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Investigating the role of executive function in brain responses to infant crying among new parents

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Abstract

Infant crying is a fundamental communication signal that captures caregiver attention and elicits caregiving responses. Executive function (EF) is critical in managing the cognitive and emotional demands of parenting, particularly in processing infant cues. This study explored the relationship between experienced EF difficulties and neural responses to infant crying among biological birthing parents. Participants were pregnant individuals from the Relationships of Parent–Infant Social, Emotional, and Brain Development project who completed the Behavior Rating Inventory of Executive Function—Adult Version during the third trimester. Postpartum, functional Magnetic Resonance Imaging measured brain activation in response to their own and other infants' cries, as well as control sounds. Greater experienced EF difficulties during pregnancy were prospectively associated with increased cry-evoked activation in lateral temporal regions, including a conjunction cluster in the left middle temporal gyrus shared across all four EF subdomains, and overlapping recruitment of regions such as the left superior temporal gyrus and right inferior frontal gyrus across multiple subdomains. These findings suggest that caregivers who report greater EF difficulties engage heightened auditory–temporal and control-related neural responses when processing infant distress signals, underscoring the relevance of EF-related individual differences for early parenting neurobiology.

Keywords: executive function; infant crying; middle temporal gyrus; superior temporal gyrus; inferior frontal gyrus

Introduction

Infant crying

Infant crying is an attachment behaviour that captures caregiver attention and motivates approach behaviours (Bowlby 1969). Caregivers infer the infant's needs from the cry's acoustic properties and context, a pre-linguistic communication that promotes survival and supports the development of language and social skills (Soltis 2004, Matsuki et al. 2022). However, identifying the cause of crying and implementing effective soothing strategies can be challenging. Excessive or inconsolable crying increases caregiver stress and can undermine self-efficacy (Donovan 1981, Fujiwara et al. 2011, Verhage et al. 2013). Since crying has been linked to the onset of child physical abuse and postpartum depression (Reijneveld et al. 2004, Radesky et al. 2013), understanding the cognitive and neural mechanisms of cry processing is critical for both basic science and intervention development.

Executive function

Difficulties in the parenting context

This study focuses on difficulties in executive function (EF) as a factor underlying individual differences in caregiving and responses to infant crying. Parenting requires multitasking—juggling domestic chores, paid work, child supervision, and direct caregiving—which increases stress (Craig 2006, Offer and Schneider 2011). Experimental work shows that competing tasks reduce empathic responses to infant cries (Hiraoka and Nomura 2016, 2020), underscoring the need for effective processing of infant stimuli. In parenting, regulating one's emotions and prioritizing the child are essential (Manczak et al. 2016). In particular, when dealing with a distressed infant, caregivers must regulate the negative emotions elicited by infant cues (Kim et al. 2016b).

Relation between executive function and parenting behaviours

EF refers to higher-order cognitive processes such as inhibition, working memory, and cognitive flexibility (Diamond 2013). These processes support the regulation of aversive emotion by enabling goal-directed control over attention and appraisal. Converging evidence shows that cognitive control of negative affect reliably engages a fronto–cingulo–insular network comprising the right inferior frontal gyrus (rIFG), dorsolateral and dorsomedial prefrontal cortex (dlPFC/dmPFC), anterior cingulate cortex, and anterior

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insula, which in turn modulates limbic activity (e.g. amygdala) in response to aversive stimuli (Aron et al. 2004, Ochsner and Gross 2005, Buhle et al. 2014, Etkin et al. 2015). In everyday parenting, these control processes help caregivers manage stress, sustain attention to the infant, and regulate their own affect in the face of distress cues—capacities linked to more sensitive caregiving.

Infant crying is typically appraised as an aversive, high-salience socio-emotional signal of infant need, and neuroimaging work indicates that it recruits auditory–temporal regions [e.g. superior temporal gyrus (STG)/superior temporal sulcus (STS)] together with prefrontal control systems implicated in attention and emotion regulation (Kim et al. 2016b, Parsons et al. 2017b; Witteman et al. 2019). These neural responses support the parsing of vocal distress signals and the top-down regulation required to select and implement appropriate soothing behaviours. At the behavioural level, individual differences in EF shape variability in parenting: EF supports parenting via stress and attention regulation and has been linked to sensitive caregiving (Barrett and Fleming 2011, Monn et al. 2017, Nordenswan et al. 2021, Tomlinson et al. 2022). Dysfunction in shifting, emotional control, and working memory can lead to a lack of emotion regulation, increasing the risk of child physical abuse (Crouch et al. 2018, 2021). Other studies have also indicated a link between deficits in EF and increased risk of harsh parenting (Bridgett et al. 2017, Li et al. 2023, Mao et al. 2023). In addition to the basic components of EF, higher-order aspects, including planning, reasoning, and problem-solving, are also relevant in the context of parenting. For instance, parents with lower abilities in problem-solving and planning tend to exhibit higher levels of harsh parenting (Deater-Deckard et al. 2012, Monn et al. 2017). Parenting inherently involves a multitasking environment, often accompanied by time pressures and stress (Craig and Jenkins 2016). In such contexts, caregivers are believed to employ both core and higher-level EFs to effectively process stimuli from their children and implement sensitive caregiving behaviours. Importantly, EF declines during pregnancy—most notably in the third trimester—due to hormonal and neural changes (Davies et al. 2018), and individual differences of EF during this period may affect postpartum parenting.

Neural basis of executive function and infant cry processing

Infant crying recruits auditory and social-perceptual systems in the superior temporal cortex (STG/STS) together with prefrontal control systems, including the inferior frontal gyrus (IFG) (Kim et al. 2016b, Parsons et al. 2017b, Witteman et al. 2019). Briefly, STG/STS supports parsing of vocal features and socio-emotional meaning, whereas IFG contributes to selection and top-down control in demanding contexts. This functional dissociation provides a principled basis for testing whether experienced EF difficulties are associated with neural responses to infant crying in the early postpartum period.

At the behavioural level, experimental manipulations of emotional regulation strategies and working memory load have been shown to change empathy and negative perceptions towards infant cries (Hiraoka and Nomura 2016, 2019, Riem and Karreman 2019). This suggests that individual differences in EFs likely play a significant role in the neural processing of infant crying. However, no studies have yet examined the relationship between the neural processing of an infant's cry and EFs.

