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RESEARCH ARTICLE

Parental brain responses to own and unknown children's emotional facial expressions: An fMRI study

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Abstract

The parent-child relationship is crucial for children's socio-emotional development. Previous research, mostly in mothers of infants, has implicated neural networks subserving reward, saliency, and theory of mind (ToM). In this preregistered study, we sought to extend these findings to fathers and older children by examining maternal and paternal brain responses to preschool-aged children's emotional faces. Our investigation included 89 parents (41 mothers, 48 fathers) and their children (44 daughters, 45 sons). We examined the effects of children's facial identity (own, unknown) and emotion (happy, neutral, sad) on parental neural activity and tested for associations with parental and child biological sex as well as parental involvement and sensitivity. Whole-brain analyses revealed differential neural activation within saliency and ToM networks related to children's identity (own > unknown), and in the postcentral gyrus related to both children's emotion (own sad > own happy) and biological sex. Notably, mothers' and fathers' neural responses were comparable. Subsequent ROI analyses, however, revealed a distinct parent by child biological sex interaction, because fathers showed less ventromedial prefrontal cortex recruitment to daughters' happy faces with increasing parental sensitivity. Taken together, this study advances our understanding of the neural underpinnings of parents', and specifically fathers' emotional child face processing.

Keywords Functional magnetic resonance imaging · Parents · Children · Emotional faces · Parental sensitivity

Introduction

High-quality parent-child relationships are pivotal for children's socio-emotional development (Zhang et al., 2025). A critical aspect of effective parenting resides in parents' ability to discern and appropriately respond to their children's needs that are often communicated through emotional facial expressions (Stern et al., 2023). In infants particularly, these facial expressions constitute a unique category of highly salient social stimuli (i.e., "Kindchenschema" or "baby schema") that trigger nurturing behaviors associated with activity within the "parental brain" (Luo et al., 2015). This "parental brain" is thought to encompass several interconnected neural networks involved in the processing of sensory information, saliency, motivation, reward, and emotion (Paul et al., 2019; Provenzi et al., 2021; Rigo et al., 2019), which are all crucial elements of high-quality parenting. The present study, like much of this literature, builds on functional magnetic resonance imaging (fMRI), which allows for the localisation of specific neural regions implicated within the parental brain. Other lines of research have

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used electroencephalography (EEG) to characterise the temporal dynamics of stimulus processing in caregivers, as it offers higher temporal resolution (Vuoriainen et al., 2022; Woronko et al., 2025). While there is a wealth of research on maternal neural responses to emotional infant and toddler faces, several important additional variables remain to be explored.

First, little is known about parental brain activity in response to older children who have outgrown the anatomically distinct salient facial features of the Kindchenschema (i.e., large eyes, high forehead-to-face ratio, round cheeks, and small nose and chin) first described in ethological studies by Lorenz (1943). Although these features are most pronounced in the faces of infants and young toddlers, they recede gradually with age, with Luo & colleagues (2020) outlining a disappearance of effect when children are 4.6 years old. Likewise, children's identity in relation to parents is an important factor to consider when investigating parental brain activity. Of the fMRI studies that included children outside the Kindchenschema age range (9 mo to 6 yr, Bartels & Zeki, 2004; 3–6 yr, Wittfoth-Schardt et al., 2012; 4–6 yr, Michalska et al., 2014; 2–10 yr, Stoeckel et al., 2014; 5–12 yr, Leibenluft et al., 2004; 5–12 yr, Kluczniok et al., 2017), many have incorporated some form of identity contrast (e.g., own versus unfamiliar children), but no study to our knowledge has specifically examined this identity effect within a *restricted preschool age range*. Therefore, our study is ideally placed to isolate neural correlates of the parent-child relationship at this specific developmental stage, avoiding the confound of age-related variability in facial morphology and parent-child interaction patterns that characterize the above studies with broader age ranges.

Second, the literature on parental brain activity thus far has predominantly focused on *maternal* brain responses, with findings often generalized to parents of all genders despite limited paternal studies (Giannotti et al., 2022a, b). Therefore, there still is an important gap in our understanding of more universal parental brain activations to children's emotional faces as research investigating both differences and similarities between caregivers remains scarce. Initial findings from studies using infant face stimuli indicate comparable brain activation patterns across mothers and fathers, including in the superior temporal sulcus (STS), medial orbitofrontal cortex (mOFC), anterior insula, inferior frontal gyrus (IFG), thalamus, putamen, and amygdala (for reviews, see Abraham & Feldman, 2022; Swain, 2011; Swain et al., 2014). However, no previous study examining parental biological sex differences has extended its focus beyond children aged 2 years, nor has it included direct comparisons between mothers' and fathers' brain activities.

Third, distinctions in neural activations between mothers and fathers may also emerge when including other variables beyond biological sex, including individual differences in parental caregiving related to parental involvement (PI) and sensitivity (PS; Abraham et al., 2014; Mascaro et al., 2017). While PI refers to the degree to which a parent actively participates in childcare activities, PS reflects a caregiver's ability to accurately perceive and appropriately respond to their child's emotional and behavioral cues (DePasquale & Gunnar, 2020). Both caregiving behaviors are associated with preschool-aged children's development, for instance PI with academic achievement (Ma et al., 2016) and PS with children's behavioral outcomes (Cooke et al., 2022). Yet, to our knowledge, no study to date has investigated how PI and PS may relate to maternal and paternal brain activity to child faces. There is, however, preliminary evidence from two functional connectivity studies showing that PI, regardless of parental biological sex, emerges as a promising mediating factor. In the first study, researchers found that mothers' and fathers' functional connectivity to and from the amygdala and STS differed significantly when accounting for the time they spent involved in childcare activities (Abraham et al., 2014). The second study found a positive correlation between the time fathers spent involved in childcare activities and increased connectivity within regions associated with mentalizing and theory of mind (ToM; Horstman et al., 2022). A recent fMRI study furthermore showed that maternal involvement, as measured through behavioral observations, was positively associated with maternal brain responses in regions underlying emotion regulation, motivation, and salience processing (Rigo et al., 2025). Moreover, other neuroimaging research suggests that maternal sensitivity may have a distinct neural profile, with highly sensitive mothers showing greater activation in the right STS in response to own versus unknown child stimuli compared with mothers with low sensitivity (Elmadih et al., 2016; Ho et al., 2020). Behavioral evidence also indicates that the responsiveness and sensitivity with which caregivers react to their child's signals, likely conveyed by emotional facial expressions, may carry additional relevance for the "parental brain" network (Giannotti et al., 2022a, b). Beyond normative variation in caregiving behavior, parental brain activity has also been examined in the context of psychopathology, documenting altered neural and hormonal responses to infant and child stimuli among parents affected, for example, by postpartum depression and anxiety (Moses-Kolko et al., 2014; Pawluski et al., 2017; Sobral et al., 2025). While the present study focuses on individual differences in caregiving within a nonclinical sample, this literature represents an important complementary line of research.

Fourth, similarly to parental biological sex, child biological sex represents an important variable that warrants further investigation, either independently or in interaction with parental biological sex. Intergenerational neuroimaging research highlights that parent-child biological sex combinations remain underutilised within research, despite behavioral

evidence suggesting that certain caregiver behaviors may depend on such combinations (Matsudaira & Yamaguchi, 2025; Rajhans et al., 2019). Fathers, for example, were shown to visually attend more to daughters' sad and anxious facial expressions (Chaplin et al., 2005), use more body and emotional language with daughters (Mascaro et al., 2017), engage in more rough-and-tumble play (RTP) with sons (Mascaro et al., 2017; McIntyre & Edwards, 2009), and spend more time with sons (Raley & Bianchi, 2006). Conversely, mothers appear to show increased implicit favorable attitudes towards daughters' sadness (Thomassin & Seddon, 2019), elaborate explicitly on emotions with daughters more (van der Pol et al., 2015), and within an observational study, tolerate anger within sons to a greater degree (Martin & Ross, 2005). Apart from such behavioral patterns, there are only preliminary findings pertaining to parental brain activity as a function of child biological sex. One study exclusively investigating fathers found greater neural responses to their daughters' happy compared with crying facial expressions in the primary visual cortices, dorsolateral prefrontal cortex (dlPFC), and ventromedial prefrontal cortex (vmPFC; Mascaro et al., 2017). In the examined sample, fathers also displayed significantly more RTP with sons than with daughters. Interestingly, greater engagement in RTP was associated with reduced vmPFC activity during the processing of happy facial expressions, but only for sons, not for daughters. These findings suggest that gendered patterns of parental behavior may be linked to corresponding differences in neural activity to children's faces.

As previously mentioned, complementary lines of research used EEG to characterize the temporal dynamics of the parental brain. We briefly highlight here the most relevant findings to the current fMRI study. First, a meta-analysis found larger late positive potential (LPP) responses to own versus unknown child faces (i.e., identity effect) and a positive association between parental LPP amplitudes and caregiving behaviors, such as observed caregiver sensitivity (Vuoriainen et al., 2022). Moreover, adults showed increased N170 and LPP amplitudes in response to crying rather than happy facial expressions of infants (Kuzava et al., 2020). Evidence for parental sex differences in ERP amplitudes is inconsistent (Hahn et al., 2016; Proverbio et al., 2006) and a meta-analysis has been unable to test if parent sex is a moderator due to the dearth of research with fathers (Kuzava et al., 2020). Notably, one recent ERP study with parents of preschoolers found an earlier P1 response to gender-stereotype-violating behaviors of boys than for girls, showing that child sex can have an effect on parental neural processing (Portengen et al., 2024). The EEG findings thus corroborate the present study's focus on child identity, emotion, and caregiving effects, but also outline a continued need for research on parental and child sex effects.

