaires

2.2.1. Socioeconomic status

Parental education and family income were assessed using the MacArthur Foundation Research Network on Socioeconomic Status and Health sociodemographic questionnaire (Operario et al., 2004). Parents reported on their highest education level (possible responses ranged from "less than high school" to "professional degree (J.D., M.D., Ph. D.)"), as well as the highest education level of their partner if applicable (86% of parents reported the education level of their partner). Average parental education ranged from 10 to 20 years ($Mdn = 16$, $SD = 2.53$, $n = 70$). Total family income was assessed by asking "Which of these categories best describes your total combined family income for the past 12 months? This should include income (before taxes) from all sources, wages, rent from properties, social security, disability and/or veteran's benefits, unemployment benefits, workman's compensation, help from relatives (including child payments and alimony), and so on." Possible responses included: Less than $5,000, $5,000 through $11,999, $12,000 through $15,999, $16,000 through $24,999, $25,000 through $34,999, $35000 through $49,999, $50,000 through $74,999, $75000 through $99,999, $100,000 through $149,999, $150,000 through $199,999, $200,000 and greater, and Unsure. Annual family income was estimated as the median value of the selected income bracket ($Mdn = \$125$ K, $SD = \$71$ K, $n = 63$). Socioeconomic status (SES) was defined as the average of Z-scored income and Z-scored years of parental education (parental education was averaged across parents if available for both parents). Participants were included in SES analyses if they had reported either income or parental education (7 parents reported only on parental education).

2.2.2. Stressful life events

Parents filled out a modified version of the Life Events Scale for Young Children (Coddington, 1972). This questionnaire asks parents to report whether specific events had happened to their child within the last 12 months (12 items), as well as how stressful the child found these events, from 0 (not stressful) to 4 (extremely stressful). Examples of items include: "Your child had a serious accident or illness," "A family

member or close relative died," and "You separated or got divorced from your partner." A stressful life events score was calculated by summing all stress ratings, and ranged from 0 to 19 ($Mdn = 1.5$, $SD = 3.93$, $n = 68$).

2.2.3. Parent-child interaction task

2.2.3.1. Procedure.
In a sub-sample of participants ($n = 30$), we collected a 15-minute parent-child interaction task modeled after the Three Bags Task (Love et al., 2005). We included the following tasks (Fig. 1):

1. A wordless picture book (*Mr. Wuffles!* by David Wiesner) about a pet cat who plays with a toy that turns out to be a spaceship of small green aliens.
2. A challenging block puzzle. Parents were given written instructions that said, "See how many of these puzzles your child can make," along with a booklet of the six hardest Wechsler Intelligence Scale for Children (WISC; Wechsler, 2014) block design puzzles, as well as one easy demonstration puzzle. We selected the six hardest block design puzzles to ensure that most 4–11-year-olds would not be able to complete the puzzles independently.
3. A free-play "curiosity box". The box had different drawers containing a variety of small novel toys and common household objects.

At the beginning of the session, the parent and child were instructed to play as they normally would at home, and an experimenter explained that timers would go off every 5 min and 30 s, to let them know when to move to the next task (30 s were provided in between tasks to allow for transition time). The experimenter then left the room for the duration of the parent-child interaction task, which was video-taped. Twenty-five (83%) children participated in the tasks with their mother, and five (17%) children participated with their father.

2.2.3.2. Coding scheme for parent behaviors.
Observer ratings of parent behaviors were captured using the PARCHISY coding scheme (Deater-Deckard et al., 1997), which consists of 7-point Likert-type scales (1 = no occurrence of the behavior, to 7 = continual occurrence of the behavior). We created a positive parenting composite that averaged the two positive behaviors in the PARCHISY coding scheme ($M = 4.58$, $SD = 0.88$, range = 2.67–6.11; Fig. 2): positive affect and positive content. Positive affect is defined by PARCHISY as "smiling, laughing," and positive content is defined as "use of praise, explanation, and open-ended questions." We also created a negative parenting composite ($M = 1.44$, $SD = 0.49$, range = 1.00–2.92), which consisted of the average between negative affect and negative content. Negative affect is defined as "rejection: frowning, cold/harsh voice," and negative content is defined as "use of physical control of task or child's hand/arm/body, use of criticism." Parent behavior ratings were determined separately for each of the three tasks, and then averaged together if at least two out of the three tasks were usable. Individual tasks were dropped if the dyad spent less than 3 min on the task (book: $n = 1$); or deviated substantially from the main task (block puzzle task: $n = 1$ engaged in free play with the blocks instead of making puzzles).

Six pairs of trained coders provided PARCHISY ratings based on video recordings of the parent-child interaction task. Coders were diverse with respect to racial, ethnic, and gender identities, but were all undergraduate students, and not parents themselves. Coders were first trained by coding several practice videos in groups, and receiving feedback. Coders in each pair then watched the videos together over Zoom, independently gave their Likert ratings, compared ratings, and came to a consensus through discussion for any ratings that differed by more than 1 point (if ratings differed by 1 point, the ratings were averaged). Nine videos (30% of the sample) were coded by all pairs to assess interrater reliability using Cronbach's alpha (*ltm* package in R): parent positive content, $\alpha = 0.90$; parent positive affect, $\alpha = 0.95$;

Table 1

Descriptive statistics of demographic and questionnaire variables. Data on ethnicity was missing for one participant.