Aims and hypothesis

Participants were drawn from the Relationships of Parent–Infant Social, Emotional, and Brain Development (RISE) project, a longitudinal birth-cohort study examining how prenatal socioeconomic adversity and cumulative risk relate to parental neurobiology and infant brain development across the perinatal period. Within this framework, we focus on experienced EF difficulties during pregnancy as one pathway through which socioeconomic contexts may shape cognitive control and emotion regulation demands in early parenting (Evans and Schamberg 2009, Hackman and Farah 2009, Blair and Raver 2012, Mani et al. 2013). To our knowledge, however, the association between experienced EF difficulties and neural processing of infant crying in new parents has not been directly characterized. The primary objective of this study is to examine the prospective relationship between EF during pregnancy and neural responses to infant crying in the early postpartum period. In addition, we assess subjective ratings of infant crying and emotional availability (EA) in relation to individual differences in EF.

EF is a multidimensional construct. Self-reported experienced EF difficulties were assessed using the Behavior Rating Inventory of Executive Function—Adult Version (BRIEF-A). Because alternative factor structures have been proposed (two-, three-, and four-factor models), we first evaluated the factor structure in our sample and then used the resulting factor- or index-level scores in subsequent analyses. In the most fine-grained specification—the four-factor model—EF difficulties are captured by internal metacognition, external metacognition, behavioural regulation, and emotional regulation.

Each of these four subdomains of experienced EF difficulties is theoretically implicated in processing and responding to infant crying. Internal metacognition encompasses working memory, initiation, and planning/organization; to soothe a crying infant, caregivers must generate a plan and initiate its implementation. External metacognition reflects performance monitoring and online adjustment of behaviour in light of the infant's feedback (e.g. Drummond et al. 1993). Emotional regulation is required to down-regulate the aversive affect elicited by infant cries. Behavioural regulation—including inhibitory control—is needed to suppress impulsive reactions and enact deliberate, goal-directed caregiving behaviours, thereby reducing the likelihood of inappropriate responses.

In the present study, we examine how difficulties in these four subdomains of experienced EF—internal metacognition (problem solving/initiation), external metacognition (performance monitoring), emotional regulation, and behavioural regulation—relate to brain activation during infant-cry processing.

We formulated the following overlap and domain-specific hypotheses about relations between experienced EF difficulties and brain responses to infant crying. First, we expected that, across all four subdomains of experienced EF difficulties, higher scores would covary with stronger cry-related recruitment of a cognitive control/salience network—including dlPFC, anterior cingulate cortex (ACC) (especially dorsal anterior cingulate cortex (dACC)), ventrolateral prefrontal cortex (VLPFC), and anterior insula—consistent with prior work on goal maintenance, conflict monitoring, and top-down control (Aron et al. 2004, Fleming and Dolan 2012, Niendam et al. 2012, Buhle et al. 2014, Etkin et al. 2015, Friedman and Robbins 2022, Rodríguez-Nieto et al. 2022).

For internal metacognition (problem solving/initiation), we predicted that greater difficulties would be associated with stronger cry-related activation in frontoparietal control regions (e.g. intraparietal sulcus (IPS) within the frontoparietal network) that support trial-by-trial implementation of task sets (Dosenbach et al. 2007). For external metacognition (performance monitoring), we expected that higher difficulties would show stronger cry-related recruitment of error-responsive frontoparietal nodes (dlPFC, inferior parietal lobule (IPL), and cerebellum) implicated in rapid behavioural adjustment following performance monitoring (Dosenbach et al. 2007). For emotional regulation, we predicted that greater

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difficulties would be associated with reduced cry-related ventromedial prefrontal cortex (vmPFC) recruitment together with relatively heightened amygdala responsivity (Buhle et al. 2014, Etkin et al. 2015). For behavioural regulation, we expected that higher scores would be associated with stronger cry-related activation in the IFG, repeatedly identified as a key node for response inhibition (Aron et al. 2004, Friedman and Robbins 2022).

Materials and methods

Participants

The participants in this study were part of the RISE project. The majority were pregnant individuals recruited up to 14 weeks' gestation; however, one participant in this current sample was recruited during the third trimester of pregnancy. Interested participants who met the eligibility criteria—aged between 18 and 45 years, having a singleton pregnancy, being fluent in English, and income-to-needs ratio below 8 at the time of recruitment—were scheduled for a home/remote visit. The participant recruited during the third trimester also had the option of a lab visit for their first session. Exclusion criteria included current use of psychotropic medications, a lifetime diagnosis of psychiatric or neurological illnesses other than depression, anxiety, or post-traumatic stress disorder, testing positive for non-cannabis illicit substances, or reporting heavy nicotine or alcohol use. It should be noted, however, that five participants met the criteria for bipolar disorder (I or II) or cyclothymic disorder or experienced a manic or hypomanic episode based on the SCID assessment, even if this was not reported during initial screening. The demographic information of the current participants ($n = 88$) is detailed in Table 1. Note that the EF measures discussed later were obtained during the third trimester ($n = 137$); therefore, some participants who dropped out and did not participate in the MRI session are included in the EF assessments. To obtain more reliable results by using the largest possible sample size, the factor analysis of the questionnaires measuring EFs included participants who did not participate in the MRI.

All procedures were approved by the University of Denver Institutional Review Board (IRBNet ID 934172, first approved on 29 July 2017). Informed consent was obtained from all participants prior to participation.

Procedures

The procedure for this study was structured around the stages of pregnancy and the postpartum period. For participants who met the eligibility criteria, home visits were conducted during each trimester of their pregnancy. Specifically, the mean gestational weeks at the time of the visits were as follows: first trimester at 14.74 weeks (SD = 3.64), second trimester at 23.04 weeks (SD = 2.07), and third trimester at 33.22 weeks (SD = 1.69). It should be noted that one participant who was recruited during the third trimester is not included in these means. Prior to the onset of the COVID-19 pandemic in March 2020, researchers conducted home visits during which participants provided informed consent and completed measures concerning their income and demographics. Following March 2020, participants continued their involvement remotely from their homes. At the third prenatal data collection point, participants completed the BRIEF-A to assess executive functioning difficulties. A few weeks postpartum, as detailed in Table 1, participants underwent functional Magnetic Resonance Imaging (fMRI) tasks, inclusive of infant cry tasks. In addition, parent–infant interactions were observed in the home setting at an average of 2.32 weeks postpartum (SD = 1.77). Until March 2020, these interactions were video-recorded by researchers during home visits.

Table 1. Characteristics of the participants.