In line with the considerations outlined above, our aim was to achieve a more comprehensive understanding of parental brain responses to children's emotional faces by focusing on preschool-aged children (rather than infants), considering both parental and children's biological sex, as well as examining individual differences in parental caregiving. To address these goals, we utilized a well-validated fMRI paradigm initially described by Strathearn et al., (2008), which used happy, neutral, and sad children's emotional facial stimuli stemming from their own and unknown children to discern between the effects of identity and emotion on parental neural activity. We recruited parents of preschool-aged children beyond the Kindchenschema range (mean 5.5 years) and collected data from mothers ($N = 41$) and fathers ($N = 48$), alongside comparable sample sizes for daughters ($N = 44$) and sons ($N = 45$). We also incorporated measures of PI and PS to systematically examine the associations between self-reported caregiving and parental neural activity. Our hypotheses and analyses were preregistered (AsPredicted #65147).

We expected that parental brain activity would be modulated by child identity and emotional expression, with heightened neural activation in reward, saliency, and ToM networks, particularly for the contrasts "own versus unknown" and "own happy versus unknown happy" (Q1). Furthermore, we hypothesized habituation of parental brain responses to child emotional faces (Q2); please see the supplementary materials for any content pertaining to this question as it did not yield any significant results. Moreover, we hypothesized that individual differences in parental caregiving, specifically higher PI and/or PS, would be associated with stronger neural responses to "own versus unknown" children (Q3). Finally, with respect to biological sex, we predicted differences between mothers and fathers primarily in regions subserving ToM, while we did not formulate any specific directional hypotheses for child biological sex (Q4, Q5). Beyond these preregistered aims, we exploratorily examined additional caregiving-brain associations as a function of both parental and child biological sex in 12 *a priori*-specified regions-of-interest (ROI).

Materials and methods

Sample

Data were collected as part of two separate studies examining parent-child interactions, relationship quality, attachment, and caregiving. The studies took place at the Max Planck Institute of Human Cognitive and Brain Sciences in Leipzig, Germany, and were approved by the local ethics committee. Parents took part in a magnetic resonance imaging session, including a structural scan and two functional scans, of which one functional scan is reported here. While we aimed to collect a final sample of 50 fMRI scans

per parent group, we had to prematurely halt data collection due to the COVID-19 pandemic. Our final sample therefore consists of 89 fMRI scans in unrelated parents, with 48 fathers (*M*age = 39.49, *SD* = 5.15) and 41 mothers (*M*age = 36.85, *SD* = 4.57) of 45 sons (*M*age = 5.64, *SD* = 0.4) and 44 daughters (*M*age = 5.62, *SD* = 0.44). See supplementary materials for more detailed information on the sample.

Experimental procedure

Parents participated in two sessions. The first session was used to create child emotional face expression stimuli (see supplementary materials Fig. S1). During the fMRI task as part of the second session, each parent was presented with a total number of 120 face images that belonged to six conditions according to a 2 (identity: own, unknown child) by 3 (emotion: neutral, happy, sad) factorial design (i.e., 20 face images per condition). The unknown child images were gender matched and randomly chosen from another participating child for each parent. Face images were presented for 2 s in a pseudo-randomized order and the inter-stimulus interval was jittered between 3–5 s (Fig. 1). This paradigm design was guided by prior work (Kluczniok et al., 2017; Stoeckel et al., 2014; Strathearn et al., 2008).

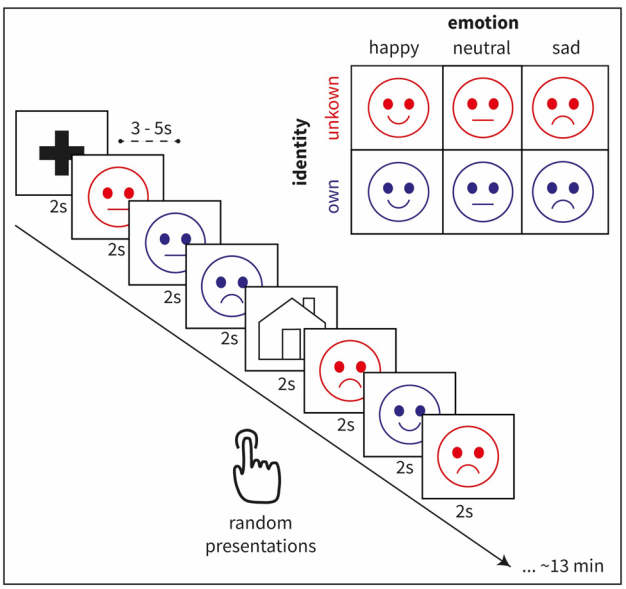


Fig. 1 Schematic overview of experiment stimuli and presentation. Notes. The figure illustrates, in a schematic fashion, an excerpt of a possible sequence of the fMRI paradigm. The first slide was always a fixation cross, followed by face images. The onset of pseudo-randomized images, i.e., the same condition was never presented twice in a row, was randomly jittered between 3-5 s and interspersed by a picture of a house. Parents passively viewed face images and had to acknowledge house images by a button press as an attention check. Children's biological sex across own and unknown stimuli was always matched

Directly after the fMRI scan, parents provided subjective valence ratings of all face images on a 5-point Likert scale, with 1 (very negative) and 5 (very positive; see supplementary Table S2). Furthermore, apart from one father who completed it several days after the fMRI session, all other parents completed an online questionnaire battery before the imaging session (*M* = 43.75 days, *SD* = 61.42, range: 262 days before to 9 days after). The online battery included demographics and personality questionnaires probing PI and PS.

Questionnaire measures

Parental involvement and sensitivity

We utilized the 14-item Parental Responsibility Scale (PRS; McBride & Mills, 1993; German translation by the authors), which rates who plans and manages common caregiving tasks (5-point Likert scale, higher = greater responsibility for that parent) to assess PI. Reliability was high for mothers (α =.91) and fathers (α =.83). PS was assessed with the German-validated Situation-Reaction Questionnaire (PS-SRQ; Hänggi et al., 2010), which includes two situation vignettes in a behavior-oriented response format, capturing parents' ability to perceive and respond to their child's cues on a 5-point Likert scale (higher = greater agreement to act in a specific way). Reliability was high for mothers (α =.84) and fathers (α =.89). Please refer to supplementary materials for more information on both questionnaires.

Behavioral and demographic data analyses

Behavioral and demographic data, such as valence ratings and participant age, gender, etc., were analyzed with appropriate *t*-tests or nonparametric alternatives in RStudio version 4.4.1 (RStudio Team, 2020).

fMRI data acquisition, preprocessing, and first-level analysis

We acquired fMRI data with a Siemens MAGNETOM Skyra Fit 3 T (Siemens, Erlangen, Germany) and a 32-channel head coil. Structural brain scans were obtained using a T1-weighted Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (TR = 2300 ms, TE = 2.98 ms, flip angle = 9°, FoV = 256 mm, voxel size: 1×1×1 mm, 176 slices). For functional images, we used a MINNESOTA multiband sequence with an acceleration factor 3 (Feinberg et al., 2010; Moeller et al., 2010) with TR = 2000 ms, TE = 22 ms, flip angle = 80°, FOV = 204*204 mm, matrix size = 82x82 mm, voxel size = 2.5-mm isotropic, interleaved, and slice gap 0.25 mm. Images were shown to parents via mirrors attached to a head coil and a screen at the back of the bore.

fMRI data were analyzed by using SPM12 (Wellcome Center for Human Neuroimaging, 2014) in MATLAB R2019b (MathWorks Inc., 2019). The first five volumes of the functional time series were discarded to allow for signal equilibration, and all other images were visually inspected for potential signal loss. Volumes were slice-time corrected with the middle slice used as reference to correct for acquisition time differences. Images were then realigned by using a least squares approach and a rigid-body registration to correct for head motion, co-registered to individual structural images using a rigid body transformation in three dimensions, and normalized to Montreal National Institute (MNI) space by using a standard T1-weighted average scan provided by SPM8 (ICBM152; dimensions: 91×109×91; voxel size: 2 mm). Finally, images were spatially smoothed with an 8-mm full width at half-maximum (FWHM) Gaussian kernel and high pass filtered at 128 s.

First-level analysis of preprocessed fMRI images was carried out with a general linear model (GLM), modeling six main conditions for our 2x3 factorial design, including identity and emotion as events and convolving them with the hemodynamic response function (HRF; Friston et al., 1994). Six realignment parameters obtained during preprocessing were included as regressors of no interest to account for head motion. An explicit mask was used to restrict analysis to within-brain voxels.

Second-level fMRI analyses

All our main second-level hypotheses and data analyses were preregistered (AsPredicted #65147).

