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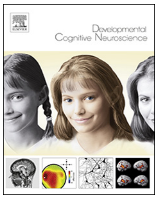

Neural correlates of early deliberate emotion regulation: Young children's responses to interpersonal scaffolding☆

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ABSTRACT

Deliberate emotion regulation, the ability to willfully modulate emotional experiences, is shaped through interpersonal scaffolding and forecasts later functioning in multiple domains. However, nascent deliberate emotion regulation in early childhood is poorly understood due to a paucity of studies that simulate interpersonal scaffolding of this skill and measure its occurrence in multiple modalities. Our goal was to identify neural and behavioral components of early deliberate emotion regulation to identify patterns of competent and deficient responses. A novel probe was developed to assess deliberate emotion regulation in young children. Sixty children (age 4–6 years) were randomly assigned to deliberate emotion regulation or control conditions. Children completed a frustration task while lateral prefrontal cortex (LPFC) activation was recorded via functional near-infrared spectroscopy (fNIRS). Facial expressions were video recorded and children self-rated their emotions. Parents rated their child's temperamental emotion regulation. Deliberate emotion regulation interpersonal scaffolding predicted a significant increase in frustration-related LPFC activation not seen in controls. Better temperamental emotion regulation predicted larger LPFC activation increases post- scaffolding among children who engaged in deliberate emotion regulation interpersonal scaffolding. A capacity to increase LPFC activation in response to interpersonal scaffolding may be a crucial neural correlate of early deliberate emotion regulation.

1. Introduction

Emotion regulation, the ability to modulate the parameters of an emotional experience (Gross, 2013), is hypothesized to comprise two non-mutually exclusive response types. Automatic emotion regulation is an immediate, reactive response at the onset of an emotional challenge, while deliberate emotion regulation is a distinct, longer-unfolding, effortful response (Gross, 2013). The ability to implement deliberate emotion regulation, to hold in mind and willfully control emotions, is a crucial skill hypothesized to emerge in early childhood (Kopp, 1989; Zelazo and Cunningham, 2007) that forecasts later functioning across academic, behavioral, and social domains (Eisenberg et al., 2014). In particular, the capacity to regulate negative emotions such as irritability has a longstanding impact on mental health, functioning, and human capital (Campbell et al., 2014; Wakschlag et al., 2019). The field has also seen a dramatic increase in clinic- (Kovacs et al., 2006), school- (Domitrovich et al., 2005), and home-based (Rasmussen et al., 2018) programs designed to scaffold and strengthen deliberate emotion regulation in young children. However, there have been surprisingly few empirical investigations of deliberate emotion regulation in the early childhood period and thus major gaps in understanding the key features of this skill when it emerges, particularly its neural basis. Our goal was to understand the immediate, in-vivo, neural and behavioral changes that occur with implementation of deliberate emotion regulation in young children in order to understand the early development of this skill and identify patterns of competent

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☆ Portions of the findings included in this manuscript were presented as a poster at FLUX: The International Congress for Integrative Developmental Cognitive Neuroscience, St. Louis, MO (September 8, 2016).

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vs. deficient responses.

Between the ages of 3 and 6 years, dramatic changes in the volume, thickness, and white matter diffusion of the prefrontal cortex support rapid advances in myriad executive functions, such as inhibitory control, attentional shifting, and working memory (Giedd et al., 1999). These executive functions are postulated to form the basis for young children's earliest deliberate emotion regulation strategies (e.g., considering other things to play with when a peer won't share a desired toy) (Kopp, 1989). As intentional capacities increase in early childhood, the emerging deliberate emotion regulation skillset becomes amenable to scaffolding from adults. This interpersonal scaffolding involves two-way caregiver, teacher, therapist, etc., conversations with children in which adults probe children's broader understanding of the causes, consequences, and social function of emotions and provide information designed to shape this understanding (Thompson, 2014). Longitudinal work by Kochanska and colleagues showed that how mothers intervened to assist their child during a negative emotion challenge predicted the child's ability to tolerate the same negative challenge by themselves one year later (Kochanska et al., 2001). This hypothesized interaction between plastic neural systems supporting application of executive functions to emotional challenges, and amenability to direct instruction, suggests interpersonal scaffolding-based techniques may similarly strengthen deliberate emotion regulation in early childhood. Advancing this theoretical framework requires directly testing the unique effect of interpersonal scaffolding on young children's neural activation during emotional challenges.

The assumption that deliberate emotion regulation emerges in early childhood, and responds to interpersonal scaffolding, has resulted in a proliferation of education, mental health, and even media-based programs to target or repair this skill in early childhood (Morris et al., 2014; Rasmussen et al., 2018). For example, deliberate emotion regulation classroom curricula, such as the widely used *Second Step* program, provide teachers with materials and lesson outlines, such as role-playing games, puppets, and socio-emotional stories, to help children prospectively develop strategies for socio-emotional conflicts and recovering from emotional challenges (Frey et al., 2000). A similar approach is employed in children's educational television programming (Rasmussen et al., 2016), and more recently, mobile apps for preschoolers that coach children to use strategies such as counting and taking deep breaths when they get angry (Rasmussen et al., 2018). A deficient deliberate emotion regulation skillset in early childhood is also an etiological factor, and clinical target, for myriad forms of emerging psychopathology, including anxiety (Kendall and Hedtke, 2006), depression (Kovacs et al., 2006), and aggression (Frey et al., 2000). Manualized treatments targeting deficient deliberate emotion regulation have similar therapeutic approaches irrespective of disorder type. In an initial, psycho-education phase, a therapist may spend several one hour sessions scaffolding a child's understanding of the physiological sensations and cognitions associated with emotions (probing the child's understanding of emotions and modifying the session based on their responses), and teaching deliberate emotion regulation strategies (e.g., diaphragmatic breathing, reappraisal). Children then transition to a training and practice phase where the therapist coaches the child to implement deliberate emotion regulation during simulated and real-life negative emotion challenges, for example, a peer conflict or blocked goal (Leff et al., 2001). However, the dissemination of these programs has advanced far beyond even a basic empirical understanding of the fundamental characteristics of deliberate emotion regulation in early childhood. Moreover, many deliberate emotion regulation programs and interventions lack or have mixed clinical efficacy (Morris et al., 2014) and lack a mechanistic foundation, suggesting an urgent need for studies elucidating unique behavioral and neural changes children exhibit during deliberate emotion regulation.