Characteristic	N = 88
Age at first trimester	28.67 (5.56)
Participant's ethnicity (Hispanic or Latino)	27 (31%)
Participant's race	
American Indian/Alaska Native	3 (3.5%)
Asian	1 (1.2%)
African American	12 (14%)
Native Hawaiian or Other Pacific Islander	1 (1.2%)
Caucasian	55 (64%)
Other	14 (16%)
Average income-to-need ratio during pregnancy	3.47 (2.42)
Infant sex	
Female	49 (56%)
Male	39 (44%)
Parity	
Primiparous	19 (22%)
Multiparous	68 (78%)
Cannabis screen positive at the time of fMRI scans	12 (14%)
BRIEF-A internal metacognition	158.78 (30.10)
BRIEF-A external metacognition	101.14 (17.14)
BRIEF-A behavioural regulation	99.42 (16.03)
BRIEF-A emotional regulation	99.72 (16.75)
Postpartum days at the time of fMRI scans	37.95 (21.58)
EA sensitivity	5.45 (1.11)
EA nonintrusiveness	5.51 (1.07)
EA Nonhostility	5.21 (1.25)

BRIEF-A scores presented are summed *T*-scores for each factor (internal metacognition, external metacognition, behavioural regulation, and emotional regulation).

After March 2020, due to the shift to remote visit procedures, interactions were recorded remotely while participants remained at home. For a small number of participants without adequate home communication facilities, interactions were recorded in the lab during visits with their children. These recordings were then evaluated for EA (Biringen et al. 2014, see below).

Measures

Executive function

Executive functioning challenges in participants were assessed using the BRIEF-A (Roth et al. 2005). The BRIEF-A comprises 75 items, each rated on a three-point scale. This tool measures difficulties in executive functioning in everyday situations across nine factors, with higher scores indicating more significant impairments in each respective function. Previous studies have commonly condensed these nine factors (Inhibit, Shift, Emotional Control, Self-Monitor, Initiate, Working Memory, Plan/Organize, Task Monitor, and Organization of Materials) into two higher-order factors (behavioural regulation and metacognition) and a Global Composite that includes all nine factors (Roth et al. 2005). However, recent studies have proposed alternative BRIEF-A structures (Gioia et al. 2002, Roth et al. 2013, Donders and Strong 2016), such as a three-factor model (behavioural regulation, emotional regulation, and metacognition) and a four-factor model (behavioural regulation, emotional regulation, internal metacognition, and external metacognition).

In this study, confirmatory factor analysis (CFA) was conducted using the age-adjusted *T*-scores derived from the raw scores of the BRIEF-A. CFA was chosen to test the suitability of previously proposed factor structures for our sample. The four-factor model derived from this broader dataset demonstrated good absolute and relative fit indices, as detailed in Table 2. Aligning with our goal to assess the impact of executive functioning in a multidimensional

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Table 2. BRIEF-A model goodness of fit.

Model	RMSEA	CFI	TLI	SRMR	AIC	BIC
One factor model	0.13	0.94	0.92	0.06	8,117.74	8,170.30
Two factor model	0.09	0.97	0.96	0.04	8,081.64	8,137.12
Three factor model	0.09	0.97	0.96	0.04	8,085.00	8,146.32
Four factor model	0.06	0.99	0.98	0.03	8,069.39	8,139.47

RMSEA, root mean square error of approximation; CFI, Comparative Fit Index; TLI, Tucker–Lewis Index; SRMR, standardized root mean square residual; AIC, Akaike Information Criterion; BIC, Bayesian Information Criterion.

manner, we adopted the four-factor model. Each factor score was calculated by summing the *T*-scores of the corresponding subscales. The defined factors are as follows: internal metacognition, which includes Planning, Initiating, and Working Memory; external metacognition, encompassing Task Monitoring and Organization of Material; behavioural regulation, covering Inhibitory Control and Self-Monitoring; and emotional regulation, involving Shifting and Emotional Control. Internal consistency was satisfactory to excellent across the four BRIEF composites: internal metacognition (α = .93), external metacognition (α = .80), behavioural regulation (α = .81), and emotional regulation (α = .81). Our dataset does not include performance-based EF tasks or clinical diagnoses; therefore, criterion validity could not be directly examined in this sample. Nevertheless, prior work provides convergent and discriminant validity evidence for the BRIEF-A: studies have shown convergence between task-based EF performance and BRIEF-A ratings and have demonstrated that BRIEF-A differentiates clinical groups (e.g. ADHD) from controls (Chang 2011, Erkkilä et al. 2018). Accordingly, we use BRIEF-A to index experienced EF difficulties.

Emotional availability

In this study, the EA of participants during their interactions with infants was assessed. Participants were asked to engage naturally with their infants for 10 min, as they would typically do in their daily lives. EA was successfully assessed for the 73 parent–infant dyads.

The recorded sessions were analysed using the EA scales (Biringen et al. 2014). The participant's sensitivity scale evaluates the caregiver's ability to provide warm and emotionally connected care, focusing on aspects like affect, clarity, timing, flexibility, acceptance, and the amount of interaction without conflict (Bornstein et al. 2008, Biringen et al. 2014). Nonintrusiveness assesses the participant's support for her child without being overdirective, overstimulating, overprotective, or interfering (Bornstein et al. 2008, Biringen et al. 2014). Nonhostility measures the participant's communication with her child, focusing on patience, pleasantness, and harmony while avoiding rejection, abrasiveness, or antagonism (Bornstein et al. 2008, Biringen et al. 2014). Each of these scales ranges from 1 to 7, with higher scores reflecting more optimal parental behaviours in the respective areas. Structuring was not evaluated as part of the EA scales in this study. This decision was taken into consideration due to the infants' young age and a limited range of interactions related to structuring. In such instances, an accurate assessment of structuring could not be ensured. To evaluate interrater reliability, we randomly selected a subsample of 14 dyads (≈19% of the total sample), which were double-coded independently by two trained raters who were blinded to other study data. We computed intraclass correlation coefficients (ICC[2,1]). The EA scales demonstrated acceptable to good interrater reliability: Sensitivity (ICC = 0.794, $P < .01$), Nonintrusiveness (ICC = 0.626, $P < .01$), and Nonhostility (ICC = 0.739, $P < .01$). These findings indicate that EA coding was reliable in the current sample.