In line with our 2x3 factorial design and Q1, we first calculated all whole-brain second-level group contrasts of identity and emotion, as well as their interaction as individual one-sample *t*-tests across all participants. For Q3, we then added PI and PS as covariates and conducted whole-brain multiple regression analyses for the preregistered contrasts of interest "own > unknown" and "own happy > unknown happy," as well as the contrast "own happy > own sad" that emerged as another meaningful contrast from the Q1 analyses (one regression for each covariate). Finally, for Q4 and Q5, we conducted additional whole-brain independent two-sample *t*-tests for the same three contrasts (one *t*-test for parental and child biological sex, respectively). For Q2 pertaining to habituation analysis, please refer to the supplementary materials.

For all whole-brain analyses, we used a combined statistical threshold of $p < 0.001$ uncorrected at the voxel level (cluster-determining threshold; CDT) with $k > 20$, and subsequent $p < 0.05$ FWE-correction at the cluster level. All peak coordinates were anatomically labelled using the Automated Anatomical Labelling (AAL3v1) atlas within MRIcroGL (v1.2.20220720; Rorden, 2025). Please note that we did not include child age as a covariate. Although children of fathers were slightly older than children of mothers, the difference in child age (0.24 years; i.e., younger than 3 months) was smaller than its within-group variability ($SD = 0.45$ and $SD = 0.33$) and unlikely to be developmentally meaningful within our prespecified, narrow 5–6-year age range. However, as fathers were on average 2.64 years older than mothers, we ran exploratory sensitivity analyses for questions pertaining to preregistered group differences (Q3-Q5), by including parental age as a covariate in the analyses for our three main contrasts of interest. Apart from Q3, which we discuss further in the supplementary materials, these sensitivity analyses remained unchanged and therefore confirmed our primary results.

Exploratory region of interest (ROI) analyses

As indicated in our preregistration, we further examined the two preregistered and one additional contrast emerging from Q1 in 12 *a priori*-defined anatomical regions of interest (ROI). Region of interest MNI coordinates were identified based on results from an unrelated previous study by Abraham et al. (2014; see supplementary materials Table S1), which utilised infant stimuli. We selected this study, because it directly compared maternal and paternal neural activity, meaningfully informed our parental involvement analyses, and because prior work indicates broadly comparable activation across infant and older-child stimuli (Rigo et al., 2019). We conducted these analyses to increase sensitivity to effects in regions with strong *a priori* theoretical relevance and to allow extracted activation values to be related to other study variables of interest. Around MNI coordinates extracted from Abraham & colleagues (2014), 5 mm spheres were created and neural activation parameter (beta) extraction was performed via the MarsBaR toolbox (release version 0.44; Brett et al., 2002). Next, linear models allowing for all main and interaction effects were calculated. Specifically, we investigated in four exploratory models how ROI activation was related to 1) PI and PS scores, 2) parental and child biological sex, 3) parental and child biological sex with PI, and 4) parental and child biological sex with PS. We used Bonferroni correction for these exploratory analyses to control for multiple comparisons (i.e., number of ROIs per contrast).

Results

Descriptives

Our two groups (i.e., mothers and fathers) did not differ in education or income. Nonetheless, there were significant differences in adult and child age, PI, and PS. On average, mothers and their children were significantly younger than

fathers and their children; mothers were more involved with and sensitive towards their children (see Table 1 and supplementary materials). Three fathers had to be excluded from PI and PS analyses due to incomplete questionnaires, leaving a total of 86 included participants for these analyses.

Subjective valence ratings

Directly after the fMRI session, parents were asked to subjectively evaluate all emotional child face images regarding their valence. These analyses revealed a main effect of emotion $F(2, 522) = 1055.44$, $p < 0.001$ but no main effect of, or interaction with, identity, as valence ratings followed a consistent pattern of "happy > neutral > sad" for both own and unknown children. Please refer to supplementary materials Table S2 for means of all valence ratings per identity, emotion, parental as well as child biological sex.

Whole-brain fMRI results

Q1: Main and interaction effects of identity and emotion

Whole-brain main and interaction effects of child identity (own, unknown) and emotion (happy, neutral, sad) revealed several large clusters of neural activity across both parent groups. A summary of the most pertinent findings is provided below and in Fig. 2.

The main effect of the preregistered identity contrast "own > unknown" revealed increased activation in lower- and higher-level visual areas, anterior cingulate cortex (ACC), pre-supplementary motor area (pre-SMA), insula, cerebellum, midbrain, dlPFC, and anterior temporoparietal junction (TPJ). For the other preregistered contrast "own happy > unknown happy," we observed increased BOLD signal change in pre-SMA, motor cortex, cerebellum, anterior and medial cingulate cortex, putamen, and a large visual-occipital-temporal network. The findings of the second contrast were very similar to the contrast "own happy > own sad" showing increased activity in visual-occipital regions and SMA, and neural activation for the "own > unknown"

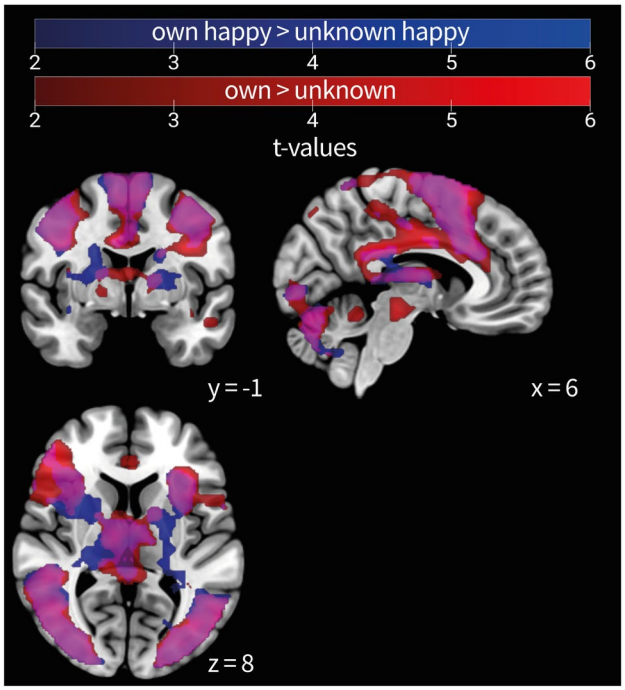


Fig. 2 Overlap of whole-brain *t*-test activation for the contrasts "own > unknown" and "own happy > unknown happy". Notes. Neural activation maps (*t*-values) for the two main contrasts of interest. Red colors indicate regions that were significantly ($p<0.001$) activated by the identity contrast "own > unknown", while blue colors indicate regions that were significantly activated by the identity by emotion contrast "own happy > unknown happy". Purple colors show the overlap of both contrasts

Table 1 Descriptive statistics for questionnaires and respective significance tests

	Fathers $n = 48$, *Mean* (*SD*)	Mothers $n = 41$, *Mean* (*SD*)	Between-group test statistics
Adult age	39.49 (5.15)	36.85 (4.57)	$t(86.86) = -2.55$, $p = 0.012$*
Child age	5.74 (0.45)	5.50 (0.33)	$W = 646.5$, $p = 0.0084$**
Education	3.49 (0.76)	3.47 (0.76)	$W = 845$, $p = 0.9146$
Family income	7.11 (1.25)	7.31 (1.25)	$W = 882.5$, $p = 0.4794$
Parental involvement	3.18 (0.39)	3.80 (0.55)	$t(71.26) = 5.93$, $p < 0.001$***
Parental sensitivity	2.98 (0.3)	3.5 (0.26)	$t(85) = -8.73$, $p < 0.001$***

Significance threshold at *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

contrast showed considerable overlap with the contrast "own happy > unknown happy" (Fig. 2). For a comprehensive list of all these activations as well as of all the other contrasts of our 2x3 factorial design, including a discussion specifically for the "unknown > own" and "own sad > unknown sad" contrasts, please refer to supplementary materials Tables S3 and S4.

Q2: Habituation of parental brain responses to child emotional faces

Please refer to the supplementary material for these analyses and their (non-significant) results.

Q3: Links with parental involvement and sensitivity

Via whole-brain multiple regression analyses with PI and PS as covariates, we tested whether PI or PS relate to neural activity within the two preregistered and one additional contrast as part of Q1. However, these analyses did not yield any significant activations after FWE-correction. There nonetheless was one cluster of interest for the contrast "own happy > unknown happy" in relation to PI within the IFG that was approaching significance (FWE-corrected $p = 0.053$). Yet, within our exploratory sensitivity analysis that included parental age as a covariate, this cluster did reach significance (FWE-corrected $p = 0.023$). We discuss this result further in the supplementary materials (Fig. S2).

Q4 and Q5: Parental and child biological sex

Whole-brain two-sample *t*-tests probing for parental biological sex differences within the three Q1 contrasts did not yield any significant results.

Subsequent whole-brain two-sample *t*-tests probing for child biological sex differences revealed one significant cluster in the postcentral gyrus for the contrast "own happy > own sad" when comparing "daughters > sons." To further explore and decompose this interaction effect, we extracted cluster parameters (betas) and computed post-hoc comparisons in R. In doing so, we found that sad emotional facial expressions of sons ($M = -0.90$, $SD = 0.63$) resulted in significantly greater activation of the postcentral gyrus than sad emotional facial expressions of daughters ($M = -1.47$, $SD = 0.78$) $t(88) = -3.81$, $p < 0.001$ (Fig. 3).

