Dyadic Neural Similarity During Stress in Mother–Child Dyads

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Shared psychological processes between individuals occur most between a mother and her child because the mother–child bond is one of the closest forms of human attachment, in which a mother and her child are essentially wired to connect. We recruited mother–child pairs ($N_{dyad} = 19$; adolescent: $M_{age} = 13.74$, 11 males; mothers: $M_{age} = 44.26$), who each completed an fMRI scan. We examined dyadic neural representational similarity as adolescents completed a stress task and mothers observed their child's performance during the same task. On average, mothers and their children did not show similar neural patterns during stress. However, neural similarity varied depending on family connectedness, such that only dyads reporting high family connectedness showed similar neural profiles. Importantly, increased neural similarity was associated with reduced stress in youth, suggesting that shared neural profiles in mother–child dyads enhance adolescents' psychological well-being.

Shared psychological processes between individuals occur most between mothers and their children (Kochanska & Aksan, 1995) because the mother–child bond is one of the closest forms of human attachment (Ainsworth, Blehar, Waters, & Wall, 2015; Bowlby, 1980). In particular, mothers provide social learning opportunities and references on which children can base their actions, thoughts, and feelings, conferring emotional adjustment across development (Boyum & Parke, 1995). Indeed, high levels of dyadic coordination between mothers and their children have been well documented, such that children exhibit similar patterns of emotional expression and regulation as their mothers (Morris, Silk, Steinberg, Myers, & Robinson, 2007). This shared emotional processing even occurs in real time (Harrist & Waugh, 2002), such that mothers' and infants' heart rates become synchronized during interactive play (Feldman, Magori–Cohen, Galili, Singer, & Louzoun, 2011). Recent imaging evidence has indicated that such dyadic coordination in mother–child affect is promoted by maternal sensitivity that recruits the empathy network of mothers' brains, such as the anterior insula and anterior cingulate cortex (ACC; Feldman, 2016). Importantly, studies have demonstrated that such dyadic concordance provides critical inputs for social and emotional well-being in developing youth (Boyum & Parke, 1995; Feldman, 2016; Harrist & Waugh, 2002; Lee, Miernicki, & Telzer, 2017a).

Significant work has begun to examine biological forms of interpersonal similarity in parent–child dyads, including physiological (e.g., heart rate; Feldman et al., 2011), hormonal (e.g., cortisol levels; Papp, Pendry, & Adam, 2009) and emotional similarity (e.g., shared affect; Feldman, Greenbaum, & Yirmiya, 1999). Although years of functional magnetic resonance imaging (fMRI) research have advanced our understanding of how the brain is involved in complex social processes, the scope of prior neuroimaging research has largely been limited to single individuals. In this study, we examined shared dyadic psychological processes by employing brain scans in mothers and their adolescent children as they engaged in a stressful task. We focus on stress for several reasons. First, adolescents are especially vulnerable to stressors as evidenced by greater physiological and psychological reactivity to stress (Lupien, McEwen, Gunnar, & Heim, 2009), as well as elevated and more prolonged hypothalamic pituitary adrenal (HPA) axis activation compared to children or adults (see Klein & Romeo, 2013). Heightened stress leads to an amalgam of

detrimental outcomes, including poorer physical health (G. E. Miller et al., 2009), substance use onset (Byrne & Mazanov, 2016), and school-related problems (Evans & Schamberg, 2009). Thus, it is essential to understand the social and biological factors that promote healthy stress responses.

Second, extensive human and animal research indicates that stress reactivity and regulation are strongly shaped by social relationships early in life that continue to shape the regulation of stress throughout the lifespan (see Hostinar, Sullivan, & Gunnar, 2014). Attachment figures, largely the maternal stimulus, play a key role in stress buffering, a product of both experience-expectant and experience-dependent neurobehavioral development (Hostinar et al., 2014). Indeed, attachment has been highly conserved over evolution and is observed across mammalian species, yet the quality of attachment depends on learning and maternal sensitivity (Ainsworth et al., 2015; Bowlby, 1980). Thus, strong mother–child attachment relationships yield psychological, emotional, and social benefits that support healthy development, including effective coping (Kerns, Abraham, Schlegelmilch, & Morgan, 2007) and fewer externalizing and internalizing symptoms (Fearon, Bakermans-Kranenburg, Van IJzendoorn, Lapsley, & Roisman, 2010; Groh, Roisman, van IJzendoorn, Bakermans-Kranenburg, & Fearon, 2012), relations that last into adolescence and adulthood (Sroufe, Egeland, Carlson, & Collins, 2005). Although maternal buffering of stress is largely studied in infancy and childhood, the maternal bond remains a key relationship in adolescence, when parents still provide essential social scaffolding to promote effective emotion regulation (Guassi Moreira & Telzer, 2016; Lee et al., 2017a).

Given that the attachment system is rooted in the central nervous system, and mothers and their children are essentially wired to connect (Ainsworth et al., 2015; Bowlby, 1980), we tested whether neural concordance (i.e., similar neural profiles in mothers and their adolescent children) explain the relationship between strong mother–child relationship quality and adolescents' lowered stress. Because youths' affective and behavioral profiles depend on the quality of the parent–child relationship (Peterson & Rollins, 1987), our primary prediction was that mother–child dyads with higher family connectedness would show more finely tuned neural profile similarities. Finally, because dyadic similarity plays an important role in youths' adjustment (Boyum & Parke, 1995; Harrist & Waugh, 2002), we further

explored whether the dyadic neural similarity is predictive of adolescents' overall stress.