Functional magnetic resonance imaging measure

Infant cry task

In the fMRI task, participants were exposed to four different types of sounds: their own infant's cry (own cry), another infant's cry (other cry), white noise matched to their own infant's cry, and white noise matched to another infant's cry. Prior to the COVID-19 pandemic, researchers visited the homes of participants and recorded the infant cries in the family's home environment for use in fMRI tasks. Following the onset of the COVID-19 pandemic, participants used their smartphones to record their infants' cries and sent the audio files to the research team. These recordings were then processed to eliminate background noise. Additionally, our cry processing involved matching the acoustic properties of the control sounds to ensure comparability. Other infant cries were sourced from infants of similar postpartum age to our participants and have been used in previous research (Kim et al. 2010, 2011). For the control sounds corresponding to both the own-cry and other-cry conditions, we generated envelope-matched white noise by imposing each original cry's amplitude envelope onto a white-noise carrier (editing performed in Cool Edit Pro, Version 2.0; Syntrillium Software, Phoenix, AZ). This procedure preserves temporal dynamics (e.g. amplitude modulation and duration) while removing speech/vocal fine structure. The experiment employed a 2 × 2 factorial design with the within-subject factors Sound (cry, envelope-matched noise) and Identity (own, other). Each stimulus instance was presented five times across two sessions.

The task was organized into two sessions, each featuring five blocks of crying stimuli and five blocks of control stimuli. Each stimulus was presented for a duration of 20 s, amounting to a total of 10 trials per condition across both sessions. The blocks were separated by intervals varying from 8 to 12 s, with an average interval of 10 s between blocks. Participants were instructed to focus on each auditory stimulus and to allow their emotional and cognitive reactions to unfold without restraint. This approach was adopted to capture participants' spontaneous thoughts and emotions elicited by the sounds, thereby reducing the potential for extraneous cognitive activities that could arise from responding to queries during the task.

Perception of infant crying

Following the fMRI task, participants rated each construct—arousal, urgency, health, aversiveness, and care/approach—on a five-point Likert scale for own-cry and other-cry separately, based on items commonly used in infant-cry perception research (Zeskind and Marshall, 1988, Out et al. 2010, Schoenmaker et al. 2015). Because these are single-item indicators, internal consistency indices are not applicable, and no test–retest data were collected. For analysis, we averaged the own- and other-cry ratings for each construct to form a composite, which reduces random error relative to a single observation.

Image acquisition and preprocessing

In this study, fMRI was performed using a Siemens 3T Magnetom Prisma Fit scanner. The image acquisition process included collecting high-resolution anatomical T1-weighted images and T2*-weighted gradient echo-planar imaging (EPI) images.

For the anatomical T1-weighted images, the parameters were set to acquire 208 slices with a repetition time (TR) of 2400 ms, an echo time (TE) of 2.22 ms, a flip angle of 8°, a field of view of 256 mm^2, and a voxel size of 0.8 mm^3. Whole-brain BOLD images were acquired with a simultaneous multi-slice (multiband) gradient-echo EPI sequence (TR = 460 ms, TE = 27.2 ms, flip angle = 44°, voxel size = 3.0 mm isotropic, 56 slices, multiband factor = 8, A ≫ P phase encoding).

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Table 3. Correlations between BRIEF-A and EA scales.

	Sensitivity			Nonintrusiveness			Nonhostility		
	r	P	q	r	P	q	r	P	q
Internal metacognition	−.090	.468	.500	−.090	.476	.952	−.190	.133	.171
External metacognition	−.080	.500	.500	−.020	.871	.973	−.170	.171	.171
Behavioural regulation	−.280	.018	.072	−.110	.372	.952	−.310	.011	.044
Emotional regulation	−.080	.494	.500	.000	.973	.973	−.180	.134	.171

Values are Pearson's *r*. Two-tailed *P* values are shown uncorrected and corrected using the Benjamini–Hochberg false discovery rate (FDR). FDR correction was applied within each EA outcome (Sensitivity, Nonintrusiveness, Nonhostility; four tests per family, $q < .05$). For transparency, when a single BH–FDR was applied across all 12 correlations, no associations survived at $q < .05$. Significant *q* values are in bold.

Table 4. Correlations between BRIEF-A and cry perceptions.

	Arousal			Urgent			Aversive			Health			Approach		
	r	P	q	r	P	q	r	P	q	r	P	q	r	P	q
Internal metacognition	−.180	.165	.330	.380	.003	.008	.130	.316	.373	−.160	.221	.294	−.080	.568	.963
External metacognition	−.220	.096	.330	.280	.028	.037	.240	.063	.127	−.050	.715	.715	−.150	.261	.963
Behavioural regulation	.110	.391	.391	.370	.004	.008	.120	.373	.373	−.240	.066	.132	−.050	.722	.963
Emotional regulation	−.130	.314	.391	.250	.053	.053	.240	.063	.127	−.290	.023	.091	.000	.987	.987

Values are Pearson's *r*. *P* values are shown uncorrected and corrected using the Benjamini–Hochberg false discovery rate (FDR). FDR correction was applied within each cry-perception outcome (arousal, urgent, aversive, health, and approach; four tests per family, $q < .05$). For transparency, when a single BH–FDR was applied across all 20 correlations, only the internal-urgent and behavioural-urgent associations met $q < .05$. Significant *q* values are in bold.

Statistical analysis

Preliminary analyses

First, to identify potential confounding factors, we calculated Pearson correlation coefficients between continuous demographic variables and each score of the BRIEF-A. For dichotomous demographic variables, we conducted *t*-tests with each score of the BRIEF-A as the dependent variable. Next, to investigate the relationship between executive functioning challenges and parenting behaviours, a Pearson correlation analysis was performed between the four factors of the BRIEF-A and the three factors of the EA scales. To control for multiple comparisons, we applied the Benjamini–Hochberg false discovery rate (FDR) correction. Correction was performed within each outcome domain (i.e. within each EA scale and within each cry-perception rating), with $q < .05$ considered significant. Both uncorrected *P* values and FDR-adjusted *q* values are reported in Tables 3 and 4. For transparency, we also note in the table footnotes the results of applying a single BH–FDR across all tests within each table.

Functional magnetic resonance imaging analysis

For this study, fMRI data preprocessing was conducted using fMRI prep 20.2.1, based on Nipype 1.5.1, alongside Analysis of Functional NeuroImages (AFNI), adhering to a rigorous workflow. Anatomical data were processed to correct for intensity non-uniformity and skull-stripped using Advanced Normalization Tools (ANTs), followed by brain tissue segmentation and cortical reconstruction with recon-all in FreeSurfer. Spatial normalization was achieved via antsRegistration to the MNI152NLin2009cAsym template.