Exploratory analyses linking parental and child biological sex and parental sensitivity

Finally, we conducted additional exploratory analyses in 12 predefined anatomical ROIs pertaining to parental and child

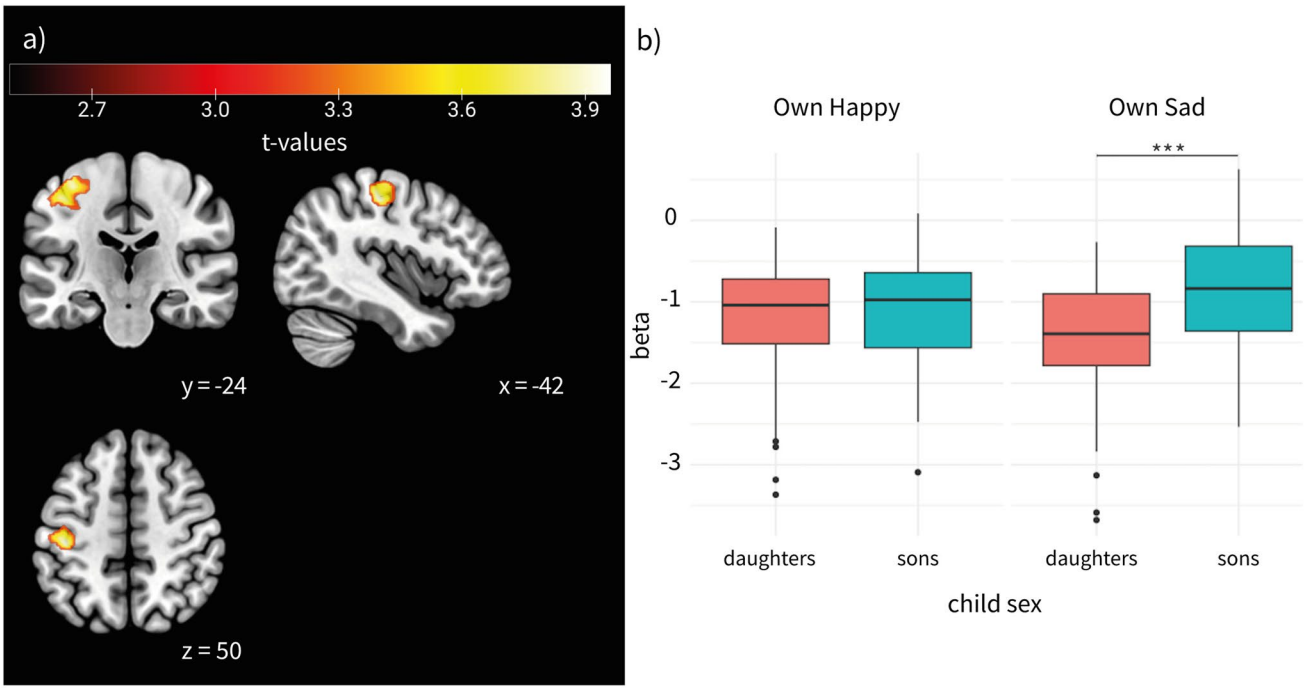


Fig. 3 Neural activation in the postcentral gyrus comparing "daughters vs sons" on "own happy vs own sad" pictures. Notes. **a** Anatomical localisation of the significant child biological sex effect in the postcentral gyrus.; **b** Boxplot depicting extracted and averaged beta values by child biological sex (daughters vs sons; x-axis) and emotion (happy vs sad; y-axis). ***p<0.001. Error bars indicate +/- 1.5 interquartile range (IQR)

biological sex as well as PI and PS, while controlling for multiple comparisons via Bonferroni correction, using the three contrasts as part of Q1.

These analyses yielded significant effects for two analyses in the left vmPFC where activity for the contrasts "own > unknown" and "own happy > unknown happy" was linked to parental and child biological sex as well as PS. For the higher order contrast "own happy > unknown happy," there was an interaction between parent biological sex, child biological sex, and PS $F(3, 86) = 22.58$, $p < 0.001$.

To investigate and decompose the finding associated with the contrast "own happy > unknown happy" further, we separated the groups based on parent-child pairs, which revealed a strong negative correlation between brain activity and PS for father-daughter pairs ($r = -0.7$, $p < 0.001$), but not for father-son pairs ($r = 0.13$, $p = 0.51$), mother-daughter pairs ($r = 0.08$, $p = 0.68$), nor mother-son pairs ($r = -0.26$, $p = 0.28$; Fig. 4). Moreover, we extracted beta parameters for the "own happy" and "unknown happy" conditions for each group separately, which showed that the negative

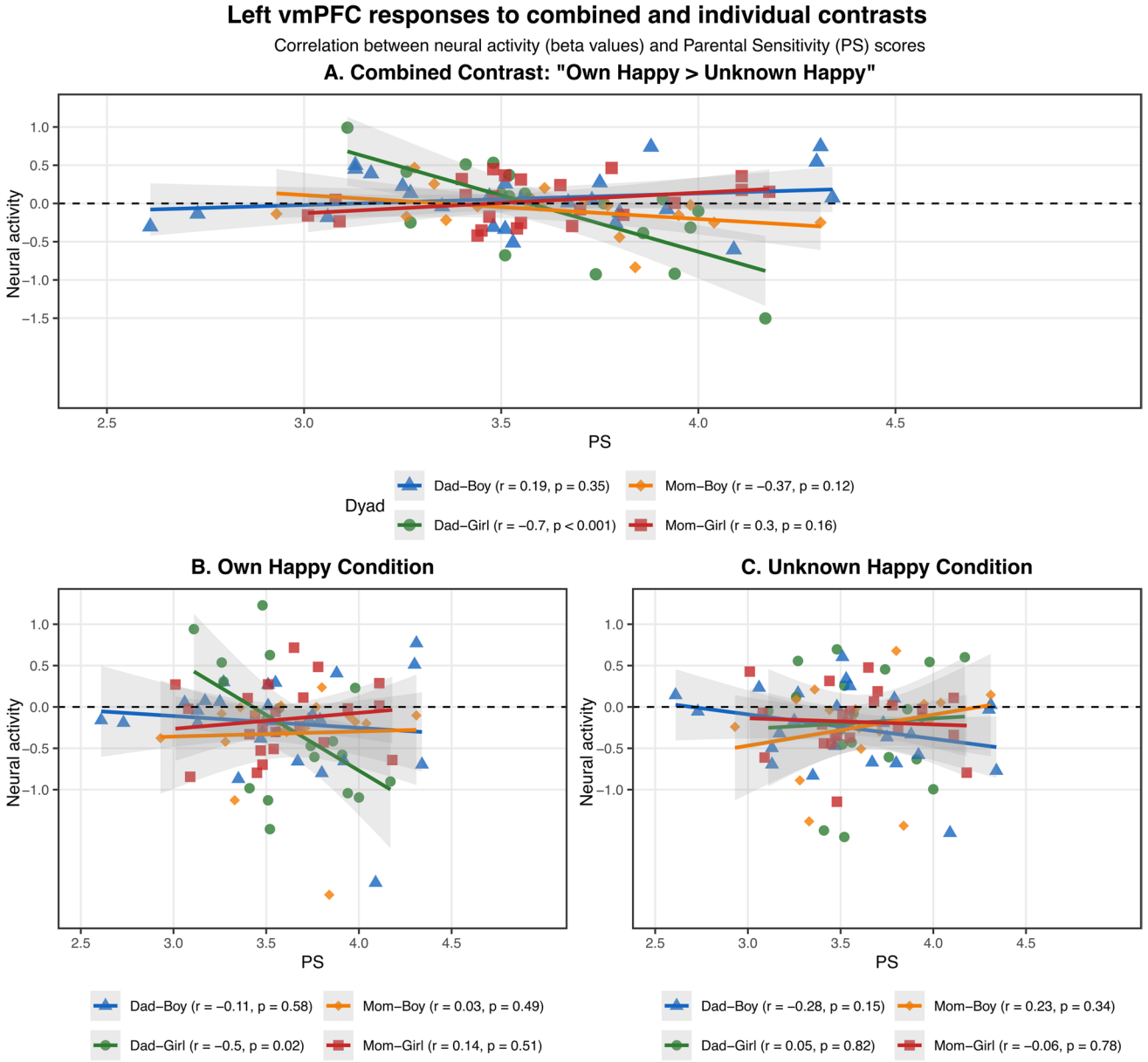


Fig. 4 Decomposition of the interaction with PS for the contrast "own happy vs unknown happy" within the left vmPFC. Notes. Top panel: extracted neural activity (betas; y-axis) from the left vmPFC for the overall contrast "own happy vs unknown happy" correlated with PS for each parent-child combination (colored lines). Bottom panels: extracted neural activity for the "own happy" (right graph) and "unknown happy" (left graph) conditions separately. There only was a significant negative correlation between vmPFC activity and PS for fathers seeing images of their daughters in the "own happy" condition (shown in green)

correlation for father-daughter pairs was unique for "own happy" images ($r = -0.5$, $p = 0.02$). Furthermore, we utilized the four PS subscales and correlated these with vmPFC activity for the separate parent-child groups. In doing so, the subscale "empathy" emerged as the only significant subscale associated with brain activity ($r = -0.48$, $p = 0.037$). For the decomposition of the lower-order contrast "own > unknown"; please see supplementary material Fig. S3.