To test these predictions, we used a well validated behavioral paradigm that induces stressful experiences and has reliably elicited neural activation in stress-related regions (e.g., anterior insula; Lyons & Beilock, 2011; Strang, Pruessner, & Pollak, 2011). During the stress task, math problems were preceded with different cues which indicated the difficulty of the following math problem (unambiguous easy cue, unambiguous hard cue, and ambiguous cue [i.e., unknown difficulty level]). We examined neural similarity patterns during two types of stress: uncertainty-induced stress (i.e., ambiguous cue) and difficulty-induced stress (i.e., unambiguous hard cue). We expected that the ambiguous cue would induce emotional stress given that uncertainty or unpredictability induces stressful and unpleasant experiences (S. M. Miller, 1981). Also, we expected that unambiguous hard cues would increase stressful experiences when the cue predicted the presence of difficult math problems. Given our primary expectation for the different types of stressors, our *a priori* regions of interest included the anterior insula and dorsal anterior cingulate cortex (dACC). The anterior insula is involved in responding to stressful or painful situations such as facing challenging mathematical problems (Lyons & Beilock, 2011; Strang et al., 2011), especially when future events are uncertain or less predictable (Singer, Critchley, & Preuschoff, 2009). The dACC reflects cue-elicited anticipatory processing (Sarinopoulos et al., 2009), especially when certain or high-probability outcomes are expected (Shidara & Richmond, 2002). Moreover, each of these regions marks key features of parent-child concordance and reciprocity in affect sharing as a part of the empathy network in the brain (Singer, 2006). Building on these findings, we expected that neural concordance in the anterior insula and dACC in mother–child dyads would be altered by the type of stress (uncertain vs. predictable but difficult) and would be associated with the quality of family connectedness.

METHODS

Participants

A total of 20 mother–child dyads participated in this study (total $n = 40$). Although no study has examined neural pattern similarity between

mothers and their children,[1] we considered a reported median sample size of multiple groups during 2014–2015 fMRI studies (e.g., Poldrack et al., 2017) and on previous representational similarity and pattern classification studies (e.g., Visser, Scholte, Beemsterboer, & Kindt, 2013). The parent who participated was the female primary caregiver. One adolescent was excluded due to excessive motion during the scan (highest relative slice-to-slice movement >7 mm; mean displacement: relative = 0.56 mm; absolute = 3.18 mm) and hence the corresponding mother was also excluded. Thus, nineteen healthy dyads (adolescents: M_{age} = 13.74 years, SD = 0.42, range = 13–14 years, 11 males; mothers: M_{age} = 44.26 years, SD = 7.68, range = 32–64 years) were analyzed in this study. All children were biologically related to their mothers, but one parent was a grandparent. All participants provided written informed consent and assent approved by the university's institutional review board.

Questionnaire Measures

Mother–child family connectedness. To assess family connectedness, mothers and adolescents each completed the Family Identity Scale (Fuligni & Flook, 2005), in which they used a 5-point Likert scale (1 = *strongly disagree* to 5 = *strongly agree*) to indicate how much their sense of self was internalized to their family values (e.g., "I feel like a valued member of my family" and "My family is important to the way I think of myself as a person"). This scale measures how much individuals feel they are mutually respected, supported, and share values in the family relationship context (Fuligni & Flook, 2005), and this measure has successfully been linked to neural processing in previous studies (Telzer, Masten, Berkman, Lieberman, & Fuligni, 2010). The eight items were averaged, such that higher scores indicate greater family connectedness for each individual (α = .80 and .75 for child and mother respectively; Pearson-r = −0.07, p = .78; paired-t = −0.5, p = .96). Adolescents' and their mothers' scores were averaged into one composite score representing dyadic family connectedness.

Adolescents' stress perception. Adolescents completed the Perceived Stress Scale (PSS; Cohen & Williamson, 1988), which measures general stress with 10 items (e.g., "How often have you felt nervous or stressed?" on a 5-point scale: 1 = *never* to 5 = *very often*; α = .77), in which higher scores indicate greater stress. One adolescent did not complete the PSS.

Experimental Task Design and Procedure

In this study, we modified a task used in previous studies (Lyons & Beilock, 2011; Strang et al., 2011), which separates anticipation of doing arithmetic problems and actual completion of the problems (Figure 1), a task which reliably elicits stress responses (e.g., heightened galvanic skin response) and associated neural circuitry (e.g., insula activation; Strang et al., 2011). During an fMRI scan, adolescent participants completed the stress task, which was recorded, and their mothers viewed their child's corresponding task performance. At the beginning of each trial, adolescent children were presented with either an unambiguous or ambiguous cue (M = 2 s, ranging from 1.5 to 3 s) that indicated the difficulty level of the following problem. For the unambiguous cue, a red square indicated that the upcoming problem was hard and a green square indicated that the upcoming problem was easy. For the ambiguous cue, a purple square indicated that the upcoming problem could be either hard or easy (possibility for each is 50%). Adolescent children were then presented with one arithmetic problem (e.g., easy problem: "2 + 1 = ?"; hard problem: "5×5 + 2−24 = ?") for 5 s and were asked to provide the correct answer (ranging from 1 to 10) by pressing one of ten