Neuroimaging studies in adults suggest negative emotional challenges activate a dynamic interaction between limbic structures, such as the amygdala, hippocampus, and striatum, that reflect threat- or reward-response, and prefrontal areas that down-regulate these subcortical regions (Blair, 2012; Coccaro et al., 2011). The dorsolateral and ventrolateral prefrontal cortices, collectively the lateral prefrontal cortex (LPFC), may differentiate mature deliberate versus automatic emotion regulation. In several functional magnetic resonance imaging (fMRI) studies, healthy adults showed stronger LPFC responses, with greater amygdala down-regulation, during deliberate emotion regulation compared to automatic emotion regulation (Ochsner et al., 2004). School-age children (ages 7–13) also showed increased LPFC activation during reappraisal of negative stimuli, with weaker activation compared to adolescents or adults (Silvers et al., 2016), raising the possibility that deliberate emotion regulation's emergence in early childhood depends on a capacity to increase LPFC activation. However, at present, neuroimaging studies of deliberate emotion regulation, and particularly studies that simulate interpersonal scaffolding, have not been extended to children under the age of 6 years.

Our goal was to investigate young children's neural and behavioral changes during deliberate emotion regulation, and how parent-rated temperamental emotion regulation predicted these neural changes, using a novel paradigm that simulated interpersonal scaffolding. Sixty 4 to 6-year-old children were randomly assigned to a deliberate emotion regulation interpersonal scaffolding or a control condition. Children completed a frustration task immediately before and after the interpersonal scaffolding/control condition while LPFC activation was recorded via functional near-infrared spectroscopy (fNIRS). We simultaneously recorded facial expressions via video, and prompted children to self-rate their emotions, during fNIRS recording. Parents rated their child's temperamental emotion regulation prior to the experiment.

We expected that children who received interpersonal scaffolding would be more likely to exert deliberate emotion regulation, and exert it more effectively, compared to children who did not receive interpersonal scaffolding. We expected deliberate emotion regulation exertion to manifest as an increase in LPFC activation accompanied by a decrease in negative facial expressions and improvement in self-rated emotion. We hypothesized that, across groups, children rated by caregivers as being better at recovering from emotional challenges in daily life would show stronger evidence of deliberate emotion regulation in the lab. Given that deliberate emotion regulation is believed to emerge in early childhood, we considered that children in either group could exert deliberate emotion regulation, but expected, at the group level, this process to be significantly boosted by interpersonal scaffolding. We therefore hypothesized that children in the interpersonal scaffolding group would exhibit larger pre-post-increases in frustration-related LPFC activation, and show stronger associations between change in activation and affect, self-rated emotion, and caregiver temperamental emotion regulation, compared to controls. Accordingly, we examined changes in LPFC activation, and associations between change in activation and study variables, in the full sample and in separate groups.

2. Methods

2.1. Subjects

Sixty children between 4 and 6 years ($M = 4.9$ years, $SD = 0.9$) were recruited from the community via flyers and internet advertisements and randomly assigned to deliberate emotion regulation interpersonal scaffolding or control groups. Children were identified by their parents as 50% male, 63% Caucasian, 32% African American, and 5% Asian. Exclusionary criteria were diagnosis of any mental disorder, developmental disability or delay, or history of head trauma with loss of consciousness. Despite random assignment, interpersonal scaffolding group children were older than controls ($t(58) = -2.1$, $p < .05$). Therefore, we controlled for child age in all analyses. Groups did not differ by sex, race, income, or receptive vocabulary score on the Peabody Picture Vocabulary Test, Fourth Edition (Dunn and Dunn, 2012) (all $p > .17$). Experimental procedures were approved by the local Institutional Review Board.

2.2. Questionnaires

Parents completed the *Falling Reactivity/Soothability* subscale of the Child Behavior Questionnaire (CBQ) (Rothbart et al., 2001) as an assessment of their child's emotion regulation from a temperamental perspective. This subscale assesses the child's rate of recovery from a peak distress, excitement, or general arousal (e.g., "changes from being upset to feeling better within a few minutes"). Items were rated on a 7-point scale (1 = Extremely Untrue, 7 = Extremely True). Reliability of the scale was acceptable (α = .72).

2.3. Frustration task

All children first completed a novel frustration task called "Incredible Cake Kids". An animated movie introduced children to a fictional town with a bakery run by "Gus" the baker. Gus explained to children that they had to run the bakery while he ran an errand. The experimenter told children to select the "most delicious cake" to bake for each customer from an array of similar cakes, that selecting correctly was an objective skill, upon which they would be evaluated, and that some children were better at than others. Children completed a practice version of the game to ensure they understood the rules. Next, children completed 30 trials of the Incredible Cake Kids task. For each trial, children saw a cartoon avatar ("the customer") on the screen and three cartoon cakes (See Fig. 1). For each trial, children had two seconds to choose the most delicious cake by touching it, followed by two seconds of "anticipation", and two seconds of positive ("happy") or negative ("grumpy") feedback, which, unbeknownst to the child, was predetermined. If children didn't choose a cake during the two second window, they were shown a "warning" image of an empty cake tray (signifying the customer did not receive a cake) for 2 s and the experimenter prompted the child to choose more quickly. The task comprised 18 negative feedback trials and 12 positive feedback trials. The task was constructed to be an event-related design with choice, anticipation, and feedback comprising positive and negative events separated by a 2–12 second jittered rest period. The task was designed to induce feelings of frustration in young children through repeated, unavoidable negative feedback, similar to frustration paradigms commonly used in older children and adolescents (Deveney et al., 2019, 2013; Perlman and Pelphrey, 2010, 2011). The task used no repeating customers or cakes in order to measure frustration related to negative evaluation as opposed to error response following expectancy violation. Every 10 trials the child was prompted to self-rate their current emotion by choosing from seven cartoon faces ranging from negative to positive affect (Perlman et al., 2015, 2014). The first two emotion self-ratings occurred immediately after a negative trials, and the third emotion-self-rating occurred immediately after a positive trial. Emotion self-rating scores ranged from 1 (most negative) to 7 (most positive) with a score of 4 representing no/neutral affect.