Discussion

In this preregistered fMRI study, we investigated the neural correlates of mothers' and fathers' brain activation in response to emotional facial expressions of either their own or an unknown preschool-aged child. We assessed differences in brain activation related to child identity (own, unknown) and emotional facial expression (happy, neutral, sad), biological sex (parental, child), and individual differences in parental caregiving, as measured by PI and PS.

Our whole-brain analyses revealed differential neural activation within saliency and ToM networks related to children's identity and in the postcentral gyrus related to children's emotion and biological sex. Although mothers and fathers' neural responses were generally comparable, subsequent ROI analyses revealed a distinct father-daughter interaction; fathers exhibited reduced vmPFC responses to daughters' happy faces as PS increased.

Q1: Main and interaction effects of identity and emotion

As part of our primary hypothesis, we anticipated heightened parental brain activation in reward, saliency, and ToM networks for the identity contrast "own > unknown." As expected, our whole-brain analyses revealed significantly increased activation for "own > unknown" child images in regions subserving ToM (i.e., TPJ; Kanske et al., 2015), reward (i.e., VTA; Camara et al., 2009), and saliency processing (e.g., insula and ACC; Uddin, 2015). These findings align with prior studies that found similar identity effects in mothers using infant (Barrett et al., 2012; Strathearn et al., 2008; 2009) and toddler (Luo et al., 2015; Mascaro et al., 2014) stimuli. Furthermore, we found significantly increased activity in primary visual areas, pre-SMA, and motor areas. Activation in the primary visual cortex activity is frequently reported in parents when processing children's faces (Paul et al., 2019; Strathearn et al., 2008). Activation of motor areas has been frequently reported, leading researchers to propose that preparatory neural processes prime parents to respond appropriately to child cues, such as offering comfort or joining in laughter (Paul et al., 2019; Provenzi et al., 2021). Notably, SMA activity during empathic mirroring of own versus unknown child facial expressions has been linked to maternal sensitivity, with reduced SMA responses observed in mothers with compromised caregiving capacities, suggesting that SMA engagement reflects not only motor preparation but also the quality of a parent's empathic response to their own child's emotional expressions (Swain & Ho, 2022).

As predicted, the identity by emotion interaction contrast of "own happy > unknown happy" yielded a similar neural activation pattern to our overall "own > unknown" identity contrast. This finding is consistent with earlier studies suggesting that the combined influence of processing positive facial emotions from one's own child evokes a stronger response than either identity or emotion condition alone (Barrett et al., 2012; Strathearn et al., 2008; 2009). Furthermore, if one's own child's happiness holds greater salience than sadness, the "own happy > own sad" contrast should reveal comparable activation patterns. This was the case in our study, as we observed increased neural activity within primary visual areas, SMA, and precuneus specifically for the contrast "own happy > own sad." Similar patterns have been found in previous studies utilizing infant (Piallini et al., 2015; Strathearn et al., 2008) and toddler (Mascaro et al., 2017) stimuli. Collectively, these findings suggest that, even beyond the Kindchenschema stage, parental brains remain highly attuned to their own children's facial emotional expressions, demonstrating the enduring strength of the parent-child bond.

Parents rated all images in a post-fMRI valence rating task to control for subjective perception of the presented stimuli. The analysis revealed that perceived valence solely differed based on emotion (happy > neutral > sad) but not on child identity (own, unknown), and there was no interaction between. Therefore, the neural effects associated with identity and the identity by emotion interaction are likely to reflect unique neural activity coupled to caregiving-related stimuli.

Q2: Habituation of parental brain responses to child emotional faces

Please refer to the supplementary material for the discussion of these (non-significant) results.

Q3: Links with parental involvement and sensitivity

We conducted three whole-brain multiple regression analyses to investigate the relationship between individual caregiving behaviors, such as PI and PS and parental brain activity. In our whole-brain analyses, we did not identify compelling evidence indicating a relationship between self-reported PI or PS and neural activity, because neither analyses meet the stringent FWE threshold. Notably, one cluster

in the left IFG in the PI regression analyses approached significance ($p = 0.053$) in our primary analyses, and reached significance in our exploratory sensitivity analyses ($p = 0.023$) when including parental age as a covariate, as discussed further in the supplementary material. An exploratory ROI analysis allowed us to discern effects of PS on neural activity, as described in following sections.

Q4 and Q5: Parental and child biological sex

In examining brain activation differences between mothers and fathers, our expectations were twofold. While we predicted comparable activation in reward- and saliency-related areas, we hypothesized activation differences in ToM regions (Abraham et al., 2014; Paul et al., 2019; Provenzi et al., 2021). During our whole-brain independent two-sample *t*-tests, no significant differences emerged between parents in any of the specified networks. Thus, our findings support previous studies proposing that parental brain activation is generally comparable between mothers and fathers (Abraham et al., 2014; Abraham & Feldman, 2022; Feldman, 2015).

Moreover, while we did not observe any widespread parental brain activation differences as a function of child biological sex, our analyses revealed one notable finding for the interaction contrast between "own happy > own sad" and "daughters > sons" in the postcentral gyrus. Activity in this region was selectively increased for sad pictures featuring sons.

Reviewing the existing literature, it is evident that the postcentral gyrus plays a crucial role in social cognition, including processing, and representing emotions, such as sadness (Cao et al., 2018; Silani et al., 2013). Our finding of heightened postcentral gyrus activation when parents viewed images of their sad son's points to an increased demand of additional emotional processing that may be linked to the child's biological sex. This specificity could reflect societal norms, as boys in Western cultures are often discouraged from openly expressing emotions, such as sadness (Brody & Hall, 2009). Moreover, behavioral research shows that parents tend to socialize emotional expression differently based on their child's sex, with distinct patterns of response emerging as early as preschool (Chaplin & Aldao, 2013; Eisenberg et al., 1998; Levant et al., 2006; Mascaro et al., 2017).

Such cultural expectations may influence parents' interpretation of their sons' emotional cues, resulting in increased mentalizing and neural activity in regions such as the postcentral gyrus when children have reached early childhood. This variation in socialization could also explain why studies focusing on infants and toddlers have not found sex differences in parental neural responses, because these gendered expectations might not yet be salient. However, more research is needed to further characterise such an effect.

Exploratory analyses linking parental and child biological sex and parental sensitivity

As described above, no significant whole-brain effects emerged for correlations between parental brain activity and PI and PS scores across all parents (Q3). However, previous research suggests that nuanced differences between parental brain activity and caregiving behaviors arise when parental biological sex is considered (Atzil et al., 2012; Luo et al., 2015; Rajhans et al., 2019). Indeed, after accounting for PI and PS, our exploratory analysis revealed sex-specific associations for PS and parental neural activity, in selected ROIs.

When separating our sample into unique parent-child biological sex pairs, a significant association between parental brain activity in the left vmPFC for the contrasts "own > unknown" and "own happy > unknown happy" and PS was present. Extracting parameter (beta) estimates for this vmPFC activity pattern showed that fathers with higher PS scores exhibited less vmPFC responses for "own" and "own happy" faces stemming from daughters. Exploring this effect even further, we correlated PS subscales with vmPFC activity to discover which of the four subscales, belonging to the PS questionnaire, might drive this effect. Interestingly, only the subscale "empathy" replicated the significant negative relationship for father-daughter pairs. Thus, fathers who self-reported more empathy to their daughters during the behavioral vignettes of the PS self-report questionnaire showed decreased vmPFC activation when seeing their own daughter's happy face in the MRI scanner.

Looking at the literature, this effect appears puzzling at first. Typically, greater vmPFC activity has been linked to a plethora of processes including affective ToM (Kanske et al., 2015), emotion regulation (Suzuki & Tanaka, 2021), and affective processing specifically for happy faces (Ebner et al., 2012). Moreover, most parental brain studies performed in mothers have found increases in vmPFC activity to their "own child" stimuli, which has been linked to increased reward processing (Luo et al., 2015; Noriuchi et al., 2019; Paul et al., 2019; Rigo et al., 2019; Stoeckel et al., 2014; Strathearn et al., 2009). Therefore, it should be anticipated that higher sensitivity in fathers would positively correlate with vmPFC activity, contrary to our findings. Yet, one study specifically examining fathers' neural responses to "own happy" child stimuli also found decreased vmPFC activity. Mascaro & colleagues (2017) showed that fathers of sons, but not daughters, exhibited reduced activity in the vmPFC in response to "own happy" stimuli, which correlated with increased levels of RTP. Fathers with sons were found to also engage in more RTP and spend more time in such activities compared to their interactions with daughters.

One possible explanation for the reduced vmPFC activity lies within the neural efficiency model. This model

hypothesises that individuals with greater intelligence require fewer neural resources to complete a given task, reflected in *lower* brain activation (Neubauer & Fink, 2009). This framework, typically applied to cognitive abilities like working memory, also appears to extend to affective processing. A recent review identified the vmPFC as one region where higher emotional intelligence is linked to reduced activation (Martin-Aguiar et al., 2026). Moreover, emotional competence training was shown to reduce prefrontal activation during emotion regulation (Hansenne et al., 2014), and greater empathic abilities predicted less activation across a network including prefrontal regions during self-other conflict (Montandon et al., 2023). Additionally, a review on cognitive intelligence noted that neural efficiency effects are most consistent in prefrontal regions and moderated by variables such as biological sex and task complexity (Neubauer & Fink, 2009).