Functional data were preprocessed by generating reference volumes, applying motion correction with mcflirt, and conducting slice-time correction with AFNI's 3dTshift. Head-motion parameters were estimated, and the BOLD time series were resampled in native and standard spaces. Confounding factors, including framewise displacement and global signals, were computed, and noise components were identified via CompCor. The resulting time series were subjected to high-pass filtering before extracting principal components for noise correction. These preprocessing steps were selected to minimize artefacts while accurately reflecting brain activity, as further described in the fMRIPrep documentation.

First, we analysed brain activity individually and created contrast images between conditions for each participant. In the first-level analysis, the six-dimensional motion parameters related to head movement were set as covariates. These parameters were corrected for three axes of translation and three axes of rotation to mitigate potential motion-related artefacts in the fMRI data.

At the group level, AFNI's 3dLME was utilized to create whole-brain linear mixed-effects models. These models included the four factors of BRIEF-A as between-subjects factors and sound (cry, noise) and condition (own, control) as within-subject factors. In the processing of infant crying, there is potential for confounding by demographic variables such as maternal age (Giardino et al. 2008), parity (Drummond et al. 1993, Kurth et al. 2014), the interval between delivery and fMRI scans (Parsons et al. 2017a), socioeconomic status (Kim et al. 2016a), and cannabis use (Powers et al. 2023). We included days postpartum as well as participants' age and parity as covariates, based on their significant associations with EF indexes in the current data (Table S1, see online supplementary material for a colour version of this table).

For multiple comparison corrections, AFNI's 3dClustSim programme with the spatial autocorrelation function (ACF) option was used. Cluster-size thresholds were derived from the residual spatial ACF estimated with 3dFWHMx and 3dClustSim, and we applied a voxelwise threshold of $P < .001$ (F-statistic) together with a minimum cluster extent of $k \geq 16$ voxels, corresponding to an approximate cluster-level familywise error rate of $P < .05$ under the ACF model. Activation data were extracted from each cluster identified in the whole-brain analysis. The extracted data were used to decompose interaction findings, investigating how brain activity in various conditions related to executive functioning challenges.

To test for common neural substrates across EF subdomains, we conducted a conjunction cluster analysis targeting regions that showed EF-by-sound interactions for all four BRIEF-A indices. For each index, we obtained the 3dLME F-statistic map for the EF-index × sound (cry vs. noise) interaction and thresholded it using AFNI's 3dClusterize with a voxelwise threshold of $P < .001$ (one-sided,

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NN = 2) and a minimum cluster size of $k \geq 16$ voxels, yielding cluster maps for behavioural regulation, emotional regulation, internal metacognition, and external metacognition. Each thresholded map was then binarized using 3dcalc (value = 1 inside suprathreshold clusters, 0 otherwise). The four binary maps were multiplied voxelwise with 3dcalc to identify voxels that survived thresholding in the models, producing a conjunction mask.

Results

Executive functions and demographic variables

Table S1 (see online supplementary material for a colour version of this table) presents the correlation coefficients between continuous demographic variables and each score of the BRIEF-A, as well as the *t*-values for dichotomous demographic variables. Maternal age was positively correlated with difficulties in internal metacognition and external metacognition scores, suggesting that older participants have weaker daily metacognitive functions. For dichotomous demographic variables, parity was significantly associated with behavioural regulation. This indicates that multiparous birthing parents experience greater difficulties in behavioural control.

Executive function and emotional availability

Zero-order Pearson correlations between BRIEF-A indices and EA scales are shown in Table 3. At the uncorrected level, higher behavioural regulation difficulties were associated with lower Sensitivity and lower Nonhostility, indicating that caregivers reporting more behavioural-regulation difficulties tended to be rated as less sensitive and more hostile during free interaction with their infants. Benjamini–Hochberg FDR correction was then applied within each EA outcome. Under this procedure, only the association between behavioural regulation and Nonhostility remained significant ($q = .044$); all other correlations did not survive correction.

Executive function and cry perception

Zero-order Pearson correlations between BRIEF-A indices and cry-perception ratings are shown in Table 4. At the uncorrected level, greater difficulties in internal metacognition, external metacognition, and behavioural regulation were each associated with higher perceived urgency of infant crying. Benjamini–Hochberg FDR correction was then applied within each perception outcome (arousal, urgent, aversive, health, and approach; four tests per scale, $q < .05$). Under this procedure, the three associations with urgent ratings remained significant; no other correlations survived correction. Overall, caregivers reporting greater EF difficulties tended to perceive infant cries as more urgent.

Executive function and brain activation to infant crying

A whole-brain analysis was conducted for each of the four sub-levels of the BRIEF-A (Table 5).

Table 5. Activation regions showing significant interaction between experienced executive function difficulties and infant cry (cry vs. white noise).

		MNI coordinate							
BRIEF-A	**Cluster**	**x**	**y**	**z**	**Voxels**	**Laterality**	**Region**	**Broadman area**	**F value**
Behavioural regulation difficulty									
	1	37	13	−19	54	R	Inferior frontal gyrus	BA 47	29.08
	2	−60	−45	5	25	L	Superior temporal gyrus	BA 22	19.62
Emotional regulation difficulty									
	1	−51	−27	28	124	L	Inferior parietal lobule	BA 40	20.88
	2	52	6	−28	52	R	Middle temporal gyrus	BA 21	20.87
	3	46	−11	−36	31	R	Inferior temporal gyrus	BA 20	16.56
	4	−48	−2	−12	31	L	Superior temporal gyrus	BA 38	22.62
	5	39	−26	8	31	R	Superior temporal gyrus	BA 13	32.01
	6	−57	6	15	27	L	Precentral gyrus	BA 44	18.63
	7	42	−33	41	26	R	Inferior parietal lobule	BA 40	14.33
	8	42	3	24	20	R	Inferior frontal gyrus	BA 6, 9	20.77
Internal metacognition difficulty									
	1	−48	−42	5	60	L	Superior temporal gyrus	BA 22	18.76
	2	52	−38	0	48	R	Middle temporal gyrus	BA 22	27.55
	3	54	−14	−12	25	R	Middle temporal gyrus	BA 21	14.96
External metacognition difficulty									
	1	52	−38	3	193	R	Middle temporal gyrus	BA 22	30.88
	2	61	16	15	179	R	Inferior frontal gyrus	BA 44	31.25
	3	−57	−48	5	140	L	Middle temporal gyrus	BA 21	25.7
	4	46	10	56	124	R	Middle frontal gyrus	BA 6	23.28
	5	39	1	−19	120	R	Superior temporal gyrus	BA38	27.67
	6	49	−33	41	112	R	Inferior parietal lobule	BA 40	26.84
	7	39	−6	−40	55	R	Middle temporal gyrus	BA 20, 21	16.99
	8	46	22	0	44	R	Inferior frontal gyrus	BA 47	21.94
	9	61	−60	3	35	R	Middle temporal gyrus	BA 21	19.94
	10	−33	−60	−57	31	L	Cerebellar tonsil		26.1
	11	25	−66	41	25	R	Precuneus	BA 7	13.65
	12	46	−66	−16	22	R	Fusiform gyrus	BA 37	17.76
	13	−66	−6	5	16	L	Superior temporal gyrus	BA 22	16.95
	14	64	−38	27	16	R	Inferior parietal lobule	BA 40	15.52