	Full Sample	Parenting Sub-Sample
Age	$M = 8.36$ ($SD = 1.74$)	$M = 7.58$ ($SD = 1.78$)
	$n = 70$	$n = 30$
Gender		
Male	48 (69%)	16 (53%)
Female	22 (31%)	14 (47%)
Race		
White	40 (57%)	7 (23%)
Black	14 (20%)	12 (40%)
Asian	4 (6%)	2 (7%)
Other	1 (1%)	1 (3%)
Multiracial	11 (16%)	8 (27%)
Ethnicity		
Hispanic/Latino	1 (1%)	0 (0%)
Not Hispanic/Latino	68 (97%)	29 (97%)
Parent Education (years)	$Mdn = 16$ ($SD = 2.53$)	$Mdn = 15$ ($SD = 2.64$)
	$n = 70$	$n = 30$
Completed college	39 (56%)	12 (40%)
Did not complete college	31 (44%)	18 (60%)
Annual Household Income (median)	$Mdn = \$125$ K ($SD = \$71$ K)	$Mdn = \$62.5$ K ($SD = \$76.4$ K)
	$n = 63$	$n = 26$
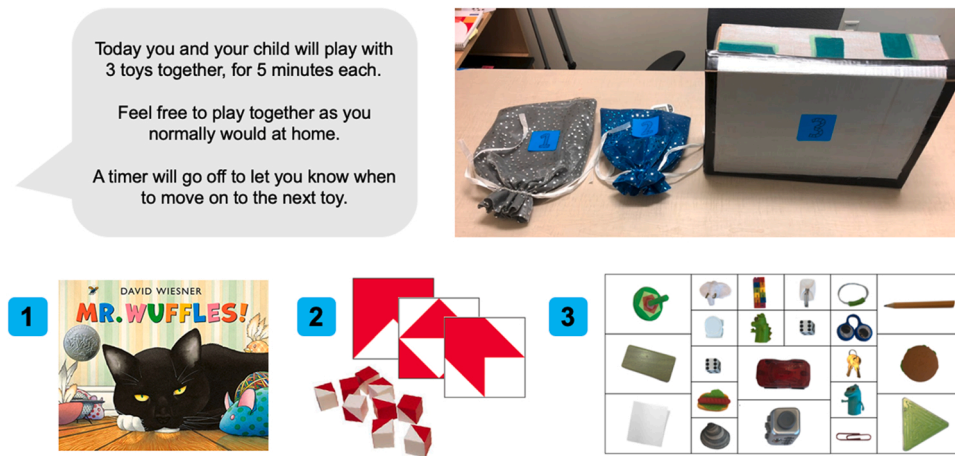
Fig. 1. Parent-child interaction task ($n = 30$). There were three 5-minute toys: 1) a wordless picture book, 2) a challenging block puzzle, and 3) a free-play box with drawers containing a variety of novel toys and common household objects. Parents and children were instructed to play together as they normally would at home, and timers were used to indicate when to move to the next toy.
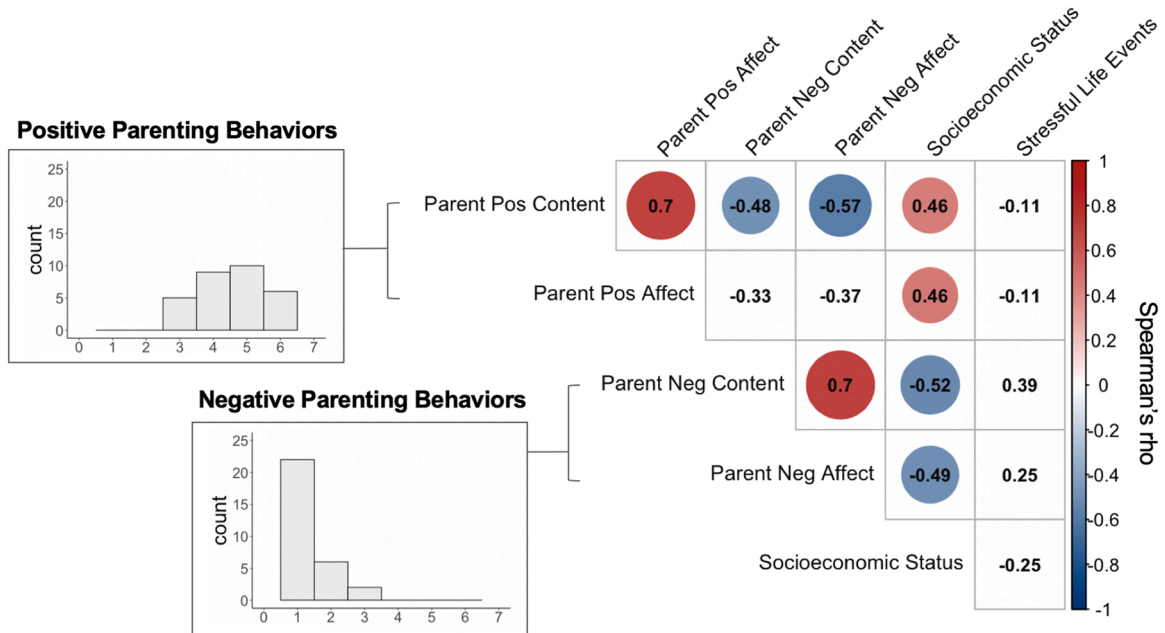
Fig. 2. Spearman correlations among the parenting behaviors observed during the parent-child interaction task (positive content, positive affect, negative content, and negative affect), socioeconomic status, and stressful life events. Histograms show the distributions for positive parenting behaviors, which averaged across positive content and positive affect, and for negative parenting behaviors, which averaged across negative content and negative affect. Parent positive content was defined as the use of praise, explanation, and open-ended questions; positive affect was defined as smiling and laughing; negative content was defined as criticism and the use of physical control of the task or the child's body; and negative affect was defined as frowning and harsh tone. Circles indicate a correlation that is significant at $p < .05$, after correcting for multiple comparisons using the Benjamini & Hochberg false discovery rate (FDR; size of the circle is proportional to effect size).

parent negative content, $\alpha = 0.93$; parent negative affect, $\alpha = 0.97$. In the sub-sample with both parent-child interaction data and movie fMRI data, all videos were coded by at least two pairs, and ratings were averaged across coding pairs. Positive parenting behaviors were not significantly related to the child's age ($r_s(28) = -0.30, p = .11$), gender ($t(28) = -1.16, p = .26$), or race ($F(3, 26) = 0.78, p = .546$). Negative parenting behaviors also were not significantly related to the child's age ($r_s(28) = 0.12, p = .52$), gender ($t(28) = -0.60, p = .55$), or race ($F(3, 26) = 1.07, p = .39$).

Correlations among the parent-child interaction measures, SES, and stressful life events are presented in Fig. 2. Higher frequency of positive parenting behaviors was significantly associated with lower frequency of negative parenting behaviors ($r_s(28) = -0.49, p = .006$). Higher SES was associated with higher frequency of positive parenting behaviors

($r_s(28) = 0.49, p = .006$), and lower frequency of negative parenting behaviors ($r_s(28) = -0.54, p = .002$). Exposure to stressful life events was not significantly related to positive parenting behaviors ($r_s(28) = -0.13, p = .49$), and was marginally related to greater frequency of negative parenting behaviors ($r_s(28) = 0.34, p = .07$).