2.4. Deliberate emotion regulation interpersonal scaffolding

2.4.1. Interpersonal scaffolding group

After the Incredible Cake Kids task, interpersonal scaffolding group children completed a novel coloring activity created by the research team designed to simulate highly structured emotion-related psychoeducation (See Fig. 1), such as modules from the "Coping Cat" therapeutic manual and "Second Step" curriculum (Frey et al., 2000; Kendall and Hedtke, 2006). The purpose of the coloring activity was to prime children to think about emotions, and build a common emotion vocabulary across children, so that all participants would understand the prompt to deliberately regulate negative affect (described below). The use of cartoons and coloring provided a developmentally appropriate venue for helping children describe bodily sensations and cognitions associated with emotion with an unfamiliar adult. Children interacted with a post-doctoral clinical psychology trainee with expertise

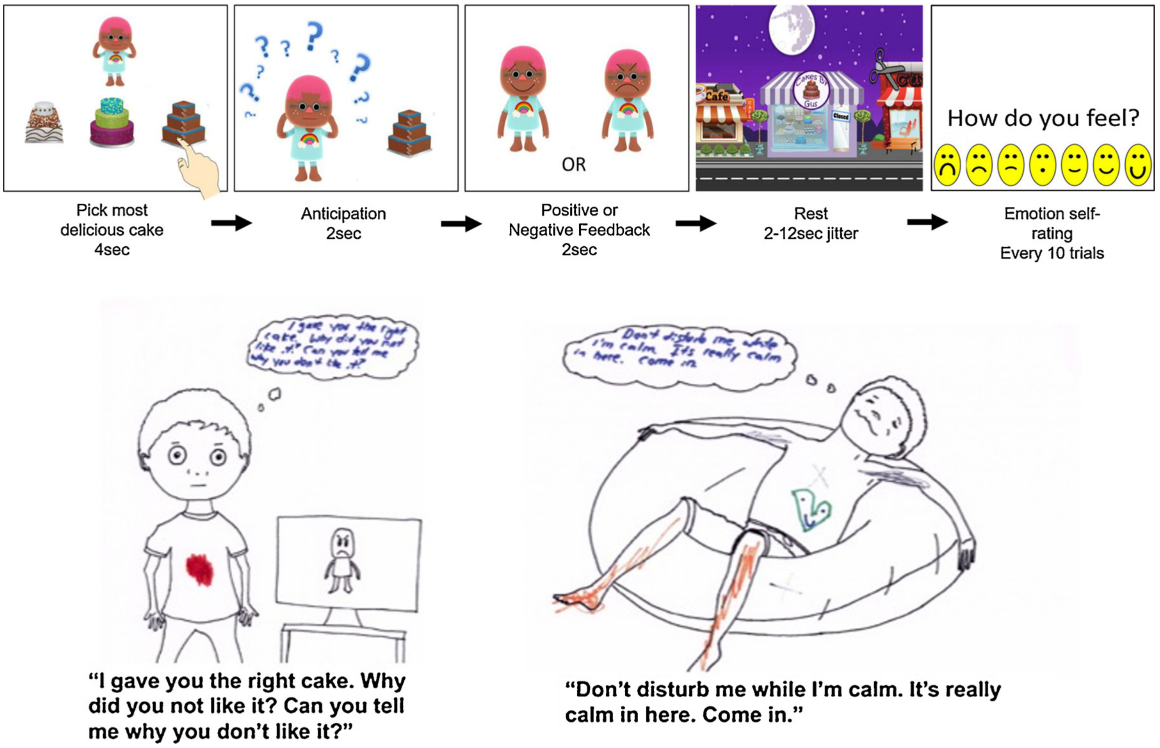

Fig. 1. Top: Depiction of the Incredible Cake Kids Task. Bottom: A child assigned to deliberate emotion regulation therapeutic scaffolding (male, age 5) colors in physiological sensations, and generates cognitions, associated with anger (left) and relaxation (right) during the cartoon game. Children in the control group were given the same cartoons with non-emotion instructions.

treating early childhood psychopathology. Children were shown a cartoon of a child (gender matched, race indeterminate) who saw a grumpy customer in the Incredible Cake Kids game that made them “really angry”. Children were coached to color inside the cartoon’s body for 5 min to indicate where the cartoon child felt the emotion (“Use the markers to show where the boy/girl feels the anger in his/her body”). Next, children were coached to generate ideas about what the cartoon was thinking when they felt angry (“What is the boy/girl thinking when s/he feels angry?”). Children were then given a picture of the same child floating in a swimming pool who is “really relaxed”. For 5 min, children were, again, instructed to color the picture to indicate where the child felt emotion in his/her body and articulate what the child might have been thinking.

2.4.2. Control group

The control condition was designed to mimic interaction with an experimenter through the same child-friendly coloring activity, with no emotion-related discussion. Children assigned to the control condition were given identical cartoons and timing parameters but provided non-emotional instructions (e.g., “Here’s a cartoon but its black and white. You can use these markers to add some color however you’d like”).