Maternal age, parity, and postpartum days until MRI were included as covariates in all models. All clusters were identified using AFNI's 3dClusterize with a voxelwise *F*-statistic threshold of $P < .001$, NN2 connectivity, and a minimum cluster size of $k \geq 16$ voxels; only clusters that meet this extent criterion are reported.

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Behavioural regulation

Regarding difficulties in behavioural regulation, an interaction between difficulties in behavioural regulation scores and sound type revealed two significant clusters. The first cluster was located in the rIFG, and the second in the left STG (L STG) as detailed in Table 5 and illustrated in Fig. 1. In all clusters, difficulties in behavioural regulation scores were positively correlated with the difference in brain activation between the infant cry condition and the white noise condition (*rs* > .34, *Ps* < .002). Specifically, higher difficulties in behavioural regulation scores were significantly associated with greater activation in response to infant cry sounds (*rs* > .30, *Ps* < .005), but not with activation in response to matching white noise sounds (*Ps* > .153).

Emotional regulation

For the difficulties in emotional regulation, the interaction between difficulties in emotional regulation scores and sound type identified eight clusters, primarily in the temporal lobes, including the inferior temporal gyrus (ITG), STG, and middle temporal gyrus (MTG), as shown in Table 5. In all clusters, difficulties in emotional regulation scores were positively correlated with the difference in brain activation between the infant cry condition and the white noise condition (*rs* > .34, *Ps* < .002). Specifically, higher difficulties in emotional regulation scores were significantly associated with increased activation in response to infant cry sounds (*rs* > .22, *Ps* < .036). Regarding the matching white noise sounds, Clusters 3 and 5 were significantly associated with ERI scores (Cluster 3: $r = -.33$, $P = .002$; Cluster 5: $r = .22$, $P = .022$), but no significant associations were found in the other clusters (*Ps* > .301).

External metacognition

Regarding the difficulties in external metacognition, 14 clusters centred around the temporal lobes were identified (Table 3 and Fig. 1). In all clusters, difficulties in external metacognition were positively correlated with the difference in brain activation between the infant cry condition and the white noise condition (*rs* > .30, *Ps* < .006). Specifically, scores were predominantly associated with brain activity in response to cry sounds (*rs* > .28, *Ps* < .009), and no significant association was found with white noise conditions (*Ps* > .108).

Internal metacognition

Finally, for difficulties in internal metacognition, significant associations were found in three clusters: the L STG, right MTG, and right STG. In all clusters, difficulties in behavioural regulation scores were positively correlated with the difference in brain activation between the infant cry condition and the white noise condition (*rs* > .33, *Ps* < .003). Specifically, brain activation was significantly related to the scores only in the cry sound condition (Cry condition: *rs* > .31, *Ps* < .004; White noise condition: *Ps* > .146).

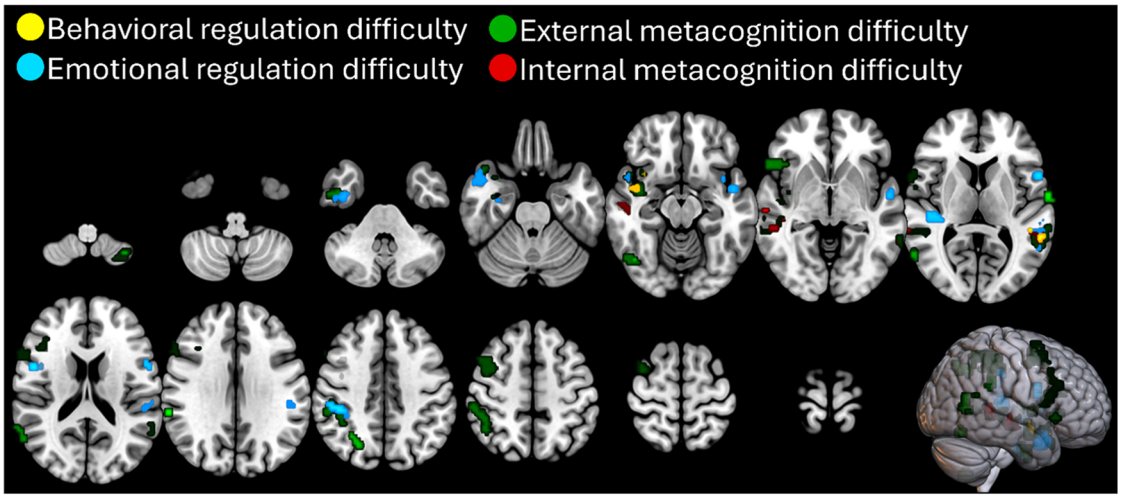


Figure 1. Brain activation patterns in response to infant cry: interaction effects of experienced executive function difficulties (cry vs. white noise).

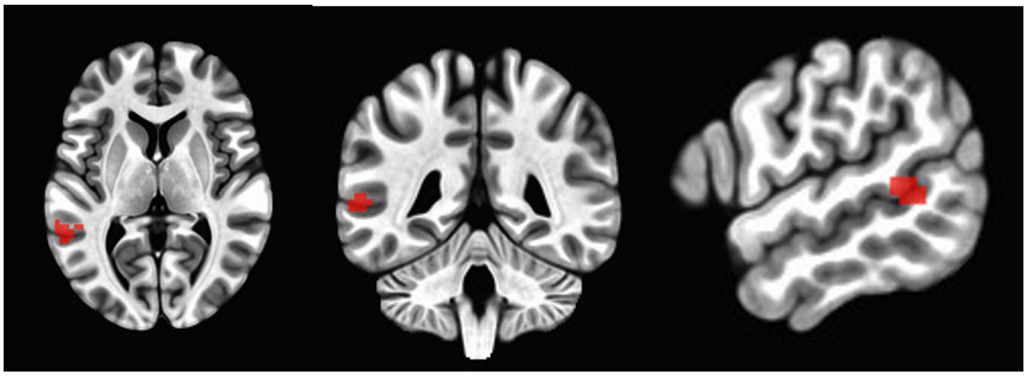


Figure 2. Conjunction cluster across EF subdomains. Voxels showing a significant EF-index × sound (cry vs. noise) interaction for all four BRIEF-A indices (behavioural regulation, emotional regulation, internal metacognition, and external metacognition). The highlighted cluster corresponds to the left middle temporal gyrus (LMTG).