2.3. Movie fMRI stimuli

During the scan session, participants watched Pixar's "Piper", a 5-minute animated short film about a baby sandpiper who overcomes their fear of the ocean. The movie includes positive and negative emotional events, as well as rich parent-child interactions. Participants from the ASD study watched the Piper movie without audio ($n = 40$), due to the study's pre-existing data collection procedures (audio of the

movie includes soundtrack music, and background noises like birds chirping to communicate, waves crashing, etc., and does not include any dialogue). In order to account for differences in the movie-watching experience due to having no audio, we controlled for dataset in all analyses that include data from both studies.

2.3.1. Neuroimaging data acquisition

Before the scan, participants were acclimated to the scan environment by practicing in a mock scanner that simulates MRI noises. Participants practiced staying still by watching a brief movie clip that paused whenever they moved their head by more than 1 mm. During the actual MRI session, a researcher stayed with the child, standing next to the scanner table to reassure them, as well as to remind them to stay still if the child started to move.

Imaging was performed at the Center for Advanced Magnetic Resonance Imaging and Spectroscopy (CAMRIS) at the University of Pennsylvania. Scanning was conducted using a Siemens MAGNETOM Prisma 3 T MRI scanner with the vendor's 32-channel coil. A whole-brain, high-resolution, T1-weighted 3D-encoded multi-echo structural scan (MEM-PRAGE) was collected (acquisition parameters: TR = 2530 ms, TI = 1330 ms, TEs = 1.69 ms/3.55 ms/5.41 ms/7.27 ms, BW = 650 Hz/px, 3x GRAPPA, flip angle = 7°, voxel size = 1 mm isotropic, matrix size = 256 × 256 ×176, FOV = 256 mm, total scan time = 4:38). This sequence used interleaved volumetric navigators to prospectively track and correct for subject head motion (Tisdall et al., 2012). A 5-minute T2 * -weighted gradient echo multiband EPI functional scan was also collected (acquisition parameters: multiband acceleration factor = 3, TR = 2000 ms, TE = 30.2 ms, BW =1860 Hz/px, flip angle = 90°, voxel size = 2 mm isotropic, matrix size = 96 × 96, 75 axial slices, FOV = 192 mm, volumes = 150, 5 dummy scans). Participants watched the 5-minute Piper movie during the functional scan. PsychoPy2 (v1.90.2; Peirce et al., 2019) was used to ensure that the beginning of the functional scan would trigger the start of the movie, so all participants' functional data would be time-locked to the same movie events.

2.3.2. Preprocessing

The functional imaging data were preprocessed using Nipype, a Python-based framework for flexibly integrating neuroimaging analysis tools (Gorgolewski et al., 2011). The software packages used in this preprocessing pipeline included FMRIB Software Library (FSL v5.0.8; Jenkinson et al., 2012), FreeSurfer (v6.0.0; Dale et al., 1999), Advanced Normalization Tools (ANTs v2.1.0; Avants et al., 2011), and Nipype's implementation of Artifact Detection Tools (ART; http://www.nitrc.org/projects/artifact_detect/).

Simultaneous realignment and slice timing correction was conducted using an algorithm implemented in Nipy (Roche, 2011). Outlier volumes in the functional data were defined using ART based on composite motion (greater than 1 mm of head displacement between volumes) and global signal intensity (greater than 3 standard deviations from the mean).

The following confounds were regressed out of the functional data: 6 realignment parameters (3 translations, 3 rotations) and their first-order derivatives, outlier volumes flagged by ART (one nuisance regressor per outlier), composite motion, and linear and quadratic polynomials to detrend the data. Five principal components were also derived from segmentations of both cerebrospinal fluid (CSF) and white matter (WM), and regressed from the data, to correct for physiological noise like heart rate and respiration (aCompCor; Behzadi et al., 2007). The CSF and WM segmentations were derived from Freesurfer's individual parcellations of the lateral ventricles and total white matter, respectively; these segmentations were transformed into functional space. Confound regression occurred within a skull-stripped functional mask which was created using FSL's Brain Extraction Tool (BET; Smith, 2002); BET's fractional intensity threshold was set at 0.4.

The functional data were high-pass filtered with a cutoff of 100 s, spatially smoothed with an isotropic 6 mm Gaussian kernel (FWHM),

and normalized to the OASIS-30 Atropos template (in MNI152 2 mm space) in a two-step process. First, the median functional image was coregistered to the reconstructed surfaces using FreeSurfer's bbregister (Greve and Fischl, 2009); next, the structural image was registered to the OASIS-30 Atropos MNI152 template using ANTs. The transformation matrices generated by these two steps were concatenated, allowing images to be transformed directly from functional to MNI space in a single interpolation step.

2.3.3. Summary of motion considerations

The effects of motion during the structural scans were minimized using prospective motion correction (Tisdall et al., 2012). Movie fMRI has been shown to reduce head motion, especially in younger children (Greene et al., 2018). In the current study, participants had an average head displacement of 0.20 mm (range = 0.05–0.72 mm, SD = 0.14 mm, significantly non-normally distributed, W = 0.80, $p < .001$), and an average of 3.10% outlier volumes, as defined by ART (SD = 4.09%, significantly non-normally distributed, W = 0.73, $p < .001$; note that ART outliers were defined as volumes with greater than 1 mm total head displacement, or greater than 3 standard deviations from the mean for global signal intensity). Thus, no participants exceeded our motion threshold of 1 mm average head displacement (3 translations, 3 rotations), or > 20% outlier volumes. Higher percent outlier volumes was marginally correlated with younger age ($r_s(68) = -0.23$, $p = .051$) and lower SES ($r_s(68) = -0.21$, $p = .08$). All analyses controlled for the number of outlier volumes.