2.5. Deliberate emotion regulation measurement

After completing the interpersonal scaffolding/control portion of the study, children were told they would replay the Incredible Cake Kids game again, but with different customers and cakes. Interpersonal scaffolding group children were instructed to deliberately regulate negative affect using vocabulary generated by the child (e.g., “Kids try different things so that the grumpy customers won’t bother them. Some kids try to keep their bodies calm. When they feel anger in their belly (points to child’s anger drawing), they try relaxing their belly, arms, and legs like they’re floating in an inner tube (points to child’s relaxation drawing)”; “Instead of thinking, ‘why don’t they like my cake?’ some kids try thinking ‘I’m calm’”). (See Appendix for full deliberate emotion regulation instructions.) Control children were re-told the original instructions to choose the most delicious cake for each customer. The two Incredible Cake Kids tasks had the same number of positive/negative trials and were counter-balanced across subjects.

2.5.1. fNIRS instrument and analysis

Non-invasive optical imaging was performed using a CW6 fNIRS system (Techen, Inc, Milford, MA) with a probe comprising 4 light-source emitter positions containing 690 nm (12 mW) and 830 nm (8 mW) laser light, and 8 detectors. The average inter-optode distance was 3 cm. As in our previous work (Grabell et al., 2017; Li et al., 2016; Perlman et al., 2015), the probe was positioned per international 10–20 coordinates with the interior medial corner of the probe aligned with FpZ and extended over Brodmann areas 10 (ventrolateral prefrontal cortex) and 46 (dorsolateral prefrontal cortex) on each hemisphere, comprising 10 channels reduced into 4 regions of interest (see Fig. 2). Children sat in front of a touch-screen computer that recorded their responses. Analysis was conducted using the NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018). Data were collected at 20 Hz and re-sampled to 1 Hz. fNIRS data is recorded as changes in the light from a source position incident on a detector position as a function of time. Signals were converted to optical density, and then to oxy- and deoxy-hemoglobin concentration estimates, via the modified Beer-Lambert law with a partial pathlength correction of 0.1. A general linear model was then used to assess task activation. Since the shape of the hemodynamic response was not assumed, a finite impulse response (FIR) model was used to model activation at each second for the 20 s following stimulus onset for each condition in order to visualize when the HRF peak occurred. Coefficient estimates were obtained using the autoregressive iteratively-reweighted least squares (AR-IRLS) approach, as it accounts for serial correlations in the data, including those from systemic physiological and motion artifacts (Barker et al., 2013). Group-level mixed-effects models were used to assess task activation at each time point, and the peak of the HRF response was then identified via visual inspection. Subject-level task effects were then quantified by averaging across this window. All subsequent analyses used these beta values that were time-averaged across the peak of the HRF window. These channel-wise time-averaged coefficients were then averaged across channels within each of the 4 regions of interest.

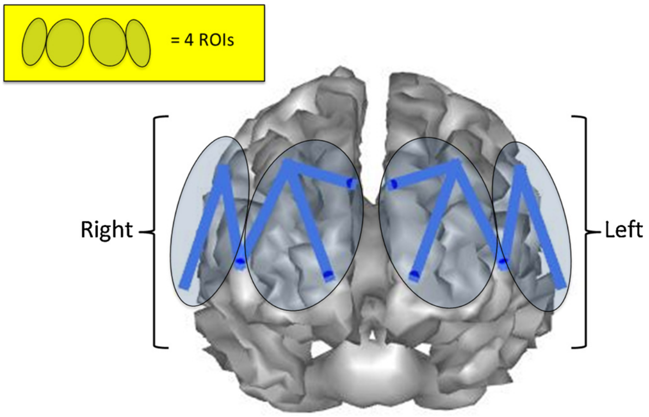

Fig. 2. fNIRS probe superimposed on 3D mesh brain, denoting 10 channels grouped into 4 regions of interest (ROIs), and right and left hemispheres.

2.5.2. Facial coding

Throughout the paradigm facial expressions were recorded using a high definition camcorder mounted above the touchscreen computer. Facial codes comprised a subset of facial movements, or Action Units (AUs), from the Facial Actions Coding System (FACS), an anatomically-based facial coding system (Ekman and Friesen, 1977). Coders were three FACS-trained laboratory members who passed the FACS certification test and a child FACS test custom-designed by our laboratory. Pre- and post-interpersonal scaffolding/control condition videos were separated into distinct files, assigned to coders in a random order, and coded on mute blind whether epochs were win or frustration trials. Coders had no knowledge of the task or the study’s hypotheses and were only assigned subjects with whom they had no previous interaction. Coders denoted the presence or absence of FACS codes for each 2-second feedback window using ELAN software (Brugman et al., 2004). Based on our hypotheses and prior literature on child facial expression (Grabell et al., 2018), the following facial movements were coded and aggregated across negative feedback trials for each Incredible Cake Kids game: brow raiser (AU 1 and 2 combined into a single code), brow lowerer (AU 4), eye constriction (AU 6), nose wrinkler and upper lip raiser (AU 9 and 10 combined into a single code), lip corner depressor (AU 15), lip tightening or pressing (AU 23 and 24 combined into a single code), and jaw drop and mouth stretch (AU 26 and 27 combined into a single code). Videos were double coded by two independent coders. Reliability was calculated as agreement between coders using the formula described in the FACS manual: (Number agreed upon codes) *2/(total number of codes). If agreement for a given video was below 40%, a FACS certified supervisor reviewed the codes to assess for coder drift, retrain coder teams if needed, and reassign the video to the third coder if needed. This process occurred for 5 videos. Fifty-six subjects had codeable videos. One additional subject was removed from facial expression analyses due to low reliability. Overall inter-coder reliability was acceptable (70%).

