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Using facial muscular movements to understand young children's emotion regulation and concurrent neural activation

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Abstract

Individual differences in young children's frustration responses set the stage for myriad developmental outcomes and represent an area of intense empirical interest. Emotion regulation is hypothesized to comprise the interplay of complex behaviors, such as facial expressions, and activation of concurrent underlying neural systems. At present, however, the literature has mostly examined children's observed emotion regulation behaviors and assumed underlying brain activation through separate investigations, resulting in theoretical gaps in our understanding of how children regulate emotion *in vivo*. Our goal was to elucidate links between young children's emotion regulation-related neural activation, facial muscular movements, and parent-rated temperamental emotion regulation. Sixty-five children (age 3–7) completed a frustration-inducing computer task while lateral prefrontal cortex (LPFC) activation and concurrent facial expressions were recorded. Negative facial expressions with eye constriction were inversely associated with both parent-rated temperamental emotion regulation and concurrent LPFC activation. Moreover, we found evidence that positive expressions with eye constriction during frustration may be associated with stronger LPFC activation. Results suggest a correspondence between facial expressions and LPFC activation that may explicate how children regulate emotion in real time.

RESEARCH HIGHLIGHTS

- Early emotion regulation forecasts myriad developmental outcomes, but difficulty discerning underlying emotion regulation processes from overt behavior is a longstanding methodological problem.
- We measured children's frustration-related facial muscular movements and lateral pre-frontal cortex activation, and parent-rated temperamental emotion regulation, to better understand the in-vivo dynamics of emerging emotion regulation.
- Negative facial expressions that included eye constriction were related to weaker concurrent frustration-related lateral prefrontal cortex activation and lower parent ratings of emotion regulation.
- Findings suggest that the lateral prefrontal cortex supports emotion regulation through modulating frustration at its onset, as evidenced

by control of facial display, a correspondence that may explicate how children regulate anger in real time.

1 | INTRODUCTION

Better frustration regulation early in life predicts fewer behavior problems, healthier friendships, and higher academic achievement later in development (Mischel, Shoda, & Peake, 1988). *How* children regulate anger during frustration challenges, which are blocked goals or rewards (Berkowitz, 1989), has therefore been an area of intense interest in the developmental and clinical literatures (Gross, 2008). A long-standing methodological problem for emotion researchers, however, is disentangling emotional reactivity (the onset of emotion) from emotion regulation (the modulation of emotion) based on overt behavior alone (Gross & Thompson, 2007). For example, consider a young child who expresses very little anger when told to stop playing in order to clean up. The child's affective presentation may reflect good emotion regulation, or the child may have simply felt little frustration to begin with. Emotion regulation is hypothesized to comprise simultaneous behavioral and neural responses (Goldsmith, Pollak, & Davidson, 2008) suggesting that multi-modal approaches may explicate anger regulation *in vivo*. At present, however, studies have not linked simultaneously occurring neural and behavioral components, in the same paradigm, in real time, in young children. In the present study, we examined young children's facial expressions, a complex behavioral response to emotion, and neural activation resulting from the same frustrating event, and tested associations with parent ratings of temperamental emotion regulation.

Facial expressions have been studied by psychologists to elucidate children's emotional states and emotion regulation strategies, with much of this work carried out from the 1970s through the 1990s (Camras et al., 1990; Cole, 1986; Saarni, 1979; Zeman & Garber, 1996). One line of inquiry has focused on changes in children's facial expressions following emotional challenges to infer individual differences in emotion regulation. For example, preschoolers required to wait for a cookie showed less angry facial displays when distracting themselves compared to when focusing on the delay, suggesting that self-distraction may be an early, effective, emotion regulation strategy (Gilliom, Shaw, Beck, Schonberg, & Lukon, 2002). Another line of inquiry has focused on how individual facial muscles contract to form expressions conveying different levels of emotional salience. Much of this work has focused on the orbicularis oculi, or "eye constriction", the outer ring of muscle around the eye (see Figure 1). Eye constriction during smiling creates the "Duchenne smile" believed to be a more intense expression of joy (Duchenne de Bologne, 1990). More recent evidence suggests that eye constriction may be an intensifier of both positive and negative emotions. For example, infant eye constriction has been associated with stronger smile and cry-faces that are rated as more intense by independent observers (Mattson, Cohn, Mahoor, Gangi, & Messinger, 2013; Messinger, Mattson, Mahoor, & Cohn, 2012).