2.4. Movie fMRI analysis

2.4.1. Regressor definition

Five trained research assistants independently watched the Piper movie and used the video annotation software ELAN to label movie time points that fell into three categories: positive affect, negative affect, and parent-child interactions. Positive affect was defined as time points when the main character, Piper, appeared to be experiencing positive emotions (e.g., related to happiness, joy, excitement, etc.). Negative affect was defined as time points when Piper appeared to be experiencing negative emotions (e.g., related to fear, suspense/tension, sadness, etc.). Parent-child interactions were defined as any time points when Piper and their mother were interacting. Annotators were given the general guideline of labeling movie segments that lasted approximately 5–15 s (in order to extract events that would be suitable for block design fMRI analysis, and to constrain against very long, thematically high-level segments). All annotators were watching Piper for the first time.

Events were defined as blocks of contiguous time points where there was agreement from at least three out of the five annotators (Fig. 3). This was achieved by rounding event start and stop times to the nearest 1-second bin, and flagging only time points with at least three endorsements. The minimum event length was 1 second. In total, there were 10 positive affect events, summing to 47 s, 5 negative affect events, summing to 42 s, and 7 parent-child interaction events, summing to 91 s. The positive affect events had no overlap with negative affect events, and were evenly matched in length (47 s were included in the positive affect regressor, and 42 s were included in the negative affect regressor). The parent-child interaction events overlapped with 13 positive affect time points, and with 8 negative affect time points.

2.4.2. Whole-brain analyses

Because motion and physiological noise were already filtered out of the functional data during earlier preprocessing steps, each subject-level design matrix included only one event regressor (as well as its temporal derivative): one regressor for positive affect events, negative affect events, or parent-child interaction events. The regressors were convolved with FSL's double-gamma hemodynamic response function. We used FSL's *fsl_glm* tool to generate a contrast map for each of the
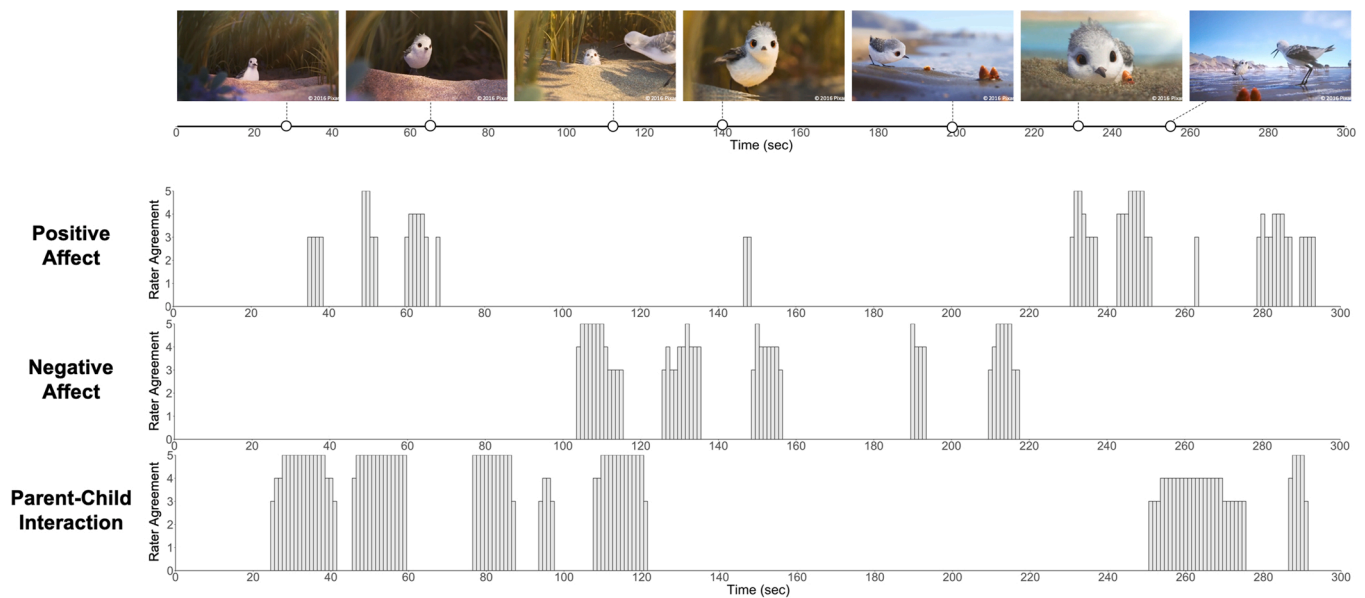
Fig. 3. Positive affect, negative affect, and parent-child interaction event regressors extracted from the Piper animated short film. Time points were only included if there was overlap between at least three out of the five independent annotators. Top row shows a summary of key events during the Piper movie narrative.

three event regressors from the preprocessed data. First-level contrast maps for positive affect, negative affect, and parent-child interaction events were then submitted to group-level analyses. Group-level analyses were performed with FMRIB's Local Analysis of Mixed Effects tool (FSL's FLAME 1). Only voxels that had unanimous coverage across subjects were tested, resulting in a mask that covered the entire brain. We ran the following GLMs (testing for both positive and negative associations, $n = 70$): 1) group average; 2) gender difference, 3) main effect of age, 4) main effect of SES, and 5) main effect of stressful life events. GLMs included the following covariates (except for models where the covariate was the main effect being tested): age, gender, number of outlier volumes, and dataset (to control for broader differences between the two studies, mainly whether or not audio was available). The group average GLM only controlled for number of outliers and dataset. In the sub-sample of participants with parent-child interaction data, we ran the following GLMs (testing for both positive and negative associations, and controlling for age, gender, and number of outlier volumes, $n = 30$): 6) main effect of positive parenting behaviors, and 7) main effect of negative parenting behaviors.

Z-statistic maps were corrected for multiple comparisons with parametric clusterwise inference using FSL's cluster tool (relies on Gaussian Random Field Theory) at a cluster-defining threshold of $z = 3.1$ ($p < .001$), neighborhood size of 26, and an FWE-corrected threshold of $p < .05$. All statistical analyses were conducted in R.

2.4.3. Region-of-interest (ROI) analyses

Due to the extensive literature on associations between parenting and amygdala function (Tan et al., 2020), region-of-interest analyses were performed using an independent amygdala ROI (bilateral amygdala from the Harvard-Oxford subcortical atlas available through FSL; Fig. 7). We examined whether socioeconomic status, stressful life events, and positive and negative parenting behaviors were related to amygdala activity during positive affect, negative affect, and parent-child interaction events.