2.5.3. Analysis strategy

We first examined descriptive statistics of study variables across the entire sample. Next, 2 (time: pre-, post-) by 2 (group: control, manipulation) mixed ANCOVA models, controlling for age, were used to test whether changes in negative feedback-related LPFC activation, self-ratings of emotion, and facial expressions, depended on interpersonal scaffolding. In order to test whether the deliberate emotion regulation condition interacted with negative affect specifically, we also examined pre-post changes in LPFC activation during positive feedback. Finally, Pearson partial correlations controlling for age and scatterplots were used to examine how changes in feedback-related LPFC activation related to changes in child self-rated emotion, facial expressions, and parent-rated emotion regulation competence. We first ran brain-behavior correlations on the entire group, and then performed post-hoc correlations to investigate differences between the manipulation and control group. Hypotheses related to group*time effects were *a priori* to data collection, probed only the LPFC and censored the rest of the cortex, and specified group differences in only one direction. Therefore ANCOVA results are presented with uncorrected p-values and accompanying effect sizes. Hypotheses related to how magnitude of change in LPFC activation was associated with individual differences in behavior and parent ratings of emotion regulation were a priori to data analysis but not data collection and allowed for bi-directional effects. We therefore controlled for multiple comparisons using the FDR correction for these tests. Prior to correlations, we tested for multivariate outliers by calculating Mahalanobis distance and identified subjects with χ^2 values of $p < .001$ (Tabachnick and Fidell, 2007) using SPSS software (IBM, Inc.). We report correlational results with and without multivariate outliers removed.

3. Results

One hundred percent of children completed the entire paradigm and yielded analyzable fNIRS and self-rated emotion data. The number of missed trials across groups and games was very low ($M = 1.3$ missed trials, $SD = 1.9$). Descriptive statistics revealed that, on average and across the entire sample, children produced a negative facial expression on 54% of negative feedback trials the first time they played the Incredible Cake Kids game, and 45% of the negative feedback trials the second time they played, suggesting the game induced negative affect. Self-ratings of emotion revealed, on average, children rated their mood as mildly positive both times they played the game ($M = 5.0$, $SD = 1.5$, range = 2–7). Frequency counts showed this mean was driven by a subset of children (33.3% during the initial game, and 43.3% during the second game) who picked the happiest face every time, even when the rating followed a frustration trial, a pattern common to studies in early childhood (Chambers and Johnston, 2002; Grabell et al., 2017). Within each game, the three emotion self-ratings were moderately to highly positively correlated with each other (smallest correlation: $r = .32$, p = .013; largest correlation: $r = .77$, $p < .001$; see supplemental Table A in Appendix), and a repeated measures ANOVA revealed ratings were not significantly different from each other ($p = .88$). Change in facial expression and change in self-rated emotion were unrelated across or within groups (all *p's* > .54). Based on manual visualization of the HRF peak between and across groups (see Supplementary Fig. A1), we averaged between 3 and 14 s for each subject. An independent-sample *t*-test revealed that control and manipulation groups were not significantly different in their LPFC activation during negative and positive feedback, self-ratings of emotion, or frequency of facial expressions, the first time they played the Incredible Cake Kids game (*p*'s > .16).

3.1. Deliberate emotion regulation interpersonal scaffolding and neural activation changes

Mixed ANCOVAs revealed no main effect of group or time at any ROI for positive or negative feedback (*p*'s > .06) but a significant group*time interaction for negative feedback (F (1, 60) = 5.54, p = .02) and positive feedback (F (1, 60) = 4.33, $p = .04$) in the middle left LPFC (see Fig. 3). Thus, subsequent analyses focused solely on activation in the middle left LPFC ROI. Paired-sample t-tests revealed that interpersonal scaffolding group children showed a significant pre-post increase in negative feedback-related LPFC activation in the middle left LPFC ($t(115) = 2.68$, $p = .008$) whereas control children showed no change in activation ($p = .49$). Interpersonal scaffolding group children also showed a significant pre-post increase in positive feedback-related LPFC activation in the middle left LPFC (t (115) = 2.17, $p = .03$) whereas control children showed no change in activation ($p = .44$). Pre-post interpersonal scaffolding/control changes in feedback-related LPFC activation were significantly different between groups for negative ($t(115) = 2.38$, $p = .02$) and positive (t (115) = 2.08, $p = .04$) feedback.

3.2. Deliberate emotion regulation interpersonal scaffolding and behavior changes

3.2.1. Emotion self-rating

The three emotion ratings within each Incredible Cake Kids game were averaged. A 2-way repeated measures ANCOVA, with group as a between-subjects factor, showed no main effect of group ($p = .60$), time ($p = .11$), or group*time interaction ($p = .59$).

3.2.2. Facial expression

A 2 (positive, negative feedback) by 2 (pre-post) repeated measures ANCOVA, with group as a between-subjects factor, revealed no main effect of feedback ($p = .39$), and a marginal effect of time (F (1,52) = 2.99, $p = .09$), such that children showed a non-significant trend of displaying less negative affect the second time they played the Incredible Cake Kids game than the first time. There was a significant feedback*time (F(1,52) = 4.68, $p = .035$) interaction. Post-hoc paired sample t-tests revealed, across the entire sample, that children produced significantly more frequent negative affect during negative feedback than positive feedback the first ($t(54) = 4.65$, $p < .001$) and second ($t(54) = 5.45$, $p < .001$) time they played the Incredible Cake Kids game and showed a significant decrease in negative expressions during negative feedback (t(54) = 2.05, $p = .045$), but not positive feedback ($p = .09$) between games. There was also a significant feedback by time by group interaction (F(1,52) = 4.62, $p = .036$).

Paired sample t-tests examining pre-post scaffolding or control condition changes, run separately by group, revealed that control children showed a marginal decrease in negative expressions during negative feedback (t(54) = 1.79, $p = .08$) not seen in the manipulation group ($p = .30$). In contrast, manipulation group children showed a marginal decrease in negative expressions during positive feedback (t (54) = 1.98, $p = .056$) not seen in the control group ($p = .63$). However, independent sample t-tests revealed no significant group difference in negative expression at either time point or for either type of feedback (*p's* > .29). In other words, the three way interaction was driven by control and manipulation group children exhibiting decreases in negative affect for different types of feedback, but these decreases were marginal, and did not result in group differences in facial expression frequency (see Supplemental Figure B in Appendix).