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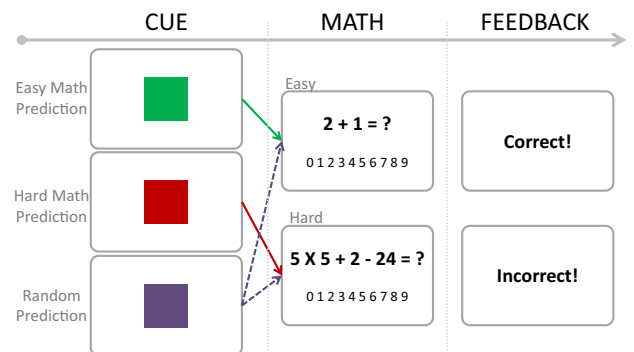[1]Although the current neural pattern representation approach with functional fMRI was first applied for mother–child dyads, our recent work that examined dyadic neural connectome similarity using the resting-state data combined with the independent component analysis (ICA) approach (Lee et al., 2017a,b; included some of the same participants.

FIGURE 1   Experimental task.

buttons using a button box. The difficulty of the hard problems was based on participants' performance. There were five difficulty levels of a math problem (1: easiest, 3: modest, 5: hardest) and all participants began at a difficulty level of 3. Correctly completing the hard problems increased the difficulty level of the following hard math problem by 1, whereas incorrectly completing the hard problem decreased the difficulty level by 1. Thus, the difficulty of the hard problems was rigged such that participants were performing at 50% accuracy (mean accuracy for the hard problems = 45.72%, SE = 2.23, and for the easy problems = 83.95%, SE = 2.95). The easy problems were all set at a difficulty level of 1. The 2-s feedback for their performance (i.e., correct or incorrect) was presented following their answer. The arithmetic problem and feedback were spaced by random interstimulus interval (ISI) jitters (M = 2 s, ranging from 1.5 to 3 s). Adolescent children completed a total of 42 trials, in which 16 trials were presented with ambiguous cues and 26 trials with unambiguous cues (10 easy cues and 16 hard cues). The order of the trials was randomized for each participant.

We administered two fMRI sessions, one to collect adolescents' neural responses when performing the math task (adolescent session) and another to assess mothers' neural activity when they viewed their child's performance (mother session). To accomplish this, adolescents always completed the scan first, and we recorded the task of their performance throughout their session. Mothers then completed a scan during which we presented the video of each mother's child's task. However, the adolescent actively completed the task, whereas the mother passively viewed the child's task. The mother saw the cue phase, the child's response, and the feedback (correct, incorrect).

fMRI Data Acquisition and Analysis

Imaging data were collected using a 3T-Siemens Trio MRI scanner with a 32-channel matrix coil. High-resolution structural images (T1-MPRAGE) were acquired first (repetition time or TR = 1.9 s; echo time or TE = 2.3 ms; field of view or FOV = 256 mm; flip angle or FA = 90°; 1 mm isotropic voxel). T2*-weighted echoplanar images (EPIs) were acquired during the math task (280 volumes; 38 slices with no inter-slice gap; TR = 2 s; TE = 25 ms; matrix = 92 × 92; FOV = 230 mm; FA = 90°; voxel size = 2.5 × 2.5 × 3.0 mm³; 0.3 mm slice gap).

Preprocessing was carried out using FEAT Version 6.00, part of FSL (the software library of the Oxford Centre for Functional MRI of the Brain). The following pre-statistics processing was applied: motion correction using MCFLIRT; non-brain removal using BET; grand-mean intensity normalization of the entire 4D data set by a single multiplicative factor; spatial smoothing applied for univariate whole-brain analysis with a Gaussian kernel of full width at half maximum (FWHM) 6 mm, but not for pattern-related analyses. Registration matrix was estimated between functional images, high-resolution structural images, and standard Montreal Neurological Institute (MNI) 2-mm brain using FLIRT, and final registration parameters were applied to the functional images for cross-participant analyses (i.e., the mother–child dyad).

Multi-Voxel Neural Pattern Analyses

We adopted representational similarity analysis (RSA) (Kriegeskorte et al., 2008) as a form of multi-voxel pattern analysis (MVPA) to evaluate neural profile similarity in mother–child dyads. The advantage of employing a neural pattern approach is that it allows us to estimate how psychological processes are represented in the brain (Kaplan, Man, & Greening, 2015) rather than simply examining whether the shared process induces more or less brain activation on average. We first estimated adolescents' brain response patterns during stress cues as their own specific neural profile index, and then we estimated their mothers' neural pattern for the same stimulus acquired independently. Finally, we calculated neural profile similarity by comparing mothers and their children's neural response pattern. We further tested whether an adolescent's neural profile could be identified by his or her mother's neural pattern in which a classifier (e.g., a linear support vector machine; SVM) was trained based on mothers' neural patterns and tested to classify their children's neural patterns. For this cross-classification purpose, we employed a form of multivariate cross-classification (Kaplan et al., 2015).