2.5. Results

2.5.1. Group average results

The positive affect events of the movie were associated with activity in regions of the default mode network, including precuneus, angular gyrus or temporoparietal junction (TPJ), middle temporal gyrus, and medial prefrontal cortex, as well as regions in orbitofrontal cortex (OFC), lateral prefrontal cortex, and somatomotor cortex (Fig. 4A). The negative affect events also showed overlap with the default mode network, in precuneus, angular gyrus/TPJ, and medial prefrontal cortex, as well as middle temporal gyrus and lingual gyrus (Fig. 4B). Finally, the parent-child interaction events were associated with activity in the superior temporal sulcus (STS), middle temporal gyrus, temporal poles, postcentral gyrus, lateral occipital cortex, and fusiform face area (Fig. 4C).

2.5.1.1. Associations with demographics and stressful life events. No significant relationships with age, gender, or stressful life events were found for positive affect, negative affect, or parent-child interaction events. During parent-child interaction events in the movie, higher socioeconomic status (SES) was related to greater activity in medial orbitofrontal cortex (OFC), controlling for age, gender, number of outlier volumes, and dataset (Fig. 5; peak voxel coordinates (MNI): -4, 32, -22, maximum z-statistic $= 4.23$, cluster volume $= 316$ voxels). Higher SES was not related to reduced activity in any brain regions, nor were there any significant relationships during positive affect or negative affect events.

2.5.1.2. Associations with parenting measures. In the sub-sample of participants with parent-child interaction data ($n = 30$), greater occurrence of negative parenting behaviors during the parent-child interaction task was related to reduced activation during positive affect events in the movie in the VTA (Fig. 6A; peak voxel coordinates (MNI): 12, -6, -14, maximum z-statistic $= 5.32$, cluster volume $= 190$ voxels) and left cerebellum (Fig. 6B; peak voxel coordinates (MNI): -34, -44, -42, maximum z-statistic $= 4.25$, cluster volume $= 183$ voxels), controlling for age, gender, and number of outlier volumes. Negative parenting behaviors were not related to activity during negative affect events or parent-child interaction events. We also found no significant effects of positive parenting behaviors on activity during any of the movie events.

Three parents were outlying in their negative parenting behaviors (more than 1.5 times the interquartile range above the third quartile), with ratings between 2 and 3 (maximum possible rating was 7; note that ratings of 2–3 in the PARCHISY coding scheme correspond to "one or two" or "a few/several" instances of negative behaviors during the
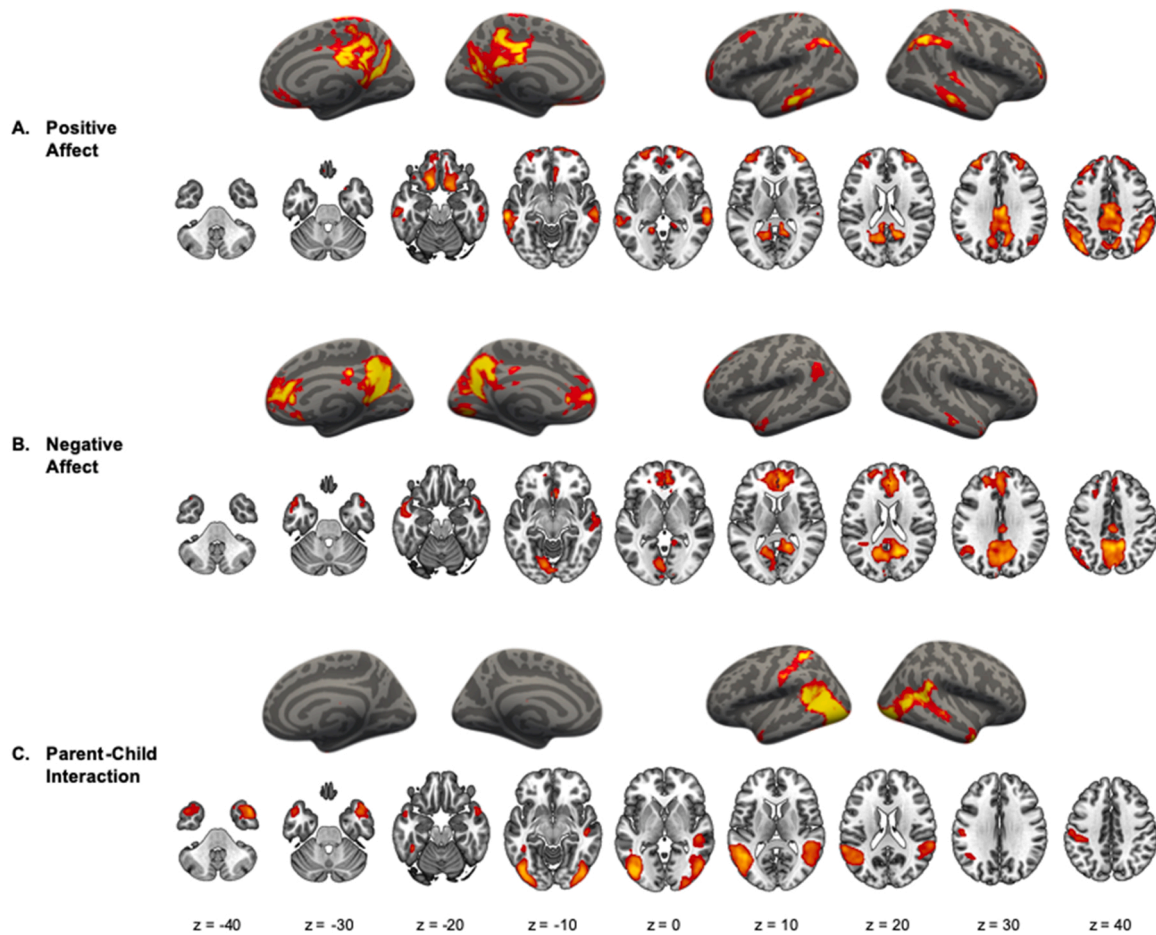
Fig. 4. Positive group average activity for the movie events related to (A) positive affect, (B) negative affect, and (C) parent-child interactions. Models controlled for number of outlier volumes and dataset, and were corrected for multiple comparisons at $z = 3.1$, $p < .05$, $n = 70$.
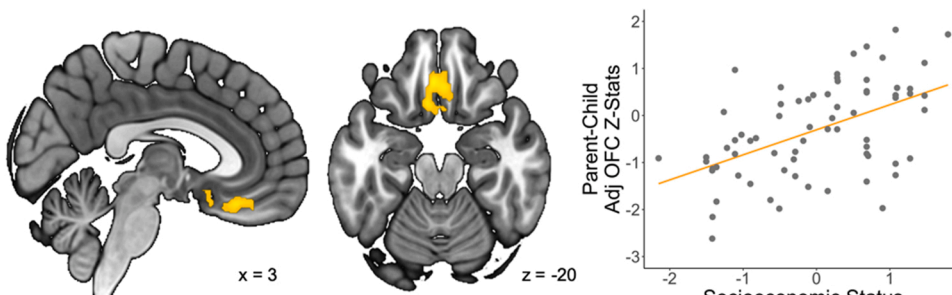