The advent of functional neuroimaging techniques, specifically fMRI, allowed researchers to study emotion and emotion regulation-related neural activation in the brain, resulting in escalating empirical interest from the mid-1990s to the present day (Lane et al., 1998; Ochsner & Gross, 2008). This research has led to a model of frustration as comprising reward, reactive aggression, and regulatory neural systems (Coccaro, Sripada, Yanowitch, & Phan, 2011), including decreased ventral striatum activation, and increased amygdala, hypothalamus, anterior insula, and periaqueductal grey activation, coupled with increased activation of various prefrontal cortex regions (Abler, Walter, & Erk, 2005; Yu, Mobbs, Seymour, Rowe, & Calder, 2014). Prefrontal cortex activation including dACC, orbitofrontal, and dorso and ventro medial and lateral areas are hypothesized to reflect modulation of salient frustration (Blair, 2016; Perlman et al., 2015). The dorsolateral (DLPFC) and ventolateral (DLPFC) prefrontal cortices, specifically, are hypothesized to support frustration regulation (Coccaro et al., 2011). The DLPFC is implicated in the development of myriad executive functions, including inhibition (Durston et al., 2002), attentional shifting (Adleman et al., 2002) and working memory (Perlman, Huppert, & Luna, 2016) that may be mobilized to manage emotional challenges in early childhood (Zelazo & Carlson, 2012; Zelazo & Cunningham, 2007). Similarly, the VLPFC is hypothesized to down-regulate negative emotion via top-down connections with subcortical structures, including the amygdala, to modulate the threat response (Wager et al., 2008). Perlman and colleagues (2014) probed portions of the DL and VLPFC (collectively, the lateral prefrontal cortex (LPFC)) in typically developing preschoolers and found stronger LPFC

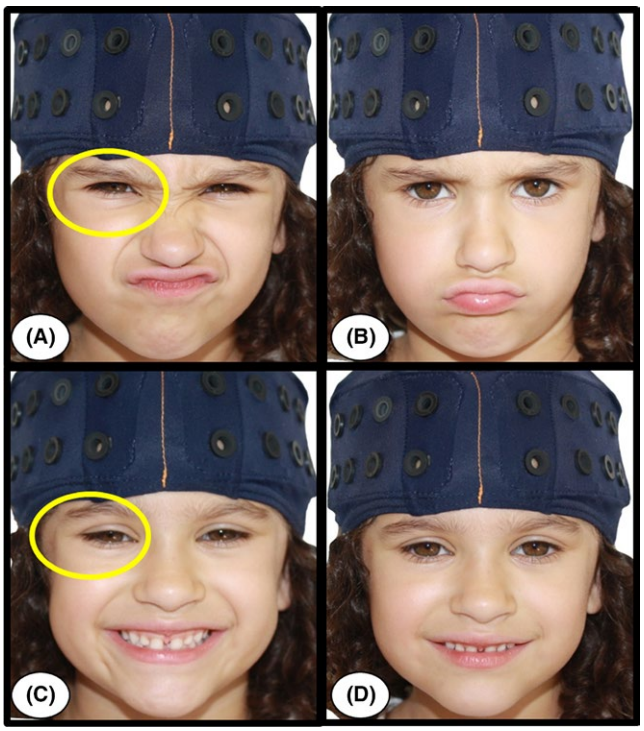

FIGURE 1 Examples of negative expressions with (A) and without (B) eye constriction (highlighted in yellow), and positive expressions with (C) and without (D) eye constriction [The author(s) have obtained the individual's or parent's/guardian's free prior informed consent to publish this image.]

responses during frustration, suggesting that this region is important for frustration modulation in early childhood.