3.3. Association between change in feedback-related LPFC activation and change in behavior

3.3.1. Self-rated emotion

Prior to performing Pearson partial correlations controlling for age, two subjects, one control and one manipulation, were identified as multivariate outliers. When the outliers were included, Pearson partial correlations showed negative feedback-related middle left LPFC activation was unrelated to change in self-rated emotion for the entire sample ($p = .38$), or either group (*p's* > .63). Associations remained non-significant when outliers were excluded. Changes in middle left LPFC activation during positive feedback were unrelated to self-rated emotion for the entire sample, or either group, regardless of whether

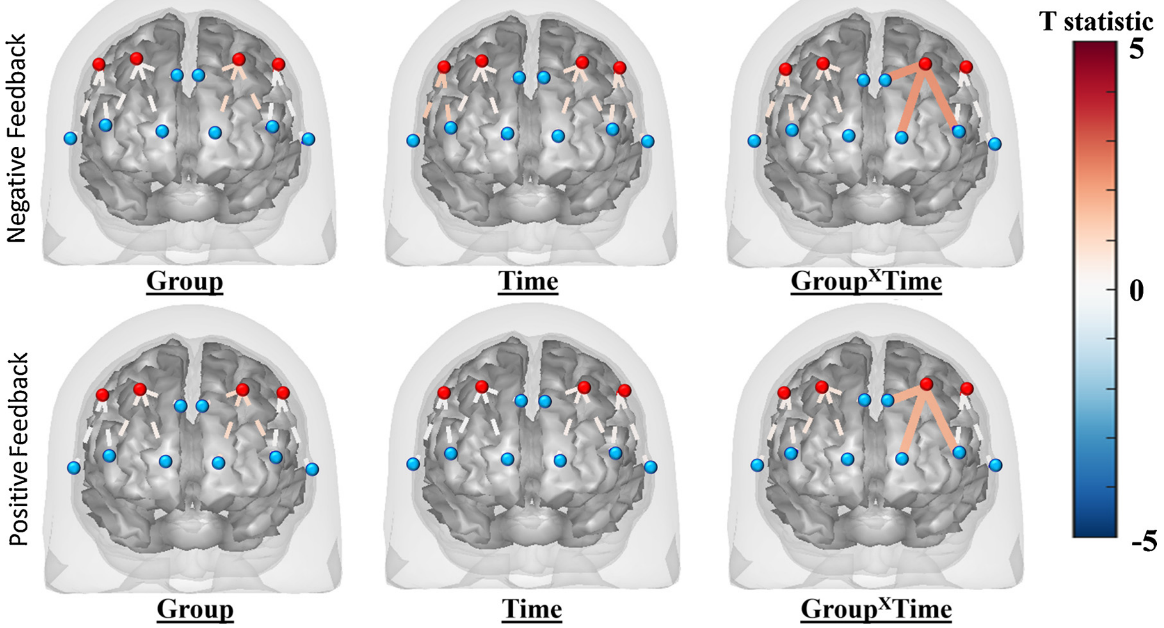

Fig. 3. Results of mixed ANCOVAs testing effects of group assignment, time, and group by time interaction on changes in LPFC oxygenated hemoglobin during positive and negative feedback, controlling for child age. Source detector pairs comprise regions of interest superimposed on a 3D mesh brain with solid lines indicating significant effects.

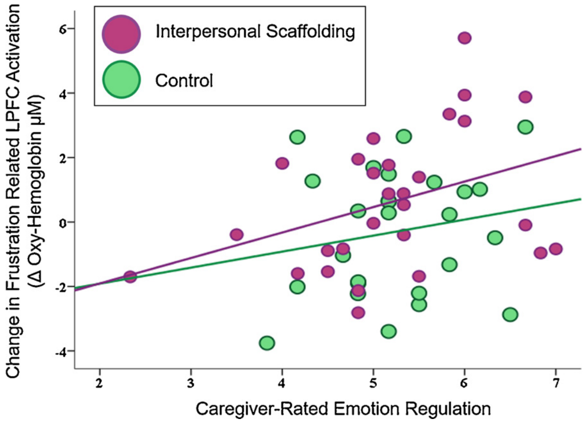

Fig. 4. Scatterplot showing association between change in middle left LPFC activation during negative feedback and caregiver-ratings on the CBQ Falling Reactivity scale.

outliers were included or excluded (*p*'s > .18).

3.3.2. *Facial expression*

Prior to performing Pearson partial correlations, one control subject was identified as a multivariate outlier. When the outlier was included, Pearson partial correlations for the entire sample showed that pre-post changes in middle left LPFC activation during negative feedback were marginally inversely related to changes in facial expression, such that increases in activation predicted decreases in negative affect at the $p = .055$ level ($r = -.26$). When split by group, controls showed a significant inverse partial correlation ($r = -.43$, $p = .012$) that manipulation children did not ($p = .30$), though this was not significant at $q < .05$ after correcting for multiple comparisons. However, when the multivariate outlier was excluded, neither the entire sample ($r = -.02$, $p = .45$), nor the control group ($r = -.19$, $p = .33$), showed a significant partial correlation between change in activation and change in facial expression. A scatterplot revealed the multivariate outlier exhibited both the highest increase in activation and largest decrease in negative expression in the control group, thus exerting inordinate leverage over the slope. Changes in middle left LPFC activation during positive feedback were unrelated to change in negative expression for the entire sample, or either group, regardless of whether outliers were included or excluded (*p*'s > .53).