Representational similarity analysis (RSA): Family relationship quality modulation in neural pattern similarity. For representational similarity analysis, we first estimated single-trial activation patterns for each cue type using least squares single methods (Mumford, Turner, Ashby, & Poldrack, 2012) where each single-level general

linear model (GLM) included regressors for the current cue event, all other remaining cue events, and all other non-interest events (i.e., nuisance regressor) including the math equation presentation and feedback phase as well as motion regressors (six motion parameters and motion outlier time points; Figure S1b in the Supporting Information). For each participant, the voxel-wise pattern of activity represented by z-values (i.e., z-transformed parameter estimates) was then extracted within each ROI region (see ROI Selection below for more details). The extracted patterns were further analyzed by calculating pairwise Pearson correlation coefficients (i.e., similarity value) between each cue trial as well as every possible pairing of other cue trials, and then applied to Fisher's r-to-z transformation (Figure S1b in the Supporting Information), producing a symmetric 64×64 similarity matrix for each dyad and for each ROI. Finally, the Pearson correlation coefficient was calculated between family connectedness and the averaged similarity values for each cue type and for each dyad to determine the effects of family connectedness on the neural pattern similarity of mother–child dyads. We focused our analysis on two types of stress; uncertainty-induced stress (i.e., ambiguous cue) versus difficulty-induced stress (i.e., unambiguous hard cue).

Multivariate cross-dyad analysis: Family relationship modulation in cross-classification of the neural pattern. Next, to examine whether we can identify an adolescent's neural patterns based on his or her mother's neural activity pattern, we used a machine-learning classifier algorithm (i.e., linear SVM). The classifier was trained on data from mothers to classify the patterns in their children.

As the first step of this analysis, namely cross-dyad classification, we trained a linear SVM on brain patterns in mothers' brains to classify testing set created from adolescents' brains. The testing and training data sets were independent of one another. To avoid possible biased training and testing procedure due to different numbers of each target and non-target pattern when we trained all mothers data at once (e.g., 16 ambiguous cue patterns from target mothers and 288 patterns from all non-target mothers with 19 classes in the model), we repeated a one-by-one pairing procedure 18 times with all possible combinations between one mother of interest (i.e., signal) and one non-interest mother brain (i.e., noise) for training procedure (e.g., pair 1: mother 1 – mother 2, ..., pair 18: mother 1 – mother 19). For the testing data, we

created the adolescent children's pairs corresponding to the mothers' training pairs in the same manner (e.g., pair 1: child 1 – child 2, ..., pair 18: child 1 – child 19) (Figure S3 in the Supporting Information). In total, this repeated training and testing procedure yielded 18 different classifiers and classification outputs for each given dyad, and we averaged these 18 classification outputs as a grand index of classification sensitivity for a given mother–child dyad (Etzel & Braver, 2013). Importantly, because we were mainly interested in how well the target adolescent brain (signal) was classified among any pairs of other adolescent children (noise) by a linear SVM trained by an independent training set, classification performance was defined not as the proportion of correct responses for both signal and noise (i.e., [proportion ("yes"|signal) + proportion ("no"|noise)]/2 or [p ("hit") + p ("correct rejection")]/2) but as the area under the curve (AUC) of receiver operating characteristic (ROC) curve, which indicates how well the classifier can identify signal as signal ("hit") in consideration of false positive error that identifies noise as signal (i.e., [p ("yes"|noise)] or [p ("false alarm")]) for a given dyad (Macmillan & Creelman, 2004). We then administered the Pearson correlation analysis between classification accuracies and family connectedness of each dyad to determine how much family connectedness influences neural pattern classification performance.

This analysis was done with the neural activity patterns (i.e., vectors) estimated during RSA analysis. The training and testing were performed using the LIBSVM implementation software available at http://www.csie.ntu.edu.tw/~cjlin/libsvm) with a linear kernel and a standard cost/penalty parameter ($c = 1$).

ROI Selection

To define the anterior insula ROI, we performed a standard two-stage mixed-effects GLM analysis to estimate cue-related changes in BOLD signal: a first individual-level GLM estimation for each event type, and then group-level random effects estimation (clusters determined by Z > 2.3 and a corrected cluster significance level of $p = 0.05$; *one-tailed*) based on the Gaussian random field theory. Finally, we collapsed all cue events regardless of cue type (unambiguous and ambiguous) and participant set (mother and adolescent child), and contrasted those with all other activation maps in math and feedback phase regardless of their difficulty level and participant set (all cue > all math + all feedback; i.e.,

orthogonal functional localizer; see Table S1 in the Supporting Information for significant regions). We identified a total of 133 active voxels, which were only involved in cue processing for both mothers and adolescent children, within the anterior insula region bilaterally at the group level. For the dACC ROI, we failed to identify cluster-activation in the dACC, and thus an anatomical ROI mask of the anterior cingulate was derived using the Harvard-Oxford probabilistic atlas (50% or higher probability of being located in the dACC region; 1159 voxels).

RESULTS

Representational Similarity Analysis

Family connectedness modulates brain pattern similarity. To test the prediction that higher family connectedness produces more attuned neural pattern similarity, we first extracted trial-by-trial representational neural patterns and calculated the similarity value of these neural patterns as an indicator of the level of dyadic neural profile similarity in each mother–child dyad ($n = 19$ dyads) for uncertainty-induced stress (i.e., ambiguous cue) versus difficulty-induced stress (i.e., unambiguous hard cue; Figure S1 in the Supporting Information). Mother–child family connectedness was defined by how much mother and child are mutually respected and supportive, and how much they share values in the family relationship context (Fuligni & Flook, 2005). We examined whether mother–child family connectedness is related to neural pattern similarity values across dyads for each cue type (see Figure 2a for averaged similarity matrix of mother–child dyad for each ROI; see also Figure S2 in the Supporting Information for individual dyad similarity matrix). Statistical significance was tested by computing a 95% confidence interval (CI) based on 50,000 bootstrap resampling.