LPFC activation occurring at frustration onset is hypothesized to underpin the facial expressions children display when regulating emotion in everyday life (Simonds, Kieras, Rueda, & Rothbart, 2007). Thus, the co-occurrence of LPFC activation and facial expressions may elucidate whether specific expressions reflect emotion regulation as opposed to low emotional reactivity. In a series of studies, Fox, Ekman, Davidson, and colleagues (Davidson, Ekman, Saron, Senulis, & Friesen, 1990; Ekman, Davidson, & Friesen, 1990; Fox & Davidson, 1988) found that facial expressions following positive and negative emotion induction were associated with EEG asymmetry. In both infants and adults, positive expressions during positive stimuli were associated with left hemisphere asymmetry, and negative expressions during negative stimuli were associated with right hemisphere asymmetry, supporting the differential involvement of the two hemispheres in approach and withdrawal motivations. Moreover, which muscles contracted to make expressions were associated with these EEG patterns such that smiling more strongly related to left-sided asymmetry when eye constriction was present compared to smiles where eye constriction was absent. More recent work by Heller and colleagues showed, in healthy adults, that contraction of the corrugator muscle while viewing negative pictures was associated with greater concurrent amygdala activation (Heller, Lapate, Mayer, & Davidson, 2014). These studies demonstrate the potential to infer neural activation from facial display, and that specific facial muscles, notably eye constriction, might be essential to making these inferences. If greater LPFC activation and lower expressed anger reflect heightened regulation of frustration, it would suggest an inverse relation between the two. Moreover, if eye constriction is an emotion intensifier that more accurately signals true distress, individual differences in the contraction of this muscle during frustration may saliently relate to underlying LPFC activation.

As technological advancements have been made, the field has moved towards multi-modal assessment to investigate questions of emotion regulation from the combined neural and behavioral perspectives. Functional near-infrared spectroscopy (fNIRS), a neuroimaging technology growing in popularity in psychological fields (Scholkmann et al., 2014), is uniquely suited for multi-modal research questions. Unlike functional magnetic resonance imaging (fMRI) and event-related potential (ERP), fNIRS is less sensitive to motion artifacts related to physical subject movement through the environment and allows the face to be easily viewed (Strangman, Boas, & Sutton, 2002). Simultaneous recordings of LPFC activation and facial expression may significantly clarify the real-time mechanics of emotion regulation and more accurately identify facial expressions that signal that emotion regulation is occurring. In the present study, we examined 65 typically developing children between 3 and 7 years who completed a well-validated and child-friendly computer task (Perlman, Luna, Hein, & Huppert, 2014; Grabell et al., 2017) that elicited frustration while LPFC activation was recorded via fNIRS and facial expressions were recorded via video. Parents rated their child's temperamental emotion regulation. We hypothesized that frequency of negative expression during frustration would be inversely associated with both magnitude of concurrent LPFC activation and temperamental ratings of emotion regulation. We further hypothesized that associations between negative facial expressions, temperamental emotion regulation, and LPFC activation would be stronger when expressions included eye constriction.

2 | METHODS

2.1 | Subjects

Young children between the ages of 3 and 7 years were recruited from the local community via paper and internet advertisements. Exclusionary criteria were diagnosis of any mental disorder, mental retardation or developmental delay, or history of head trauma with loss of consciousness. Two children were excluded from analyses due to a technical error. In addition, 11 children were removed from analyses because facial expressions could not be observed and coded for greater than 75% of the video (e.g., child moved out of the frame after recording began). The final sample included 65 children between 3 and 7 years (M = 5.04 years, SD = 1.3), 51% male, 72.3% Caucasian, 23.1% African American, and 4.6% Asian; 6.2% identified as Hispanic/Latino. Power analyses indicated that the sample size (n = 65) provided adequate power ($1 - \beta > .85$) to detect hypothesized associations between facial expressions, parent ratings of temperamental emotion regulation, and LPFC activation. Estimated effect sizes were based on previous literature showing that associations between LPFC activation and parent ratings of temperament (Perlman et al., 2014), and infant's facial expression and perceived emotional valence (Messinger et al., 2012), had moderate to large effect sizes.