Taken together, these findings suggest that specifically for fathers, increasing empathic abilities as indicated by our study, or in the case of Mascaro and colleagues (2017) increasing active and sex-specific caregiving, may enable them to process their children's "own happy" facial expressions more efficiently. Nevertheless, further research is needed to replicate and clarify these effects, including potential similarities and differences in neural activity between mothers and fathers.

Limitations

Certain limiting aspects of our study deserve consideration. First, while emerging research underscores the importance of disentangling parental brain activation from traditional family roles, future research should include non-parents, as well as primary and non-primary caregivers from both hetero- and homosexual couples (Carone & Lingiardi, 2022; Giannotti et al., 2022a, b). Second, we evaluated parental caregiving behaviors using self-report questionnaires. Future studies should also integrate direct measurements of caregiving behaviors, considering that self-report and actual behaviors may differ (Dang et al., 2020). Third and relatedly, fathers reported lower scores on PI and PS questionnaires than mothers, which may partly reflect that these questionnaires capture caregiving behaviors more commonly performed by mothers, rather than adequately capturing the ways in which fathers engage in caregiving. Subsequent studies would benefit from including a broader and more paternally inclusive range of caregiving measures (Cabrera et al., 2018; Dyer et al., 2018; Schoppe-Sullivan & Fagan, 2020). Fourth, a subset of the father sample had been examined prior to preregistration. Although these preliminary analyses did not inform the present hypotheses or preregistration, we acknowledge that prior exposure to the data cannot be entirely separated from subsequent hypotheses development. We note this in the interest of transparency. Lastly, fathers in our sample were older than mothers, consistent with demographic trends, yet we did not control for parental age in our primary analyses. As parental age may interact with parental and child biological sex in shaping parental neural responses, future studies should include parental age as a covariate or recruit age-matched parents to disentangle effects.

Conclusions

This study advances our understanding of parental brain activations by including parents of preschool-aged children who have surpassed the inherently salient "Kindchenschema" facial characteristics. Consistent with our hypotheses, we observed that the identity of the stimuli used, as well as the identity by emotion contrast "own happy > unknown happy," significantly activated ToM, saliency, and reward networks in both mothers and fathers. Additionally, we noted increased activation of the postcentral gyrus in response to "sad son" stimuli across parents, which we cautiously interpret as potentially reflecting societal expectations regarding gendered emotion expression. Moreover, our use of ROI analyses, combined with assessments of caregiver behaviors, such as self-reported PS, revealed distinctive associations between PS and activity within the left vmPFC specifically among fathers with daughters. Future investigations should employ similarly robust fMRI designs to further elucidate parental brain activations and their relationships with biological sex differences and variations in caregiving behaviors.

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Author contributions P.V. and K.P. conceived the study, K.P. and L.P. collected the data, K.P. and L.P. conducted data preprocessing, A.B. conducted data analyses, wrote the manuscript and oversaw the publication process, P.V., K.P., L.P., L.W., and G.v.P. reviewed the manuscript.

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Data and code availability The data underlying this study cannot be openly shared due to data protection restrictions. However, data and code are available upon reasonable request and after signing a data sharing agreement with the corresponding author P.V. The preregistration is available on AsPredicted under (#65147; https://aspredicted.org/CZF_KDK).

Declarations

Consent to participate Written informed consent was obtained from all participants. Parents provided written informed consent on behalf of their children.

Ethics approval This study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany.

Consent for publication Not applicable.

Conflicts of interest The authors declare that there is no conflict of interest.

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References

Abraham, E., & Feldman, R. (2022). The neural basis of human fatherhood: A unique biocultural perspective on plasticity of brain and behavior. *Clinical Child and Family Psychology Review, 25*(1), 93–109. https://doi.org/10.1007/s10567-022-00381-9

Abraham, E., Hendler, T., Shapira-Lichter, I., Kanat-Maymon, Y., Zagoory-Sharon, O., & Feldman, R. (2014). Father's brain is sensitive to childcare experiences. *Proceedings of the National Academy of Sciences of the United States of America, 111*(27), 9792–9797. https://doi.org/10.1073/pnas.1402569111

Atzil, S., Hendler, T., Zagoory-Sharon, O., Winetraub, Y., & Feldman, R. (2012). Synchrony and specificity in the maternal and the paternal brain: Relations to oxytocin and vasopressin. *Journal of the American Academy of Child and Adolescent Psychiatry, 51*(8), 798–811. https://doi.org/10.1016/j.jaac.2012.06.008

Barrett, J., Wonch, K. E., Gonzalez, A., Ali, N., Steiner, M., Hall, G. B., & Fleming, A. S. (2012). Maternal affect and quality of parenting experiences are related to amygdala response to infant faces. *Social Neuroscience, 7*(3), 252–268. https://doi.org/10.1080/17470919.2011.609907

Bartels, A., & Zeki, S. (2004). The neural correlates of maternal and romantic love. *NeuroImage, 21*(3), 1155–1166. https://doi.org/10.1016/j.neuroimage.2003.11.003

Brett, M., Anton, J.-L., Valabregue, R., & Poline, J.-B. (2002). Region of interest analysis using the MarsBar toolbox for SPM. *NeuroImage, 16*(2), S497.

Brody, L. R., & Hall, J. A. (2009). Gender, emotion, and socialization. In J. C. Chrisler & D. R. McCreary (Eds.), *Handbook of gender research in psychology: Volume 1: Gender research in general and experimental psychology* (pp. 429–454). Springer. https://doi.org/10.1007/978-1-4419-1465-1_21

Cabrera, N. J., Volling, B. L., & Barr, R. (2018). Fathers are parents, too! Widening the lens on parenting for children's development. *Child Development Perspectives, 12*(3), 152–157. https://doi.org/10.1111/cdep.12275

Camara, E., Rodriguez-Fornells, A., Ye, Z., & Münte, T. F. (2009). Reward networks in the brain as captured by connectivity measures. *Frontiers in Neuroscience, 3*, 350–362. https://doi.org/10.3389/neuro.01.034.2009

Cao, L., Xu, J., Yang, X., Li, X., & Liu, B. (2018). Abstract representations of emotions perceived from the face, body, and whole-person expressions in the left postcentral gyrus. *Frontiers in Human Neuroscience, 12*, Article 419. https://doi.org/10.3389/fnhum.2018.00419

Carone, N., & Lingiardi, V. (2022). Untangling caregiving role from parent gender in coparenting research: Insights from gay two-father families. *Frontiers in Psychology, 13*, Article 863050. https://doi.org/10.3389/fpsyg.2022.863050

Chaplin, T. M., & Aldao, A. (2013). Gender differences in emotion expression in children: A meta-analytic review. *Psychological Bulletin, 139*(4), 735–765. https://doi.org/10.1037/a0030737

Chaplin, T. M., Cole, P. M., & Zahn-Waxler, C. (2005). Parental socialization of emotion expression: Gender differences and relations to child adjustment. *Emotion, 5*(1), 80–88. https://doi.org/10.1037/1528-3542.5.1.80

Cooke, J. E., Deneault, A.-A., Devereux, C., Eirich, R., Fearon, R. P., & Madigan, S. (2022). Parental sensitivity and child behavioral problems: A meta-analytic review. *Child Development, 93*(5), 1231–1248. https://doi.org/10.1111/cdev.13764

Dang, J., King, K. M., & Inzlicht, M. (2020). Why are self-report and behavioral measures weakly correlated? *Trends in Cognitive Sciences, 24*(4), 267–269. https://doi.org/10.1016/j.tics.2020.01.007

DePasquale, C. E., & Gunnar, M. R. (2020). Parental sensitivity and nurturance. *Future of Children, 30*(2), 53–70. https://doi.org/10.1353/foc.2020.a807761

Dyer, W. J., Kauffman, R., Fagan, J., Pearson, J., & Cabrera, N. (2018). Measures of father engagement for nonresident fathers. *Family Relations, 67*(3), 381–398. https://doi.org/10.1111/fare.12317

Ebner, N. C., Johnson, M. K., & Fischer, H. (2012). Neural mechanisms of reading facial emotions in young and older adults. *Frontiers in Psychology, 3*, 223. https://doi.org/10.3389/fpsyg.2012.00223

Eisenberg, N., Cumberland, A., & Spinrad, T. L. (1998). Parental socialization of emotion. *Psychological Inquiry, 9*(4), 241–273. https://doi.org/10.1207/s15327965pli0904_1

Elmadih, A., Wan, M. W., Downey, D., Elliott, R., Swain, J. E., & Abel, K. M. (2016). Natural variation in maternal sensitivity is reflected in maternal brain responses to infant stimuli. *Behavioral Neuroscience, 130*(5), 500–510. https://doi.org/10.1037/bne0000161

Feinberg, D. A., Moeller, S., Smith, S. M., Auerbach, E., Ramanna, S., Glasser, M. F., Miller, K. L., Ugurbil, K., & Yacoub, E. (2010). Multiplexed echo planar imaging for sub-second whole brain fMRI and fast diffusion imaging. *PLOS ONE, 5*(12), Article e15710. https://doi.org/10.1371/journal.pone.0015710