3.4. *Caregiver-rated temperamental emotion regulation and negative feedback-related LPFC activation*

Prior to performing Pearson correlations, one control subject was identified as a multivariate outlier. When the outlier was included, Pearson partial correlations showed, for the full sample, a positive association between caregiver-rated temperamental emotion regulation and change in middle left LPFC activation, with medium effect size ($r = .34$) significant at $p = .005$ but not $q < .05$ after correcting for the total number of correlation tests performed. The association was such that children rated by caregivers as having an easier time recovering from an emotional challenge relative to peers tended to have larger pre-post increases in left LPFC activation. Post-hoc correlations revealed, for the manipulation group, caregiver-rated temperamental emotion regulation was also significantly positively associated with pre-post change in middle left LPFC activation, with medium effect size ($r = .35$) at the $p = .03$ but not $q < .05$ level after correcting for the total number of correlation tests performed (see Fig. 4). In contrast, there was no association between caregiver-rated emotion regulation and change in left LPFC activation within the control group ($r = .15$, $p = .21$). This pattern of results held regardless of whether the multivariate outlier was excluded or included. Changes in middle left LPFC activation during positive feedback were unrelated to parent-rated temperamental emotion regulation for the entire sample, or either group, regardless of whether outliers were included or excluded (*p*'s > .16).

4. Discussion

Deliberate emotion regulation is a skill necessary for successful social, academic, and behavioral functioning across the lifespan (Eisenberg et al., 2014) and is hypothesized to emerge and develop rapidly during the early childhood period (Kopp, 1989; Zelazo and

Cunningham, 2007). This study begins to provide a mechanistic science base for the widely disseminated home- and school-based programs designed to improve young children's deliberate emotion regulation (Morris et al., 2014; Rasmussen et al., 2018), important for further tailoring and specification of effects. Therefore, our goal was to elucidate the characteristics of emerging deliberate emotion regulation in early childhood, particularly its neural basis, using a novel task designed to replicate the interpersonal scaffolding a child would receive from an adult (e.g., parent, teacher). Deliberate emotion regulation interpersonal scaffolding was associated with a significantly larger increase in LPFC activation during negative feedback relative to the control condition, suggesting even brief interpersonal scaffolding may elicit changes in neural activation in young children. Children who were rated by caregivers as having better temperamental emotion regulation compared to peers showed the largest increase in LPFC activation during negative feedback following interpersonal scaffolding. Deliberate emotion regulation interpersonal scaffolding was also linked with increases in LPFC activation during positive feedback, but the effect size was smaller relative to negative feedback, and this activation did not predict any study variable. Counter to our hypotheses, deliberate emotion regulation scaffolding was not associated with changes in children's self-ratings of emotion (which, as described below, may relate to the utility of these ratings in very young children). We detected a feedback type by time by group interaction suggesting deliberate emotion regulation interpersonal scaffolding related to changes in frequency of affective expression, although no single post-hoc independent sample or paired sample *t*-test reached significance, suggesting these changes may not have been particularly robust. Given the present study is, to our knowledge, the first to examine in-vivo neural and behavioral changes of deliberate emotion regulation in children this young, both the significant and null findings advance an understanding of this skill needed for the field to build a core knowledge base.

The present findings suggest both continuity and discontinuity with reports of deliberate emotion regulation in older children and adults, advancing a template of deliberate emotion regulation "competence" during the developmental window when this nascent skill is hypothesized to emerge. The first investigations into the neural basis of deliberate emotion regulation employed fMRI in adults presented with negative emotion-inducing images (Ochsner and Gross, 2008). These studies found that adults prompted to exert a deliberate emotion regulation strategy, such as reappraisal, showed significantly greater LPFC activation, and reduced amygdala activation, compared to subjects prompted to view images naturally (Ochsner and Gross, 2005). McRae and colleagues subsequently found evidence that deliberate emotion regulation related to significantly greater LPFC activation in a sample ranging from 10 to 22 years (McRae et al., 2012). However, LPFC activation had a negative linear relation with age, such that children showed significantly smaller activation than adults, raising the possibility that, if the negative linear trend continued into early childhood, deliberate emotion regulation-specific neural activation could be absent or unmeasurable. The present study is, to our knowledge, the first direct evidence that a capacity to increase LPFC activation following deliberate emotion regulation prompting is present in the early childhood years and relates to individual differences in temperamental emotion regulation. The preschool and kindergarten years are characterized by a transition to more complex classroom environments and peer interactions (Ramey and Ramey, 2010) that present new emotion regulation demands (Cowan and Heming, 2005) and portend later social and academic functioning (Entwisle and Alexander, 1993; Zulauf et al., 2018). Early deliberate emotion regulation competence may depend on unique, measurable, prefrontal activation related to formulating and executing an emotion regulation strategy, while delays or weaknesses in the emergence of this activation may signal impairment. Further, the early childhood years are a period of neural plasticity, and specifically, substantial growth and myelination of the LPFC (Giedd et al., 1999), suggesting early childhood may be a window when the systems underlying deliberate emotion regulation are more amenable to input from the environment.

However, fMRI studies of deliberate emotion regulation in older children and adults also found significant group differences in self-ratings of emotion, such that deliberate emotion regulation was associated with improved self-reported mood (Ochsner and Gross, 2005). This self-rated emotion finding did not replicate in our sample of 4–6 year olds, and thus we must carefully consider the meaning of observed changes in LPFC activation given the role of this region in myriad self-regulatory functions (Miller and Cohen, 2001). Pediatric assessment researchers have long found that children under the age of 6 years are unable to reliably monitor their own emotions (Zeman et al., 2007), and tend to provide extreme responses when presented with Likert choices of emotional states (Chambers and Johnston, 2002), consistent with self-rating data reported here and in our previous work (Grabell et al., 2017). Notably, we found that children produced frequent negative facial expressions the first and second time they played the Incredible Cake Kids game, and these negative expressions occurred more during negative feedback than positive feedback, suggesting the task elicited negative emotion as designed. We contend, then, that changes in LPFC activation most likely reflect emotion regulation processes. For example, a scenario in which children, despite receiving explicit instructions to exert deliberate emotion regulation, spontaneously chose to engage in a completely non-emotional cognitive function instead (e.g., sorting, working memory), while also producing negative facial expressions, seems improbable. Moreover, we found a feedback type by time by group interaction, suggesting that changes in negative facial expressions were dependent on whether children received interpersonal scaffolding. However, unpacking this interaction did not clearly support our hypotheses, as control and manipulation children appeared to decrease frequency of negative facial expressions at different rates for different feedback types, yet post-hoc t-tests did not exceed the alpha threshold for significance. One possibility is that the facial expression data were too noisy to detect more nuanced effects, as evidenced by the fact that changes in facial expressions were uncorrelated with change in neural activation, self-ratings of emotion, or parent-rated temperamental emotion regulation. Given the present study had a relatively modest sample size, it may have been underpowered to detect facial expression group differences and associations with other variables. Across levels of analyses, the present findings raise the possibility that, in laboratory settings, emerging deliberate emotion regulation may be measurable at the neural level before it becomes reliably measureable at the behavioral level.