2.2 | fNIRS instrument and analysis

2.2.1 | Set-up

As described in previous reports (Grabell et al., 2017; Perlman et al., 2016; Perlman et al., 2014; Li, Grabell, Wakschlag, Huppert, & Perlman, 2017) non-invasive optical imaging was performed using a CW6 real-time fNIRS system (Techen, Inc., Milford, MA). The fNIRS probe comprised four light-source emitter positions containing 690 nm (12 mW) and 830 nm (8 mW) laser light, and eight detectors, mounted within a child-friendly elastic cap. The average inter-optode distance was 3 cm. The probe was positioned per international 10–20 coordinates such that the interior medial corner of the probe was aligned with FpZ. The probe was designed to extend over Brodmann areas 10, the ventrolateral prefrontal cortex, and 46, the dorsolateral prefrontal cortex, on each hemisphere using AtlasViewer software (Aasted et al., 2015). Given the reduced spatial sensitivity of fNIRS compared to fMRI, we describe this region as the "LPFC", consistent with our prior studies (Perlman et al., 2016; Perlman et al., 2014). As described in Okamoto et al. (2004), individual differences in head circumference have a negligible effect on how the probe is positioned over the cortical region of interest for each subject. Children were seated in front of a touch-screen computer that recorded their responses.

2.2.2 | Acquisition and analysis

Data were collected at 20 Hz and down sampled to 4 Hz using a custom-built Matlab-based (Mathworks, Natick, MA) acquisition software program (Barker, Aarabi, & Huppert, 2013). fNIRS data are recorded as changes in light from a source position incident on a detector position as a function of time. Signals are first converted to changes in optical density (ΔOD) over time as given by $\Delta OD(t) = -\log(I(t)/I_0)$ where $I(t)$ is the intensity of the signal recorded and I_0 is the reference signal intensity at baseline. The optical density signals are converted to oxy- and deoxy-hemoglobin estimates via the modified Beer-Lambert law with a partial pathlength correction of 0.1 for both wavelengths (e.g., DPF = 6 and partial volume factor = 60). The time-course of hemoglobin changes for each source-detector pair was analyzed using a general linear model $\Delta[Hbx] = X^*\beta + \varepsilon$, where X is the design matrix encoding the timing of stimulus events and β is the coefficient (weight) of that stimulus condition for that source-detector channel. The design matrix (X) was constructed from the convolution of the stimulus timing and duration with a canonical response model (see details in Barker et al., 2013).

To reduce effects of motion artifacts and systemic physiology, we used an iteratively auto-regressively whitened, weighted least-squares (AR-iRLS) model to solve the general linear equation (Barker et al., 2013). This regression model uses an nth order auto-regressive (AR) filter determined by an Akaike model-order (AIC) selection to whiten both sides of the GLM expression. In brief, this model uses an iterative procedure to whiten serially correlated noise and reweight statistical outliers using a robust regression procedure using a bi-square weighting function. This reweighting reduces the impact of motion artifacts since these points are generally statistical outliers from a normal distribution following autoregressive whitening. Using this model, the regression coefficients (β) and their error-covariance (Cov_β) is estimated, which is used to define statistical tests between task conditions or baseline. The regression model is solved sequentially for each data file for each subject. All source-detector pairs within a file are solved concurrently yielding a full covariance model of the noise, which is used in group-level analysis.

Group-level analyses were performed using generalized linear mixed-effects models, which can accommodate non-normal distributions that are typical of behavioral data (Lo & Andrews, 2015; McCulloch, 1997), using the task-related regression weights (β) from the first-level GLM as the dependent variable. A modified version of the Matlab function fitLME (linear mixed-effects model estimator) was used to solve the weighted maximum likelihood estimate of the parameters. The model was whitened using the error-covariance (Cov) of the first-level GLM model.

2.3 | Questionnaires

We operationalized parent ratings of their child's emotion regulation from a temperamental perspective. Here, we use Rothbart's definition of temperament as individual differences in children's emotional, motor, and attentional reactions to their environment, including recovery from emotional reactivity (Rothbart, 2007). Parents rated their child's temperamental emotion regulation using the Falling Reactivity subscale of the Child Behavior Questionnaire (Rothbart, Ahadi, Hershey, & Fisher, 2001). 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).