Fig. 5. Higher socioeconomic status (SES) was associated with greater activity in medial orbitofrontal cortex (OFC) during parent-child interaction events of the movie. SES was defined as the average of Z-scored income and Z-scored parent education. Scatterplot shows the relationship between SES and extracted Z-statistic values within the OFC result for visualization purposes, to show the distribution of the data (adjusted for covariates: age, gender, number of outlier volumes, dataset). Results were corrected for multiple comparisons at $z = 3.1$, $p < .05$, $n = 70$.

parent-child interaction task). Since there were no notable measurement issues for these three parents, their ratings likely reflect meaningful variation in the range of normative parenting behaviors. Nevertheless, we tested for robustness to removing these three data points, and found that negative parenting behaviors was still significantly related to reduced activation during positive affect events in the VTA ($t(22) = -4.20$, $p < .001$) and cerebellum ($t(22) = -3.49$, $p = .002$), controlling for age, gender, and number of outlier volumes (but note that significance is inflated because the parameter estimates were extracted from regions that were significant at the whole-brain level).
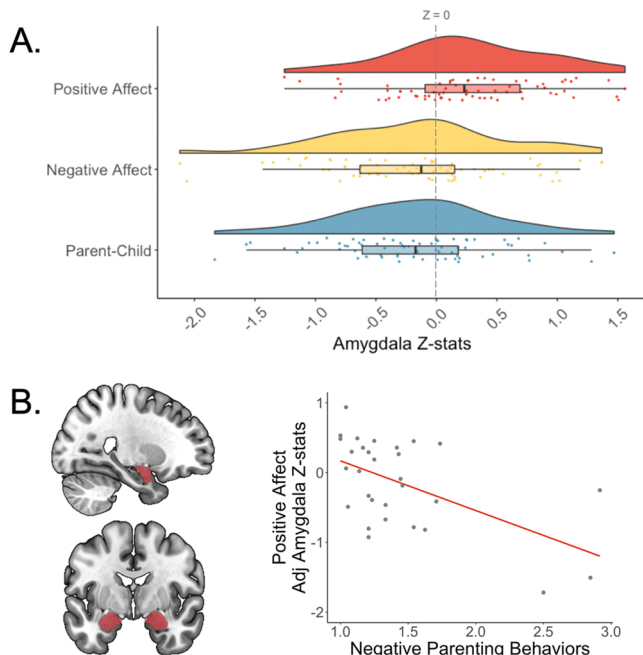
2.5.1.3. Amygdala region-of-interest analyses. The amygdala was significantly activated above baseline only during the positive affect events (Fig. 7A; $t(69) = 3.39$, $p < .001$), and was significantly activated below baseline during the negative affect events ($t(69) = -2.00$, $p = .02$) and

parent-child interaction events ($t(69) = -2.30$, $p = .01$). The amygdala was significantly more active during positive affect events relative to negative affect events ($t(68) = 3.73$, $p < .001$) and parent-child interaction events ($t(68) = 4.01$, $p < .001$).

Amygdala activity during positive affect events was not related to SES ($t(64) = -0.49$, $p = .63$). Reduced amygdala was marginally related to more stressful life events ($t(62) = -1.81$, $p = .076$), and significantly related to more negative parenting behaviors ($t(25) = -2.85$, $p = .009$; Fig. 7B). SES, stressful life events, and positive and negative parenting behaviors were not related to amygdala activity during the negative affect events (all $ps > .3$). Greater amygdala activity during the parent-child interaction events was related to more stressful life events ($t(62) = 2.09$, $p = .04$). SES and positive and negative parenting behaviors were not related to amygdala activity during the parent-child interaction events (all $ps > .2$). Three children were
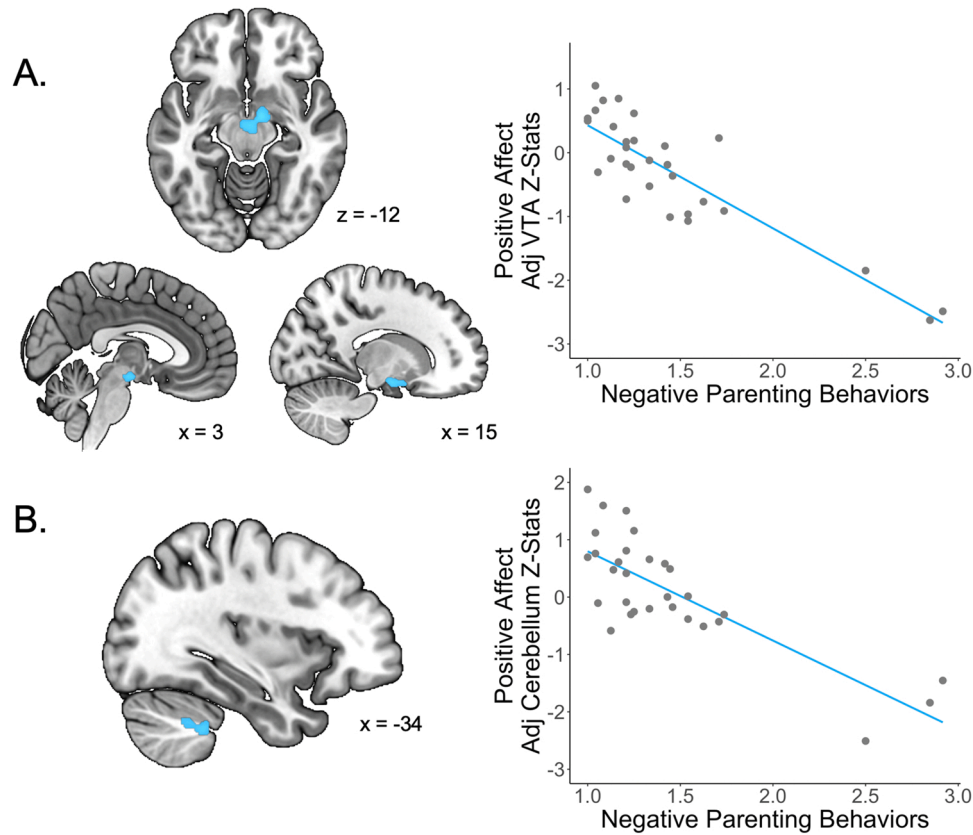
Fig. 6. Negative parenting behaviors were associated with reduced activity in the (A) VTA and (B) cerebellum during positive affect events of the movie. Scatterplots show the relationship between negative parenting behaviors and extracted Z-statistic values for visualization purposes, to show the distribution of the data (adjusted for covariates: age, gender, number of outlier volumes). Models were corrected for multiple comparisons at $z = 3.1$, $p < .05$, $n = 30$.