As shown in Figure 2b, the neural similarity in the anterior insula responding to uncertainty-induced stress (i.e., ambiguous cue) was positively correlated with mother–child family connectedness, $r(19) = .55$, $p = .016$, 95% CI = [0.25, 0.79], suggesting that higher family connectedness is associated with more neural similarity during uncertainty-induced stress processing. On the other hand, the associations for difficulty-induced stress (i.e., unambiguous hard cue) were not significant ($p = .96$, 95% CI = [−0.39, 0.49]), indicating that the anterior insula is involved more in the process of uncertainty. Results of neural similarity in the

dACC were reversed (Figure 2c). The neural pattern similarity in the dACC showed a positive correlation with the degree of family connectedness during the difficulty-induced stress, $r(19) = .64$, $p = .003$, 95% CI = [0.07, 0.84], but not during the uncertainty-induced stress ($p = .81$, 95% CI = [−0.43, 0.58]), indicating that higher mother–child family connectedness is related to more neural similarity in the dACC during certainty-induced stress.

The relationship between dyadic neural concordance and adolescents' stress. To test whether dyadic neural similarity influences adolescents' stress, a Pearson correlation analysis was performed with the neural similarity of dyads and youths' self-reported stress. For this analysis, we averaged the similarity values across the anterior insula for uncertainty-induced stress and the dACC for difficulty-induced stress as a grand neural concordance index regardless of stress type. We found that the degree of neural concordance in mother–child dyads had a significant negative correlation with adolescents' stress, $r(18) = −.58$, $p = .01$, 95% CI = [−0.84, −0.18], suggesting that adolescents who have more similar neural patterns to their mother experience less stress in daily life (Figure 2d).[2]

Given previous evidence that dyadic similarity and relationship quality between parents and their children is a key factor in promoting youths' positive adjustment throughout development (Boyum & Parke, 1995; Feldman, 2016; Harrist & Waugh, 2002; Lee et al., 2017a), we further conducted mediation analyses to examine how neural similarity and family relationship influence adolescents' stress. To test this hypothesis, we performed a mediation analysis in which mother–child family connectedness was the independent variable to predict stress as the outcome, through neural concordance as the mediator (model 1). Mediation was conducted using the procedures described by Preacher and Hayes (2008) using a bias-corrected confidence interval with bootstrapping resampling ($n = 5,000$). We found a significant indirect effect of neural concordance between family connectedness and stress (B = −.47, SE = .27, 95% CI = [−1.20, −0.06]). To probe the direction of this pathway, we conducted a similar mediation analysis in which neural similarity was entered as the independent

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[2]When the analyses were repeated with the neural similarity value of each ROI, we found the same results: dACC: $r(19) = .47$, $p = .04$; anterior insular: $r(19) = .60$, $p = .01$).
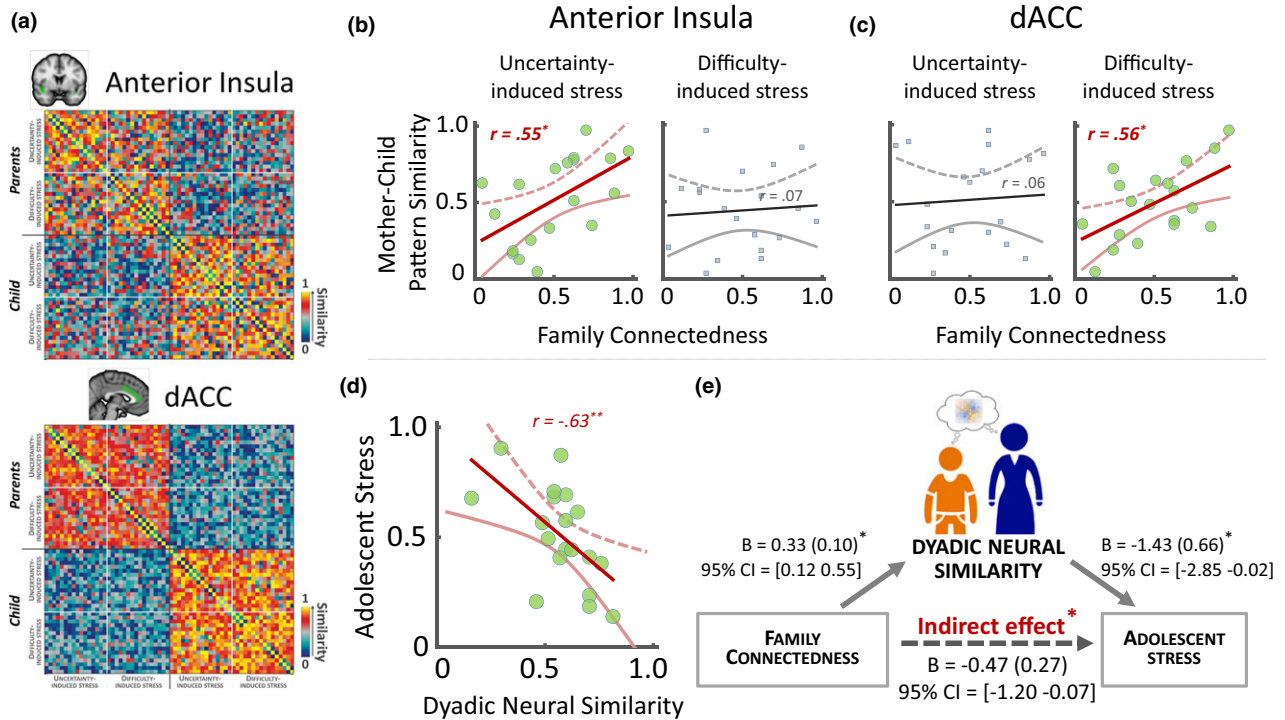
FIGURE 2   (a) Averaged representational neural pattern similarity matrix across dyads in the anterior insula and dACC as a function of the stressor. (b) Scatter plots represent the association between family connectedness and neural pattern similarity in the anterior insula and (c) dACC. The family connectedness score and similarity values are scaled to 0 and 1 for display purposes. (d) Scatter plots between the degree of dyadic neural similarity and adolescents' stress. For dyadic neural similarity, we averaged pattern similarity across ROIs (i.e., anterior insula for uncertainty-induced stress and dACC for difficulty-induced stress). (e) Mediation model of the indirect effect of family connectedness on adolescents' stress through dyadic neural similarity. Note that the magnitude and the significance of the indirect effect in the mediation analysis were calculated using bootstrapping resampling with a bias-corrected confidence interval. The red dashed line indicates 95% confidence interval of the regression line. ** $p < .01$; *$p < .05$.