Although our findings may represent a significant advancement in the study of early deliberate emotion regulation, and offer important methodological points for future research in this area, they also highlight long-standing challenges to measuring emotion processes in humans. While we rejected the null hypothesis that LPFC activation was unrelated to deliberate emotion regulation interpersonal scaffolding in early childhood, there are several interpretations of what this neural activation means. LPFC activation could plausibly reflect myriad executive functions ranging from low to high integration with directly modulating negative affect, from inhibitory control to suppress negative emotion-driven impulses, working memory to hold the "don't get mad" rule in mind, to changes in self-narration during the task. Consistent with the broad field of emotion research, various explanations are possible due to an inherent of a lack of ground truth to unequivocally know the internal motivations and emotion states of human subjects, a major topic of discussion in emotion research (Barrett, 2015) that extends to all methods of acquiring emotion data (self-report, behavioral observation, psychophysiological, etc.) (Schorr, 2001), and dates to the earliest psychological investigations of emotion (Lange and James, 1922). Moreover, consciously activating a deliberate emotion strategy by definition involves higher integration of these executive functions, relative to automatic emotion regulation (Zelazo and Cunningham, 2007), that may vary significantly from child to child (Kopp, 1989). We therefore contend the increased LPFC activation observed after deliberate emotion regulation scaffolding likely reflects a heterogeneous mixture of EF processes that may be proximal to negative emotion, such as suppressing intense anger, or more distal, such as a reappraisal strategy to prevent onset of negative emotion to begin with.

Unpacking the heterogeneity of this neural signal is a challenging and exciting next step for pediatric emotion regulation researchers. Results of the present study suggest our novel task was tolerable to young children and produced a neural signal distinct to deliberate emotion regulation interpersonal scaffolding versus the control condition. Future studies building off of our paradigm may be able to further parse the meaning of this signal by measuring concurrent psychophysiological changes, such as heart rate and galvanic skin response, that correspond to limbic system activation (Critchley et al., 2000), and investigating children's articulated emotion regulation strategies in more detail. Future research can also further parse this signal through additional experimental manipulations, such as comparing children who received different emotion regulation prompts (e.g., self-narration vs. relaxed breathing), and including a control group prompted to keep a non-emotion regulation-related rule in mind. Relatedly, deliberate emotion regulation interpersonal scaffolding comprises multiple components that may differentially contribute to immediate changes in neural activation and long-term shaping of deliberate emotion regulation. In the present study, similar to disseminated deliberate emotion regulation programs (Kendall and Hedtke, 2006), children were given psychoeducation about emotion labels, explored physiological sensations and cognitions associated with emotions, provided psychoeducation about myriad deliberate emotion regulation strategies, and prompted to come up with and exert their own strategy. Which of these scaffolding components are "active ingredients" to shaping emotion regulation, how these components work together, and which children are most likely to benefit from which components, are critical future research questions that directly relate to more tailored early emotion regulation interventions.

Finally, the present study provides a framework for future research to examine in greater detail how emotion regulation is shaped by adults during early childhood. Here, we detected neural changes in young children exposed to very brief interpersonal scaffolding following a short, mild, frustration challenge that was not expected to produce lasting changes in participants as one would expect from a multi-session intervention. Children in the present study did not acquire an explicit emotion regulation skill, such as diaphragmatic breathing or reappraisal. Rather, the interpersonal scaffolding with the clinical psychology trainee helped children build an emotion vocabulary and primed them to receive instructions to deliberately regulate emotion with whatever strategy they thought would work. A measurable neural change to brief scaffolding sets the stage to understand how the developing brain is shaped by sustained scaffolding from caregivers and teachers on a daily basis (Denham et al., 2012; Taylor et al., 2013), and by education and mental health professionals through emotion-regulation based interventions (Domitrovich et al., 2005; Havighurst et al., 2010; Kovacs et al., 2006). That children rated as having the most difficulty recovering from emotional challenges also had the weakest neural response to scaffolding raises the possibility that, in clinical practice, children with more deficient emotion regulation may benefit less, initially, from psychotherapy-based scaffolding. More intervention-focused studies are required to investigate potentially important individual differences in children's behavioral and neural responses interpersonal scaffolding that could be used to optimize early intervention. This is particularly relevant and needed given the mixed efficacy of interventions designed to train and strengthen emotion regulation in preschoolers (Morris et al., 2014). For example, developing brief response-to-scaffolding assessments capable of measuring baseline levels of this skill could help clinicians forecast, prior to treatment, the likelihood a young child might benefit from an emotion regulation scaffolding treatment, such as CBT, or the dosage required to achieve a clinically meaningful effect. Future iterations of this line of research may therefore elucidate how early, abnormal, responses to interpersonal scaffolding of deliberate emotion regulation, accompanied by weaker cortical activation, can be repaired.

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Declaration of Competing Interest

Drs. Grabell, Huppert, Fishburn, Li, Wakschlag, and Perlman, and Ms. Hlutkowsky and Jones, report no competing interests.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.dcn.2019.100708.

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