Fig. 7. Region-of-interest analysis for amygdala activation during the movie, using an independent anatomical amygdala ROI. A. Average amygdala activation to positive affect events, negative affect events, and parent-child interaction events during the movie ($n = 70$). B. Negative relationship between amygdala activation to positive affect events and negative parenting behaviors (adjusted for covariates: age, gender, number of outlier volumes; $n = 30$).

outlying in their stressful life events scores (more than 1.5 times the interquartile range above the third quartile). After testing for robustness by removing the three outlying data points, we found that stressful life events were not significantly associated with amygdala activity during the parent-child interaction events ($t(59) = 1.34$, $p = .18$). After removing the three data points that were outlying for negative parenting behaviors, we also found that the association with negative parenting behaviors was no longer significant ($t(22) = -1.48$, $p = .15$).

3. Discussion

In the current study, we used a novel movie paradigm with richly engaging emotional and social content to tap into children's affective neural responses. We explored whether variability in children's affective responses related to variability in children's early experiences: socio-economic status (SES) and stressful life events, as well as children's more proximal experiences with their parents (observed during a parent-child interaction task). Children from higher SES families showed greater activity in medial orbitofrontal cortex during parent-child interaction events of the movie. Children with greater exposure to negative parenting behaviors (i.e., negative affect and control) showed lower activity in the ventral tegmental area (VTA), cerebellum, and amygdala while processing naturalistic positive emotional content. We did not find evidence for a relationship between positive parenting behaviors and neural activity to any event type. Overall, our movie fMRI task recruited emotional and social brain regions, and is a promising paradigm for future work on the development of affective, social, and motivational processing in young children.

We observed a main effect of SES during the parent-child interaction events of the movie: higher SES was related to greater activity in medial orbitofrontal cortex (OFC). The medial OFC has been proposed to play a

role in the affective and goal-oriented evaluation of internally-generated events, like episodic memories and imagining the future (Dixon et al., 2017). Although speculative, one possibility is that higher SES fosters an enhanced ability to introspect about self- and other-related representations; a second possibility is that children from higher SES backgrounds interpreted ambiguous parent-child interactions more positively.

We found that more negative parenting behaviors were associated with reduced VTA activity during the positive affect events of the movie. Early alterations in the VTA may have a critical impact on children's socioemotional and motivational development, as the VTA is the origin of major dopaminergic projections innervating large swaths of the brain. A recent study found that placing dams in a stressful, low-resource environment drove an increase in negative parenting behaviors and resulted in long-term attenuation of VTA dopamine activity in their offspring, suggesting a potent role for early disrupted programming of VTA development (Rincón-Cortés and Grace, 2021). It has been argued that the dopamine system plays a crucial role in supporting the ability to appropriately cope with challenges (Ironside et al., 2018), and to flexibly adapt to ever-changing environmental priorities (Douma and de Kloet, 2019)—this would help explain why adversity-related disruptions of the dopamine system often lead to difficulties with nuanced behaviors like effortful reward seeking and social exploration. Negative parenting behaviors were also associated with reduced activity in the cerebellum to positive affect movie events. Beyond coordinating motor behaviors, the cerebellum plays a powerful role in modulating higher-order cognitive, affective, and social functions (Van Overwalle et al., 2014), and it may drive the maturation of cognitive and affective cortical areas early in development (Wang et al., 2014). A study in mice found that excitatory projections from the cerebellum to the VTA robustly modulated reward circuitry and were more active during social exploration (Carta et al., 2019). Early blunting of the cerebellum and VTA to positive stimuli may point to a broader pattern of early vulnerability with implications for disrupted social and motivation-related behavior.

In region-of-interest analyses, exposure to stressful life events and negative parenting behaviors were related to lower amygdala activity during positive affect movie events. The amygdala is part of an integrated network of regions responsible for complex processing of emotion, reward, and social experience (Cromwell et al., 2020). Although prior work has associated the amygdala with negative emotion and fear conditioning, the amygdala processes both positive and negative valence (Smith and Torregrossa, 2021). One study with adults found that greater cumulative activity in the amygdala during negative movie clips predicted heightened sensitivity to subsequently shown fearful faces, while greater cumulative activity in the amygdala during positive movie clips predicted a lower amygdala response to fearful faces (Pichon et al., 2015). In other words, at least in the short-term, responsiveness of the amygdala to positive emotion may help regulate responses to fear-related stimuli, and suggests a potential mechanism by which persistent blunted activity to positive emotional experiences may worsen responses to negative stimuli and alter future affective functioning.