variable to predict stress through family connectedness (i.e., the mediator). This mediation model was not statistically significant (B = −.18, SE = .30 95% CI = [−0.84, 0.33]), suggesting that family connectedness likely promotes youths' psychological well-being (i.e., lower stress) through increasing neural concordance between mothers and their children (Figure 2e).[3]
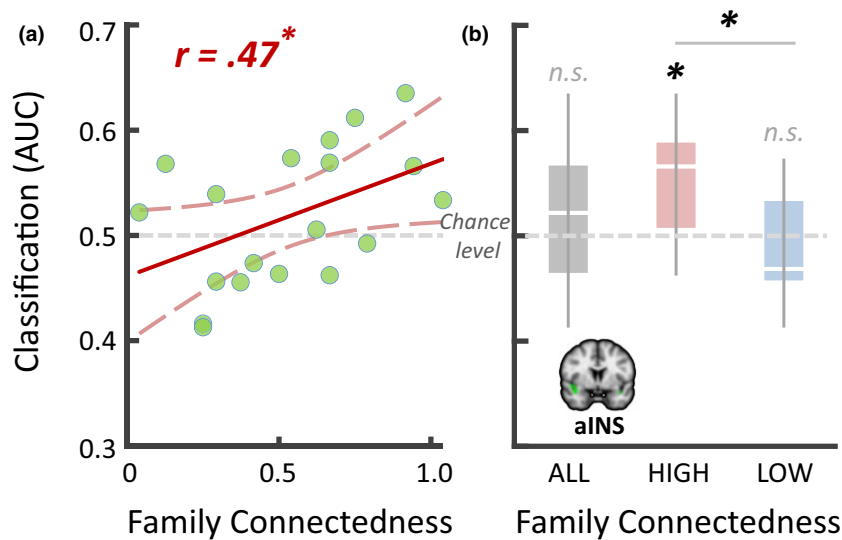
Cross-Dyad Classification

Mother–child family connectedness improves brain pattern classification in mother–child dyads. To determine whether mother–child family connectedness plays a role in the cross-dyad brain pattern

classification, a linear SVM classifier was trained by input from each mother's data to identify her child's brain (Figure S3 in the Supporting Information), focusing on neural patterns during the uncertainty-induced stress (i.e., ambiguous cue) in the anterior insula and the certainty-induced stress (i.e., unambiguous cue) in the dACC.

The averaged classification performance for brain patterns in the anterior insula across all dyads was not significant from chance level (i.e., 0.5), $t(18) = 1.22$, $p = 0.24$, 95% CI = [−0.01, 0.05], Cohen's $d = 0.58$, indicating that adolescents' brain patterns were not successfully decoded based on their mother's brain. However, we found that the classification performance for brain patterns in the anterior insula was positively correlated with mother–child family connectedness, such that higher family connectedness was associated with better decoding accuracy, $r(19) = .47$, $p = .042$, 95% CI = [0.10, 0.77] (Figure 3a). Although it is not statistically optimal to split dyads into two groups due to the small sample size, we conducted a

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[3]When we tested the mediation model with neural similarity of each ROI separately we found a significant indirect effect of the anterior insula (B = −.28, SE = .32, 95% CI = [−1.12, −0.04]), but marginal significance of the dACC (B = −.20, SE = .19, 95% CI = [−0.76, 0.02]).