2.4 | FETCH task

The Frustration Emotion Task for Children (FETCH) (Perlman et al., 2016; Perlman et al., 2015) is a validated frustration induction task that is tolerable to young children and stimulates LPFC activation. Prior to starting the task, children were shown three boxes: a blue box containing exciting and attractive toys, a red box containing small stickers, and a yellow box containing a single broken crayon. Children were asked to rate their most and least preferred prize box similar to previously used paradigms designed to set up the expectation that children would receive their desired prize (Cole, Zahn-Waxler, & Smith, 1994; Saarni, 1979). Children were told that how well they did in the game would determine from which box they would choose their final prize at the end. During the task (see Figure 2) the child competed with Sparky, "a very sneaky dog", to fetch bones by touching the bone as it appeared on the screen.

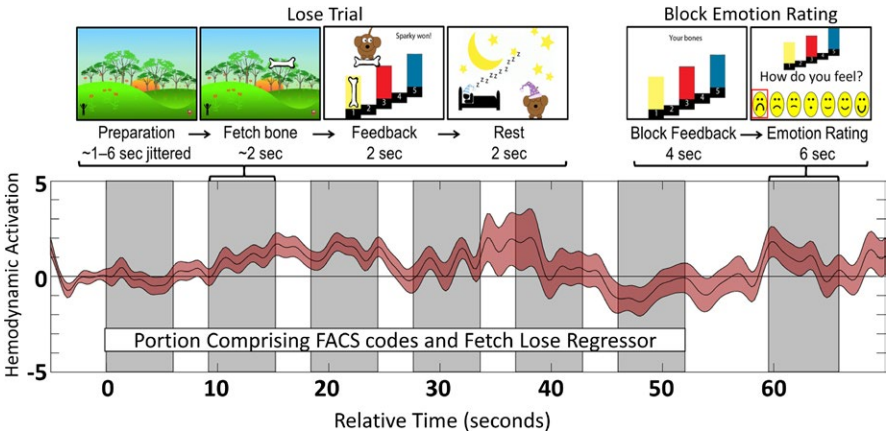

FIGURE 2 Depiction of a Frustration Emotion Task for Children (FETCH) frustration block. Individual trials and emotion rating shown in gray bars, and average hemodynamic activation with standard error shown in red. Hemodynamic activation depicted represents the average of channels that reached significance in the subject-level models. The duration of all trials comprised the FACS coding window and Fetch Lose regressor

Unbeknownst to the child, each trial was fixed where sometimes the child could fetch the bone before Sparky (win trials), but sometimes Sparky would fetch the bone before the child's possible reaction time (frustration trials). Win trials were indicated by an animated drawing depicting the child grabbing the bone and placing it within one of five boxes indicating progression towards the most desired reward (the blue box). Frustration trials showed Sparky grabbing the bone and then taking a bone out of the previously won box, indicating that the child was getting further away from the most desired reward. Five bones had to be accumulated to win a prize from the large (blue) box. Each trial consisted of 2 seconds in which the bone appeared on the screen for the child to fetch, followed by 2 seconds of feedback in which a bone was earned or removed, and then a 2-second inter-stimulus interval in which the child was told to rest. The task was animated and contained engaging sound effects. Trials were grouped into three win and two frustration blocks. Win blocks comprised five win and one frustration trial, except for the final win block, which had an extra win trial so the child would beat the game. Frustration blocks comprised five frustration and one win trial. After each block, children completed an online emotion rating by choosing from seven cartoon faces ranging from negative to positive to indicate their current mood state.