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Conjunction analysis across executive function subdomains

To test for common neural substrates across EF subdomains, we conducted a conjunction cluster analysis of EF-index × sound (cry vs. noise) interaction maps for all four BRIEF-A indices. This analysis identified a single overlapping cluster in the left MTG ($k = 30$ voxels) within the lateral temporal cortex (Fig. 2).

We also explored pairwise conjunctions across EF subdomains. Among these combinations, the significant overlap was observed for emotional regulation difficulty and external metacognition difficulty, yielding a distributed cluster primarily in the left MTG (65 voxels), with additional foci in the right temporal pole (52 voxels), L STG (26 voxels), right fusiform gyrus (25 voxels), and right supramarginal gyrus (18 voxels).

Discussion

This study provides novel insights into the relationship between experienced EF difficulties and the neural processing of infant crying among biological birthing parents. To our knowledge, it is the first to link individual differences in EF with brain responses to infant cries. At the brain level, greater difficulties across all four EF subdomains were associated with stronger cry-versus-noise activation predominantly in lateral temporal regions, with additional effects in the rIFG for behavioural regulation. A four-way conjunction analysis across EF subdomains further identified a single overlapping cluster in the left MTG, suggesting a common temporal substrate where higher experienced EF difficulties were consistently associated with enhanced cry-related activation; pairwise conjunctions indicated that emotional regulation and external metacognition difficulties additionally overlapped in a broader lateral temporal and temporo-parietal cluster. At the behavioural and perceptual level, greater behavioural-regulation difficulties were modestly associated with lower Nonhostility during parent–infant interaction, and higher internal, external, and behavioural EF difficulties were related to perceiving infant cries as more urgent.

We anticipated that multiple EF subdomains would converge on a cognitive control/salience network (e.g. dlPFC, dACC, VLPFC, and anterior insula). Instead, the only region showing consistent overlap across all four EF subdomains was a cluster in the left MTG. Together with the broader pattern of associations in STG/STS, this suggests that, in this sample, shared EF-related variance is expressed primarily in temporal rather than uniformly frontal recruitment during cry processing. In light of prior work implicating MTG and adjacent temporal regions in higher-order auditory and socio-emotional processing of vocal signals (Witteman et al. 2019), the present findings are consistent with greater engagement of temporal auditory–social systems when caregivers with higher experienced EF difficulties process infant crying. However, our data cannot distinguish whether this pattern reflects compensatory processing, heightened perceptual sensitivity, or other mechanisms.

Beyond the conjunction analysis, inspection of the cluster-level results (Table 5) indicates that lateral temporal regions (STG/MTG/ITG) and IFG recur across multiple EF subdomains. The superior temporal region comprises functionally specialized subfields. Core/belt auditory cortex on the supratemporal plane (including Heschl's gyrus and planum temporale) is thought to support spectro-temporal analysis and segregation of complex acoustic patterns; mid-STG/STS contains voice-selective 'Temporal Voice Areas' that respond more to human vocalizations than to acoustically matched non-vocal sounds, and posterior STS has been implicated in social-perceptual computations (e.g. biological motion, interactions) (Belin et al. 2000, Moerel et al. 2014, Yang et al. 2015, Isik et al. 2017, Aglieri et al. 2018). The IFG participates in domain-general control and emotion regulation as part of a fronto–cingulo–insular network that modulates limbic responses to aversive signals (Aron et al. 2004, Ochsner and Gross 2005, Buhle et al. 2014, Etkin et al. 2015). In the context of infant crying—a high-salience socio-emotional cue—prior work has therefore often discussed IFG engagement in relation to top-down control demands, while recognizing that IFG contributes to multiple psychological functions rather than a single psychological process.

The results partly aligned with our domain-specific predictions. For behavioural regulation, findings were broadly consistent with our hypothesis: greater behavioural regulation difficulties were associated with stronger cry-versus-noise activation in the rIFG, with an additional cluster in the left STG. In contrast, for internal metacognition, our prediction of stronger frontoparietal recruitment (e.g. IPS within the frontoparietal network) was not supported; instead, greater internal-metacognition difficulties were related to enhanced cry-related responses in the lateral temporal cortex (bilateral STG/MTG). For external metacognition, results were partly consistent with expectations: in line with performance-monitoring accounts, external-metacognition difficulties were associated with activation in IPL and cerebellar regions, but the most robust effects again lay in the lateral temporal areas (STG/MTG), together with additional rIFG involvement. For emotional regulation, our hypothesis of altered vmPFC–amygdala engagement was not supported; greater emotional regulation difficulties were instead linked to stronger cry-related activation in lateral temporal regions, IPL, and IFG. Across EF subdomains, these patterns suggest that experienced EF difficulties are not uniformly related to reduced recruitment of control or perceptual systems; in this sample, higher experienced EF difficulties tended to be associated with stronger cry-related responses in the auditory–temporal cortex, with subdomain-specific extensions into IFG and parietal/cerebellar regions. We do not infer a single underlying psychological mechanism from these regional effects; they may reflect greater perceptual engagement with infant distress cues, altered salience attribution, or other processes that future work should test directly.

The associations between experienced EF difficulties and cry-related responses may also reflect, in part, broader trait negative affectivity (e.g. neuroticism) or a general tendency to appraise aversive cues as more salient, rather than EF-specific mechanisms per se. Our dataset did not include dedicated personality measures or comprehensive internalizing symptom scales, so we cannot distinguish EF-specific mechanisms from shared variance with negative affect or response style. We therefore refrain from EF-specific causal claims and interpret the present results as associational, consistent with multiple plausible mechanisms. More generally, prior work indicates substantial individual variability in neural and behavioural responses to infant crying: maternal depression and internalizing symptoms have been linked to altered cry-evoked responses in salience, motivational, and regulation networks (Laurent and Ablow 2012, Kim et al. 2020); sex and parental status modulate cry processing (Seifritz et al. 2003); and motivational/personality traits and coping styles are related to cry-evoked activations (Montoya et al. 2012, Kim et al. 2022). Meta-analytic evidence nonetheless points to robust circuits recruited by cry perception across studies, including auditory cortex, a thalamocingulate pathway, dorsal anterior insula, pre-supplementary motor area (SMA)/dmPFC, and IFG, with additional motor regions consistent with preparing caregiving actions (Witteman et al. 2019). Within this heterogeneous landscape, the present findings highlight experienced EF difficulties as one

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potentially informative dimension of individual variability, particularly within higher-order temporal components of this network.