FIGURE 3   (a) Scatter plot between relationship quality and classification performance in the anterior insula. (b) Averaged classification performance on neural pattern responding to uncertainty-induced stress as a function of family connectedness when classifier was trained to identify child brain based on mother brain. Given the small sample size, this group-level comparison was conducted for exploratory purposes only to probe the effect of relationship quality on the neural classification. Error bars indicate maximum and minimum classifications. The red dashed line indicates 95% confidence interval of the regression line. The gray dashed line indicates the chance level of classification. *$p < .05$. aINS = anterior insular; HIGH = high-quality relationship group; LOW = low-quality relationship group.

subsequent group comparison to further probe the observed classification results for exploratory purposes. We divided the mother–child dyads into "high family connectedness" and "low family connectedness" (median split) and found the classification performance for high family connectedness dyads was significantly greater than chance level, $t(8) = 2.36$, $p = .046$, 95% CI = [0.01, 0.06], Cohen's $d = 1.11$, whereas the performance for low family connectedness dyads was not statistically different from chance level ($p = .25$, 95% CI = [−0.05, 0.01]). The difference between high- and low family connectedness dyads was significant, $t(17) = 2.47$, $p = .024$, 95% CI = [0.01, 0.09], Cohen's $d = 1.09$ (Figure 3b).

In addition, we also tested the classifier to classify mother's brain by training it with adolescents' neural patterns and found the same statistical significances such that higher family connectedness predicted better classification performance in terms of correlation, $r(19) = .51$, $p = .025$, 95% CI = [0.15, 0.79] and group comparison; significant difference from chance level for high family connectedness dyads, $t(8) = 2.70$, $p = .027$, 95% CI = [0.01, 0.09], Cohen's $d = 1.91$, but not for low family connectedness dyads ($p = .54$. 95% CI = [−0.05, 0.02]), and between the groups, $t(17) = 2.38$, $p = .029$, 95% CI = [0.01, 0.11], Cohen's $d = 1.08$ (Figure S4 in the

Supporting Information). These classification observations were only valid for the anterior insula responding to the uncertainty-induced stress processing, as we did not find significant effects with the dACC (all $ps > .47$).

DISCUSSION

As social beings, we are "wired to connect with others" (Lieberman, 2013). We spontaneously seek social connection to share our feelings, ideas, and experiences with others. That is, our minds are continuously coupled to those around us, and this shared psychological process influences the way we perceive, respond to, and thrive in a complex social world (Wheatley, Kang, Parkinson, & Looser, 2012). This shared social experience confers social benefits, allowing us to spontaneously embody the affective experiences of familiar others, fostering social connection, and providing the foundation for forming intimate relationships throughout life (De Waal, 2007). Indeed, the ability to simulate and embody others' experiences occurs across species (Langford et al., 2006; Singer, 2006). Yet, our understanding of how shared psychological processes are represented at the neural systems level in the brain remains unknown. The current study provides insight into how psychological processes

between mothers and their children are shared at the neural level. Our results contribute to our understanding of how two brains are tuned and work in concert, ultimately contributing to youths' well-being.

Focusing on representational neural pattern similarity, we found that mother–child dyads with greater family connectedness showed more similar neural response patterns. A subsequent multi-voxel pattern classification analysis also confirmed this dyadic neural concordance by showing that adolescents' neural patterns were successfully identified by their mothers' neural profile depending on their family connectedness. Importantly, we found that the level of dyadic neural concordance in mother–child dyads was associated with lowered stress in adolescents. Consistent with previous behavioral studies showing that dyadic similarity is a key factor in promoting positive adjustment throughout development (Barber, Bolitho, & Bertrand, 2001; Harrist & Waugh, 2002), our findings provide a neural mechanism by which this occurs—shared neural profiles between mothers and their child help to enhance adolescents' psychological well-being.

In this study, we introduced two different types of stress by presenting different cues to inform the difficulty of upcoming math problems; one explicitly predicted difficult math problem occurrences, and the other one was uninformative about the difficulty. That is, participants experienced stress by anticipation of either predictable-but-difficult math (unambiguity) or unpredictable difficult math (ambiguity). We found that mother–child dyads showed increased neural pattern similarity in the insula during the processing of ambiguity-induced stress. The anterior insula is involved in responding to stressful or painful situations as a reflection of emotional regulatory efforts especially when future events are uncertain or less predictable (Sarinopoulos et al., 2009; Singer et al., 2009). Therefore the current observation that neural similarity in the anterior insula was increased for the ambiguous cue supports previous evidence about the role of the anterior insula in the anticipatory processing of less informative stressors. In contrast, the dACC showed higher pattern similarity between mother–child dyads during the processing of unambiguity-induced stress (i.e., predictable-but-difficult cue). The dACC reflects cue-elicited anticipatory processing (Sarinopoulos et al., 2009) for certain or high probability outcomes (Shidara & Richmond, 2002). Consistent with this, we found that mother–child dyads showed greater similarity in dACC neural activation to predictable stress cues. Together,

our results provide further evidence for the mechanistic and differential roles of these two brain regions in the processing of both ambiguity and unambiguity.

Notably, mothers were scanned while watching their child's performance on a stress task, which was videotaped during the child's scanning session. That is, mothers were not actively performing the same task but instead observing how their child was doing in the stressful task, making this an ecologically valid experience for how child stress and maternal observations occur in everyday life. It is thus interesting to speculate that perhaps mothers experienced feelings of empathic engagement rather than their own actual emotional distress. Importantly, the ROI regions in this study (anterior insula and dACC) have been considered the main brain components in empathy (Singer, 2006). Indeed, the posterior probabilities of these regions from the Neurosynth database (http://www.neurosynth.org) were 61%, 77%, and 59% for empathy, pain, and stress, respectively, indicating that empathy has a stronger structure-to-function relationship with our ROI regions. Therefore, the shared dyadic neural response patterns observed in this study might be a reflection of empathic efforts of mothers to understand the child's feelings and needs and to provide congruent responses (Feldman, 2016), which induces similar neural response patterns to their own offspring.