Feldman, R. (2015). The adaptive human parental brain: Implications for children's social development. *Trends in Neurosciences, 38*(6), 387–399. https://doi.org/10.1016/j.tins.2015.04.004

Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J.-P., Frith, C. D., & Frackowiak, R. S. J. (1994). Statistical parametric maps in functional imaging: A general linear approach. *Human Brain Mapping, 2*(4), 189–210. https://doi.org/10.1002/hbm.460020402

Giannotti, M., Gemignani, M., Rigo, P., Simonelli, A., Venuti, P., & De Falco, S. (2022). Disentangling the effect of sex and caregiving role: The investigation of male same-sex parents as an opportunity to learn more about the neural parental caregiving network. *Frontiers in Psychology, 13*, Article 842361. https://doi.org/10.3389/fpsyg.2022.842361

Giannotti, M., Gemignani, M., Rigo, P., Venuti, P., & De Falco, S. (2022). The role of paternal involvement on behavioral sensitive

responses and neurobiological activations in fathers: A systematic review. *Frontiers in Behavioral Neuroscience, 16*, Article 820884. https://doi.org/10.3389/fnbeh.2022.820884

Hahn, A. C., Symons, L. A., Kredel, T., Hanson, K., Hodgson, L., Schiavone, L., & Jantzen, K. J. (2016). Early and late event-related potentials are modulated by infant and adult faces of high and low attractiveness. *Social Neuroscience, 11*(2), 207–220. https://doi.org/10.1080/17470919.2015.1059361

Hänggi, Y., Schweinberger, K., Gugger, N., & Perrez, M. (2010). Situations-Reaktions-Fragebogen zur Messung elterlicher Sensitivität (PS-SRQ). *Zeitschrift Für Entwicklungspsychologie Und Pädagogische Psychologie, 42*(1), 1–14. https://doi.org/10.1026/0049-8637/a000001

Hansenne, M., Nélis, D., Feyers, D., Salmon, E., & Majerus, S. (2014). Better neuronal efficiency after emotional competences training: An fMRI study. *Psychologica Belgica, 54*(4), 328–349. https://doi.org/10.5334/pb.av

Ho, S. S., Muzik, M., Rosenblum, K. L., Morelen, D., Nakamura, Y., & Swain, J. E. (2020). Potential neural mediators of Mom Power parenting intervention effects on maternal intersubjectivity and stress resilience. *Frontiers in Psychiatry, 11*, Article 568824. https://doi.org/10.3389/fpsyt.2020.568824

Horstman, L. I., Riem, M. M. E., Alyousefi-van Dijk, K., Lotz, A. M., & Bakermans-Kranenburg, M. J. (2022). Fathers' involvement in early childcare is associated with amygdala resting-state connectivity. *Social Cognitive and Affective Neuroscience, 17*(2), 198–205. https://doi.org/10.1093/scan/nsab086

Kanske, P., Böckler, A., Trautwein, F.-M., & Singer, T. (2015). Dissecting the social brain: Introducing the EmpaToM to reveal distinct neural networks and brain–behavior relations for empathy and theory of mind. *NeuroImage, 122*, 6–19. https://doi.org/10.1016/j.neuroimage.2015.07.082

Kluczniok, D., Attar, C. H., Stein, J., Poppinga, S., Fydrich, T., Jaite, C., Kappel, V., Brunner, R., Herpertz, S. C., Boedeker, K., & Bermpohl, F. (2017). Dissociating maternal responses to sad and happy facial expressions of their own child: An fMRI study. *PLoS One, 12*(8), Article e0182476. https://doi.org/10.1371/journal.pone.0182476

Kuzava, S., Frost, A., Perrone, L., Kang, E., Lindhiem, O., & Bernard, K. (2020). Adult processing of child emotional expressions: A meta-analysis of ERP studies. *Developmental Psychology, 56*(6), 1170–1190. https://doi.org/10.1037/dev0000928

Leibenluft, E., Gobbini, M. I., Harrison, T., & Haxby, J. V. (2004). Mothers' neural activation in response to pictures of their children and other children. *Biological Psychiatry, 56*(4), 225–232. https://doi.org/10.1016/j.biopsych.2004.05.017

Levant, R. F., Good, G. E., Cook, S. W., O'Neil, J. M., Smalley, K. B., Owen, K., & Richmond, K. (2006). The normative male alexithymia scale: Measurement of a gender-linked syndrome. *Psychology of Men & Masculinity, 7*(4), 212–224. https://doi.org/10.1037/1524-9220.7.4.212

Lorenz, K. (1943). Die angeborenen Formen möglicher Erfahrung. *Zeitschrift Für Tierpsychologie, 5*(2), 235–409. https://doi.org/10.1111/j.1439-0310.1943.tb00655.x

Luo, L., Ma, X., Zheng, X., Zhao, W., Xu, L., Becker, B., & Kendrick, K. M. (2015). Neural systems and hormones mediating attraction to infant and child faces. *Frontiers in Psychology, 6*, 970. https://doi.org/10.3389/fpsyg.2015.00970

Luo, L., Zhang, Q., Wang, J., Lin, Q., Zhao, B., Xu, M., Langley, C., Li, H., & Gao, S. (2020). The baby schema effect in adolescence and its difference from that in adulthood. *Journal of Experimental Child Psychology, 198*, Article 104908. https://doi.org/10.1016/j.jecp.2020.104908

Ma, X., Shen, J., Krenn, H. Y., Hu, S., & Yuan, J. (2016). A meta-analysis of the relationship between learning outcomes and parental involvement during early childhood education and early elementary education. *Educational Psychology Review, 28*(4), 771–801. https://doi.org/10.1007/s10648-015-9351-1

Martin, J. L., & Ross, H. S. (2005). Sibling aggression: Sex differences and parents' reactions. *International Journal of Behavioral Development, 29*(2), 129–138. https://doi.org/10.1080/01650250444000469

Martín-Aguiar, V. M., Fernández-Berrocal, P., & Megías-Robles, A. (2026). *Searching for the neural correlates of emotional intelligence: A systematic review.* PsyArXiv. https://doi.org/10.31234/osf.io/mzd94

Mascaro, J. S., Hackett, P. D., & Rilling, J. K. (2014). Differential neural responses to child and sexual stimuli in human fathers and non-fathers and their hormonal correlates. *Psychoneuroendocrinology, 46*, 153–163. https://doi.org/10.1016/j.psyneuen.2014.04.014

Mascaro, J. S., Rentscher, K. E., Hackett, P. D., Mehl, M. R., & Rilling, J. K. (2017). Child gender influences paternal behavior, language, and brain function. *Behavioral Neuroscience, 131*(3), 262–273. https://doi.org/10.1037/bne0000199

MathWorks Inc. (2019). *MATLAB (Version 9.7) [Computer software].*

Matsudaira, I., & Yamaguchi, R. (2025). Intergenerational neuroimaging's present and future: Considering sex as a biological variable to enhance knowledge of brain development through parent–offspring similarity. *Developmental Cognitive Neuroscience, 76*, Article 101635. https://doi.org/10.1016/j.dcn.2025.101635

McBride, B. A., & Mills, G. (1993). A comparison of mother and father involvement with their preschool age children. *Early Childhood Research Quarterly, 8*(4), 457–477. https://doi.org/10.1016/S0885-2006(05)80080-8

McIntyre, M. H., & Edwards, C. P. (2009). The early development of gender differences. *Annual Review of Anthropology, 38*, 83–97. https://doi.org/10.1146/annurev-anthro-091908-164338

Michalska, K. J., Decety, J., Liu, C., Chen, Q., Martz, M. E., Jacob, S., Hipwell, A., Lee, S. S., Chronis-Tuscano, A., Waldman, I. D., & Lahey, B. B. (2014). Genetic imaging of the association of oxytocin receptor gene (OXTR) polymorphisms with positive maternal parenting. *Frontiers in Behavioral Neuroscience, 8*, 21. https://doi.org/10.3389/fnbeh.2014.00021

Moeller, S., Yacoub, E., Olman, C. A., Auerbach, E., Strupp, J., Harel, N., & Uğurbil, K. (2010). Multiband multislice GE-EPI at 7 tesla, with 16-fold acceleration using partial parallel imaging with application to high spatial and temporal whole-brain fMRI. *Magnetic Resonance in Medicine, 63*(5), 1144–1153. https://doi.org/10.1002/mrm.22361

Montandon, M.-L., Rodriguez, C., Herrmann, F. R., Eytan, A., Pegna, A. J., Haller, S., & Giannakopoulos, P. (2023). Seeing in my way or your way: Impact of intelligence, attention, and empathy on brain reactivity. *Frontiers in Human Neuroscience, 17*, Article 1071676. https://doi.org/10.3389/fnhum.2023.1071676

Moses-Kolko, E. L., Horner, M. S., Phillips, M. L., Hipwell, A. E., & Swain, J. E. (2014). In search of neural endophenotypes of postpartum psychopathology and disrupted maternal caregiving. *Journal of Neuroendocrinology, 26*(10), 665–684. https://doi.org/10.1111/jne.12183

Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience & Biobehavioral Reviews, 33*(7), 1004–1023. https://doi.org/10.1016/j.neubiorev.2009.04.001