Broadly, our work is consistent with evidence that early life stress may disrupt positive valence systems (Kujawa et al., 2020). For example, our findings are consistent with a study in 11–17-year-old adolescents showing that maternal negative affect observed during an interaction task related to blunted response to positive rewards in regions that track salience, like the amygdala, anterior insula, anterior cingulate, and nucleus accumbens (Tan et al., 2014). However, the current literature on parenting and children's neural processing of positive and negative stimuli is mixed, perhaps due to study differences in age range and methods for characterizing parenting, as well as the moderating effects of different risk factors (Farber et al., 2020; Kujawa et al., 2020; Tan et al., 2020). In our study, positive parenting behaviors were not related to any differences in BOLD activity. It could be that negative parenting behaviors have a larger effect than positive parenting behaviors on brain activity related to emotion processing, and that the sample size was not

sufficient to detect smaller effects. It is also possible that our measure of positive parenting behavior did not capture the relevant features that are involved in emotion socialization; however, it is worth noting that the positive parenting score was correlated with other key study variables as expected (i.e., higher SES, less negative parenting behaviors).

Although in the current study we found no direct associations between positive parenting behaviors and child BOLD activity, it may be that positive parenting behavior plays a different role as a moderator of family process effects. For instance, it could be a protective factor in environments that are associated with greater stress exposure (Brody et al., 2019). It may also be that many parents can sustain positive behaviors for the length of a 15-minute parent-child interaction task, especially when they know they are being filmed, so variability in this measure is less meaningful than variability in negative affect and physical control. We did find that three parents with higher levels of negative behaviors contributed to the association between parenting and BOLD activity, but there were no issues with measurement in these cases. Rather, these were parents who were not able to maintain positive interactions during the lab task, and their ratings likely reflect meaningful variation in the range of normative parenting behaviors.

The use of naturalistic movie fMRI with developmental populations is increasingly popular (Vanderwal et al., 2019), due to its utility for encouraging compliance in young participants and its promise for yielding novel insights into the brain's response to more ecologically valid stimuli (Finn et al., 2020; Simony and Chang, 2019; Sonkusare et al., 2019). For example, in the current study, our positive and negative affect movie events captured not only the main character's emotional facial expressions, but also more nuanced narrative-level emotional components (e.g., the main character dealing with jarring physical or social surprises, experiencing the joy of overcoming their fears, etc.). Recent studies have used multivariate techniques to test for differences between children and adults in processing positive and negative movie clips (Camacho et al., 2019; Mitchell et al., 2021). Another study found no main effects of age in relation to valenced movie clips across 4–12-year-olds (Karim and Perlman, 2017), but did find an age x irritable temperament interaction on BOLD activity. This is consistent with the current study, where we found no effects of age. It could be that there are other moderating factors obscuring age effects, or that the kind of emotional processing elicited by our short film does not show much developmental change in our age range. Indeed, prior work that teased apart emotion reactivity and emotion regulation only found a relationship with age for emotion regulation (in ages 10 and up; (Silvers et al., 2012). Movie fMRI also shows promise for examining developmental changes in how moment-to-moment emotional content dynamically relates to brain-behavior relationships (Gruskin et al., 2020), as well as how emotional and social processing are reflected in complex patterns of brain activity, moving beyond univariate approaches (Jääskeläinen et al., 2021).

This study has a number of limitations. The analyses were exploratory, the data were cross-sectional, and multiple tests were conducted in a small sample size. Longitudinal work in a larger sample should be pursued in order to confirm associations between early experiences and responses to movie stimuli, especially for the findings with negative parenting behaviors. Second, although movie fMRI shows great promise as a method for more robustly eliciting complex processes of interest, it is important to think carefully about how the unconstrained aspects of movies may introduce confounds, like unexpected features of how the movie was crafted (i.e., to explicitly capture the audience's attention and evoke particular emotions as part of the storyline), or differences in *a priori* expectations that children of various ages may bring to movie-watching (Cantlon, 2020). For example, in the current study we did not have information on factors like whether the child had seen the movie before, or child-specific factors that could impact emotional experience, like subjective interpretation of the movie events, or individual differences in child temperament, which also relates to reward circuitry function (Guyer et al., 2014). Also, children could differ in their

level of engagement during the movie, so future work could include comprehension or attention checks. Third, the construct of emotional processing is broadly defined, and facets like emotion expression, perception, knowledge, reactivity, and regulation can all be differentially impacted by adverse early experiences (Milojevich et al., 2021). Future work with movie fMRI should consider how different sub-components of emotional processing can be effectively engaged and disambiguated. For example, given the activation of default mode regions that are also known to be involved in mentalizing during the positive and negative affect events, it could be that watching a character experience a positive or negative emotion also activates theory of mind processes. Fourth, although our use of a naturalistic parent-child interaction task provides rich data on parenting behaviors, this was a one-time 15-minute snapshot into the parent-child dynamic, which could be influenced by social desirability concerns or transient situational factors and stressors. In particular, the frequency of negative parental affect and control behaviors in this study tended to be low, and it is possible that the laboratory context made it less likely that more extreme negative behaviors would be observed. It may be useful to consider administering parent-child interaction tasks at multiple time points, using ecological momentary assessment methods to sample parent and child behaviors over many days (Leonard et al., 2022), or combining parent-child observational data with questionnaire data from multiple informants (Farber et al., 2020). Fifth, our measures of positive and negative parenting behaviors were averaged across multiple types of parenting behaviors, meaning that we cannot isolate specific parenting behaviors that might serve as promising targets for intervention, and it is unclear whether our findings would generalize to other negative caregiving experiences. Finally, due to the diversity of our participant sample, we acknowledge that there are cultural differences in parenting practices that historically have not been well accounted for in developmental research, and that warrant more sensitive, nuanced exploration in future work (Nielsen et al., 2017).

In sum, our findings suggest that exposure to negative early experiences may shape how children experience rewarding positive information. Critically, differences in neural activation are malleable. One intervention designed to train parents to increase nurturance and sensitivity to their child, and decrease negative parent behaviors, led to increased brain responses to photographs of their mothers (Valadez et al., 2020). Future work should examine structural approaches to supporting parents, so parents can best support their children.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Questionnaire data, behavioral data, and deidentified neuroimaging data used in this study are freely available at https://openneuro.org/datasets/ds004228.

Acknowledgments

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