In theory, to explain the underlying mechanism of how dyadic profile similarity between mothers and their children can occur, social referencing (Morris et al., 2007) explains that adolescents implicitly model their parents' behavior suggesting a uni-directional influence from child to parent, whereas dyadic synchrony (Harrist & Waugh, 2002) assumes bidirectional influences between child and parent in shaping psychological and behavioral profiles. These two theories have different views regarding the interactive directionality in parent–child dyads. However, our analysis of neural similarity was primarily correlational. Hence the present methodology does not directly allow for inferences about the direction of effects in neural concordance. The dyadic brain scans in this study did not constitute a form of hyperscanning in which two brains in response to the same stimuli or events are measured at the same time. Thus our observations do not contain information about how this dyadic neural similarity can be tuned in real time by their online interaction. Experimental designs using hyper-dyadic brain imaging technics to measure real-time signal-phase synchronized

processes (e.g., Hirata et al., 2014) can help us to probe the source of mother–child neural profile similarity observed in the present study.

Our results can inform future interventions that focus on reducing adolescents' stress and increasing resilience by elucidating the role of neural concordance between parents and their children as well as parent–child family connectedness. Although valuable developmental research has identified the role of parent–child attachment in adolescents' adjustment (e.g., Boyum & Parke, 1995; Harrist & Waugh, 2002), questionnaire- and observation-based approaches cannot assess the role of underlying neurobiological factors within family interactions and adolescent development. The current approach to quantify the degree of dyadic neural concordance between mothers and teenagers can be useful in predicting a broad range of adolescents' psychological adjustment and may be considered a biomarker of interpersonal connection with family and significant others. Given that family connectedness promoted youths' adjustment via neural concordance in mother–child dyads, interventions focused on increasing family connectedness and promoting greater concordance among family members may have lasting effects in reducing youths' stress. Indeed, enhanced neural similarity is associated with more day-to-day emotional synchrony in parent–child dyads, which promotes adolescents' emotional competence (Lee et al., 2017a). Thus, interventions designed to enhance family connectedness may work to promote greater synchrony in both neural and behavioral processing, thereby enhancing the psychological adjustment of youth.

Some limitations should be considered in interpreting the current findings. First, we cannot determine a causal relationship between the neural concordance, relationship quality, and adolescent's stress level given the correlation design. Importantly, our mediation model supported the pathway in which family relationship quality predicted less stress via neural concordance (i.e., model 1) whereas we failed to observe the mediation effect with neural concordance as the predictor (model 2). This increases our confidence in the proposed pathway whereby relationship quality increases mother–child neural concordance during stress, thereby decreasing adolescents' stress. These findings are consistent with previous research showing that dyadic concordance and better relationship quality are a key factor in promoting youth's psychological well-being (Boyum & Parke, 1995;

Feldman, 2016; Harrist & Waugh, 2002; Lee et al., 2017a). However, future longitudinal research should be conducted to examine more causal pathways to determine the direction of effects.

Second, we only recruited mothers and had a relatively small sample, precluding our ability to examine sex differences among adolescents, between mothers and fathers, or different sources of relationships such as between mother and peers. For example, evidence has indicated that adolescents' relationships with their parents vary depending on the primary caregiver's sex such that mother–child and father–child relationships change across development (e.g., Collins & Russell, 1991). Furthermore, adolescence is a transitional period of shifting social attention from family to peer groups (Nelson, Leibenluft, McClure, & Pine, 2005). Therefore, it is difficult to address that the observed variability in family connectedness and neural pattern similarity is due to either the ongoing transition of adolescents' social attention (from family to their peers) or to the mother–child relationship itself. Future studies should examine relationship quality and stress-buffering patterns across different dyadic pairs (e.g., peers, romantic partners, and fathers) to understand better how dyadic neural similarity changes across development and different relationship partners. Finally, youths' sex plays an important role in their social interactions (Collins & Russell, 1991), and so future research should recruit larger samples that allow for tests to compare girls and boys.

The current study provides insight into how shared psychological processes between mothers and their children are represented at the neural level. By implementing a novel combination of multivariate pattern analysis and dyadic brain scans, we identified neural patterns between individuals (e.g., mother and child dyad) that are coherent, and thus allowed us to test how mothers' brain response can be decoded based on how their children's brains respond. This interpersonal neural similarity varies depending on interpersonal connectedness. Importantly, we found that similar neural profiles in mother–child dyads promote psychological adjustment (i.e., lower stress), supporting the idea that the ability to share psychological experiences with others promotes psychological benefits throughout life (De Waal, 2007; Feldman, 2016; Wheatley et al., 2012). The current findings significantly contribute to our understanding of how two brains are tuned and work in concert, ultimately contributing to youths' well-being.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. Schematic diagram for representational similarity analysis procedure.

Figure S2. Neural pattern similarity for each dyad (a) in the anterior insular and (b) dACC.

Figure S3. Schematic diagram for the current cross-dyad classification procedure.

Figure S4. (a) The scatter plot represents the positive correlation between family relationship and brain classification performance. The dotted line indicates the chance level of classification performance (b) Cross-dyad classification results within the anterior insula during the uncertainty-induced stress processing when classifier was trained to identify mother brain based on child's brain.

Table S1. Brain regions on Cue > (Math + Feed) contrast.