Behavioural and perceptual findings provided partial, albeit modest, convergence with the neural results. At the level of observed caregiving behaviour, greater behavioural-regulation difficulties were associated with lower Nonhostility ratings during free parent–infant interaction. Although effect sizes were small, this pattern is compatible with the idea that difficulties in inhibiting maladaptive reactions are linked to a greater tendency towards hostile or irritable responses in challenging caregiving contexts, but causality cannot be inferred. For cry perception, experienced difficulties in internal metacognition, external metacognition, and behavioural regulation were associated with perceiving infant cries as more urgent. This pattern is consistent with the possibility that experienced EF difficulties co-occur with heightened perceptions of infant distress, which could in turn exacerbate stress and influence caregiving strategies. At the same time, associations with other perceptual dimensions (arousal, aversiveness, health, and approach) were not robust, and behavioural and perception effects were weaker than the neural effects, underscoring the need for cautious interpretation and replication.

Infant crying is a universal distress signal, yet how caregivers interpret and respond to cries reflects both cross-cultural commonalities and context-specific practices. Large cross-national work has identified common maternal responses and shared neural patterns to infant cries (Bornstein et al. 2017, Esposito and Bornstein 2019), suggesting a common scaffold for caregiving across countries. At the same time, caregiving norms and strategies vary markedly across cultures, and even within Western samples, evidence is mixed regarding the consequences of immediate versus delayed responding, with classic work on responsiveness and attachment coexisting with more recent findings that occasional 'cry-it-out' practices in early months were not associated with adverse attachment or behavioural outcomes (Bell and Ainsworth 1972, Gewirtz and Boyd 1977, Hubbard and van Ijzendoorn 1987, Bilgin and Wolke 2020). Developmental timing is also likely to matter: caregiving responses and strategies evolve rapidly across the first postpartum months (Kurth et al. 2014, Hiraoka et al. 2021). In the present study, scanning occurred at ~2 weeks postpartum, a window in which infant distress cues are highly salient and immediate responsiveness may be prioritized. Future work should test whether the associations observed here generalize across cultural contexts and developmental windows, and whether they differ as parents' strategies and goals shift over time.

It is important to acknowledge the limitations of this study. First, the analytic sample ($N = 88$) is modest for brain–behaviour association work; effect-size estimates should therefore be interpreted cautiously. Second, the study was not preregistered; we accordingly avoid confirmatory claims. Third, generalizability is constrained: participants were biological birthing parents recruited within the USA, and we did not measure culture-specific caregiving norms; findings may not extend to other caregiver populations. Fourth, several cry-perception variables were assessed with single items, precluding internal-consistency estimates and likely attenuating associations. Fifth, although control sounds were envelope-matched noise, residual spectral differences relative to cries remain possible and are noted as an interpretive constraint. Sixth, we did not assess fatigue or parental burnout; therefore, the present data cannot support claims that sustained cry-evoked neural engagement leads to fatigue or related downstream consequences. Future work should include validated fatigue/burnout measures to evaluate this potential pathway (Mikolajczak et al. 2018, Crouch et al. 2021). Finally, trait personality measures (e.g. neuroticism) were not examined, preventing tests of alternative accounts. Future larger, preregistered studies with broader measurement batteries are warranted. To establish developmental significance, future work should test the longitudinal relevance of cry-evoked neural responses by following families beyond the postpartum period and linking early neural markers to caregiving behaviour and child outcomes. Larger, preregistered, and culturally diverse cohorts—including performance-based EF tasks and trait personality measures—will help clarify mechanisms and robustness. If replicated, the observed associations may inform low-burden supports that scaffold attention control and emotion regulation during infant care, tailored to varying caregiving goals across cultural settings.

In conclusion, our findings indicate that higher levels of experienced executive-function difficulties during pregnancy are prospectively associated with heightened cry-evoked responses in temporal and inferior frontal regions in the early postpartum period. These difficulties were also modestly related to caregiving-relevant behaviour and perception, with greater behavioural regulation problems associated with lower Nonhostility during mother–infant interaction and with perceiving infant cries as more urgent. Although these associations should be interpreted cautiously, given the modest sample size and limited measurement scope, they suggest that experienced executive-function difficulties may serve as a cognitive marker for parents who face greater regulatory demands when responding to infant distress and who may benefit from targeted, low-burden supports during the transition to parenthood.

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Author contributions

Daiki Hiraoka (Data curation [supporting], Funding acquisition [supporting], Visualization [lead], Writing—original draft [lead], Writing—review & editing [lead]), Yun Xie (Data curation [equal], Investigation [equal], Writing—review & editing [supporting]), Shannon Powers (Data curation [lead], Investigation [lead], Writing—review & editing [supporting]), Genevieve Patterson (Data curation [equal], Investigation [equal], Writing—review & editing [supporting]), Jenna Chin (Data curation [equal], Investigation [equal], Writing—review & editing [supporting]), Nolan Brady (Data curation [equal], Investigation [equal], Writing—review & editing [supporting]), Tom Yeh (Data curation [equal], Methodology [lead], Software [lead], Writing—review & editing [supporting]), and Pilyoung Kim (Conceptualization [lead], Data curation [equal], Funding acquisition [lead], Investigation [equal], Project administration [lead], Supervision [lead], Writing—review & editing [equal])

Supplementary data

Supplementary data are available at *SCAN* online.

Conflict of interest

None declared.

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Data availability

The group-level statistical parametric maps (NIfTI images) in this study are available in an online repository and will be made publicly accessible upon publication (https://osf.io/5a863/overview?view_only=98c752c9e2e040f1971052d30bbcae1e). The underlying individual-level fMRI and questionnaire data are not publicly available because they contain information that could compromise research participant privacy and consent, and there is a non-trivial risk of re-identification even after de-identification. De-identified individual-level data may be shared with qualified researchers upon reasonable request to the corresponding author and the senior author (P.K.), under a data-sharing agreement that includes appropriate data security provisions and is approved by the corresponding author's institutional IRB.

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