Noriuchi, M., Kikuchi, Y., Mori, K., & Kamio, Y. (2019). The orbitofrontal cortex modulates parenting stress in the maternal brain. *Scientific Reports, 9*(1), Article 1658. https://doi.org/10.1038/s41598-018-38402-9

Paul, S., Austin, J., Elliott, R., Ellison-Wright, I., Wan, M. W., Drake, R., Downey, D., Elmadih, A., Mukherjee, I., Heaney, L., Williams, S., & Abel, K. M. (2019). Neural pathways of maternal responding: Systematic review and meta-analysis. *Archives of Women's Mental Health, 22*(2), 179–187. https://doi.org/10.1007/s00737-018-0878-2

Pawluski, J. L., Lonstein, J. S., & Fleming, A. S. (2017). The neurobiology of postpartum anxiety and depression. *Trends in Neurosciences, 40*(2), 106–120. https://doi.org/10.1016/j.tins.2016.11.009

Piallini, G., De Palo, F., & Simonelli, A. (2015). Parental brain: Cerebral areas activated by infant cries and faces. A comparison between different populations of parents and not. *Frontiers in Psychology, 6*, Article 1625. https://doi.org/10.3389/fpsyg.2015.01625

Portengen, C. M., van Baar, A. L., & Endendijk, J. J. (2024). Mothers' and fathers' neural responses toward gender-stereotype violations by their own children. *Social Cognitive and Affective Neuroscience, 19*(1), Article nsae025. https://doi.org/10.1093/scan/nsae025

Provenzi, L., Lindstedt, J., De Coen, K., Gasparini, L., Peruzzo, D., Grumi, S., Arrigoni, F., & Ahlqvist-Björkroth, S. (2021). The paternal brain in action: A review of human fathers' fMRI brain responses to child-related stimuli. *Brain Sciences, 11*(6), 816. https://doi.org/10.3390/brainsci11060816

Proverbio, A. M., Brignone, V., Matarazzo, S., Del Zotto, M., & Zani, A. (2006). Gender and parental status affect the visual cortical response to infant facial expression. *Neuropsychologia, 44*(14), 2987–2999. https://doi.org/10.1016/j.neuropsychologia.2006.06.015

Rajhans, P., Goin-Kochel, R. P., Strathearn, L., & Kim, S. (2019). It takes two! Exploring sex differences in parenting neurobiology and behaviour. *Journal of Neuroendocrinology, 31*(9), Article e12721. https://doi.org/10.1111/jne.12721

Raley, S., & Bianchi, S. (2006). Sons, daughters, and family processes: Does gender of children matter? *Annual Review of Sociology, 32*, 401–421. https://doi.org/10.1146/annurev.soc.32.061604.123106

Rigo, P., Giannotti, M., Filippi, B., Simonelli, A., Gemignani, M., Perzolli, S., Venuti, P., & De Falco, S. (2025). An exploratory fMRI study on the association of parental involvement in childcare with brain responses to infant vocalisations and dyadic interaction quality in same-sex mother families. *BMC Psychology, 13*(1), 1116. https://doi.org/10.1186/s40359-025-03439-9

Rigo, P., Kim, P., Esposito, G., Putnick, D. L., Venuti, P., & Bornstein, M. H. (2019). Specific maternal brain responses to their own child's face: An fMRI meta-analysis. *Developmental Review, 51*, 58–69. https://doi.org/10.1016/j.dr.2018.12.001

Rorden, C. (2025). MRIcroGL: Voxel-based visualization for neuroimaging. *Nature Methods, 22*(8), 1613–1614. https://doi.org/10.1038/s41592-025-02763-7

RStudio Team. (2020). RStudio: Integrated development environment for R (Version 4.4.1) [Computer software]. RStudio, PBC. http://www.rstudio.com/

Schoppe-Sullivan, S. J., & Fagan, J. (2020). The evolution of fathering research in the 21st century: Persistent challenges, new directions. *Journal of Marriage and Family, 82*(1), 175–197. https://doi.org/10.1111/jomf.12645

Silani, G., Lamm, C., Ruff, C. C., & Singer, T. (2013). Right supramarginal gyrus is crucial to overcome emotional egocentricity bias in social judgments. *Journal of Neuroscience, 33*(39), 15466–15476. https://doi.org/10.1523/JNEUROSCI.1488-13.2013

Sobral, M., Guiomar, R., Rezaeian, M., Vasileiadi, M., Cruz, S., Pacheco, F., Mateus, V., Palau-Costafreda, R., Pozo-Neira, J., Weidenauer, A., Moreira, H., Tik, M., Ganho-Ávila, A., & Schuler, A.-L. (2025). Neural correlates of peripartum depression: A systematic review, meta-analysis and comparison to major depressive disorder. *Molecular Psychiatry, 30*(12), 5979–6006. https://doi.org/10.1038/s41380-025-03227-2

Stern, J. A., Kelsey, C. M., Krol, K. M., & Grossmann, T. (2023). Maternal recognition of positive emotion predicts sensitive parenting in infancy. *Emotion, 23*(5), 1506–1512. https://doi.org/10.1037/emo0001125

Stoeckel, L. E., Palley, L. S., Gollub, R. L., Niemi, S. M., & Evins, A. E. (2014). Patterns of brain activation when mothers view their own child and dog: An fMRI study. *PLoS One, 9*(10), Article e107205. https://doi.org/10.1371/journal.pone.0107205

Strathearn, L., Fonagy, P., Amico, J., & Montague, P. R. (2009). Adult attachment predicts maternal brain and oxytocin response to infant cues. *Neuropsychopharmacology, 34*(13), 2655–2666. https://doi.org/10.1038/npp.2009.103

Strathearn, L., Li, J., Fonagy, P., & Montague, P. R. (2008). What's in a smile? Maternal brain responses to infant facial cues. *Pediatrics, 122*(1), 40–51. https://doi.org/10.1542/peds.2007-1566

Suzuki, Y., & Tanaka, S. C. (2021). Functions of the ventromedial prefrontal cortex in emotion regulation under stress. *Scientific Reports, 11*(1), 18225. https://doi.org/10.1038/s41598-021-97751-0

Swain, J. E. (2011). The human parental brain: In vivo neuroimaging. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 35*(5), 1242–1254. https://doi.org/10.1016/j.pnpbp.2010.10.017

Swain, J. E., & Ho, S. S. (2022). Reduced child-oriented face mirroring brain responses in mothers with opioid use disorder: An exploratory study. *Frontiers in Psychology, 12*, Article 770093. https://doi.org/10.3389/fpsyg.2021.770093

Swain, J. E., Kim, P., Spicer, J., Ho, S. S., Dayton, C. J., Elmadih, A., & Abel, K. M. (2014). Approaching the biology of human parental attachment: Brain imaging, oxytocin and coordinated assessments of mothers and fathers. *Brain Research, 1580*, 78–101. https://doi.org/10.1016/j.brainres.2014.03.007

Thomassin, K., & Seddon, J. A. (2019). Implicit attitudes about gender and emotion are associated with mothers' but not fathers' emotion socialization. *Canadian Journal of Behavioural Science = Revue Canadienne des Sciences du Comportement, 51*(4), 254–260. https://doi.org/10.1037/cbs0000142

Uddin, L. Q. (2015). Salience processing and insular cortical function and dysfunction. *Nature Reviews Neuroscience, 16*(1), 55–61. https://doi.org/10.1038/nrn3857

van der Pol, L. D., Groeneveld, M. G., van Berkel, S. R., Endendijk, J. J., Hallers-Haalboom, E. T., Bakermans-Kranenburg, M. J., & Mesman, J. (2015). Fathers' and mothers' emotion talk with their girls and boys from toddlerhood to preschool age. *Emotion, 15*(6), 854–864. https://doi.org/10.1037/emo0000085

Vuoriainen, E., Bakermans-Kranenburg, M. J., Huffmeijer, R., van IJzendoorn, M. H., & Peltola, M. J. (2022). Processing children's faces in the parental brain: A meta-analysis of ERP studies. *Neuroscience & Biobehavioral Reviews, 136*, Article 104604. https://doi.org/10.1016/j.neubiorev.2022.104604

Wellcome Center for Human Neuroimaging. (2014). *Statistical Parameter Mapping 12 (Version 7487) [Computer software]*. http://fil.ion.ucl.ac.uk/spm/

Wittfoth-Schardt, D., Gründing, J., Wittfoth, M., Lanfermann, H., Heinrichs, M., Domes, G., Buchheim, A., Gündel, H., & Waller, C. (2012). Oxytocin modulates neural reactivity to children's faces as a function of social salience. *Neuropsychopharmacology, 37*(8), 1799–1807. https://doi.org/10.1038/npp.2012.47

Woronko, S. E., Cárdenas, E. F., Bean, C. A. L., Gupta, R. S., Humphreys, K. L., & Kujawa, A. (2025). Neural reactivity to infant faces and trait mindfulness as prospective predictors of postpartum depressive symptoms. *Cognitive, Affective, & Behavioral Neuroscience, 26*(1), 294–305. https://doi.org/10.3758/s13415-025-01319-8

Zhang, H., Liu, T., Lu, L., & Liu, S. (2025). Dynamic effects of family factors on children's social and emotional competence: A systematic literature review. *Advances in Humanities and Modern Education Research, 3*(1), 134–137. https://doi.org/10.70114/ahmer.2025.3.1.P134

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