2.5 | Facial coding

Throughout the FETCH task, facial expressions were recorded using a high-definition camcorder mounted on a platform directly above the touchscreen computer. If needed, children were placed on booster seats and the angle of the platform was adjusted to ensure that the child's face was in the center of the frame before recording began. After recording, epochs comprising win or frustration blocks were denoted in the video file using ELAN software (Brugman, Russel, & Nijmegen, 2004). Epochs were further subdivided into winning and frustration trials. Facial codes comprised a subset of facial movements from the Facial Actions Coding System (FACS) (Ekman & Friesen, 1978). FACS is an anatomically based, comprehensive, objective coding system for measuring all observable facial movements, or actions units (AUs). Prior to coding, an independent FACS certified coder pilot-coded a subset of videos using the full set of FACS codes to assess which facial movements were most frequent. Based on these pilot codes, expressions we expected to see during winning and frustration, and our hypotheses, the following facial movements were coded: brow lowerer (corrugator supercilli; FACS AU 4), eye constriction (orbicularis oculi; FACS AU 6), nose wrinkler (levator labii superioris alaquae nasi; AU 9), upper lip raiser (levator labii superioris; FACS AU 10), lip corner puller (zygomaticus major, FACS AU 12), and lip corner depressor (depressor anguli oris; FACS AU 15). Onset and duration of facial codes were continuously denoted in ELAN at the frame-by-frame level. Multiple tiers were used as necessary to precisely denote the overlap of facial codes. Footage where the face was not visible enough to code was denoted as unscoreable.

Coders were five FACS-trained laboratory members who had passed the FACS certification test. Coders were also required to pass a test custom-designed by our laboratory for coding videos of children. To ensure that coders were blind to whether epochs were win or frustration blocks, win/frustration labels were hidden in the files, and videos were coded on mute. Epochs were separated into distinct files and assigned in a random order, across subjects, so that coders would be unable to determine the timing of each epoch within the whole of the task. Moreover, coders were only assigned subjects with whom they had no previous interaction (i.e., they were not present when the child was tested) and thus had no previous knowledge of the child's temperament.

To assess reliability, 52% of epochs were double coded (coded independently by two individual coders). After each epoch was double coded, the two coders re-watched the footage together to resolve discrepancies, add codes that were originally missed, or remove codes that both had originally denoted but were deemed false positives upon review. When needed, an independent FACS-certified coder served as a tiebreaker when disagreements could not be resolved or if a segment of footage was particularly difficult to code (e.g., poor video quality). After double coding, a consensus code file was created and reliability was calculated as the agreement between each coder and the consensus code using the formula described in the FACS manual: (Number of codes agreed upon by coder and consensus code) × 2, divided by (total number of facial codes scored between the coder and consensus code). Overall agreement was excellent (85%). In addition, Cohen's kappa was calculated for each AU, aggregated across subjects, using a strategy similar to Sayette and colleagues (2001). Kappa values ranged from moderate to excellent as follows: AU 4 = .85, AU 6 = .77, AU 9 = .79, AU 10 = .70, AU 12 = .50, AU 15 = .80.

Consensus coded or single coded videos were exported to an Excel spreadsheet which parsed the continuous codes into 100-ms bins that denoted whether each code was present or absent and whether the concurrent trial was a winning or frustration trial. The percentage of time each code or specific code combination was present was calculated during winning and frustration both per block and across the entire task. Negative expressions with eye constriction were defined as the percentage of time during frustration brow furrowing, nose wrinkling, lip raising, or frowning co-occurred with presence of eye constriction, or the presence of eye constriction on its own without smiling (i.e., wincing). Negative expressions without eye constriction were defined as the percentage during frustration these movements occurred without the presence of eye constriction. Although not related to our original hypotheses, to test whether associations between negative expressions, parent rating of temperamental emotion regulation, and neural activation were specifically due to negative facial movements as opposed to overall expressivity, we also tested associations with percentage of positive expressions during frustration. Positive expression variables included percentage of smiling during frustration with eye constriction (lip corner raising with eye constriction), and without eye constriction (just lip corner raising). All facial expression variables were converted into *z*-scores.

2.6 | Analysis strategy

First, bivariate correlations were used to test associations between negative and positive expressions and parent rating of temperamental emotion regulation. Next, group-level generalized linear mixed-effects models were used to examine associations between negative and positive expressions and LPFC hemoglobin levels during frustration. We corrected for multiple comparisons using the False Discovery Rate correction (Benjamini & Hochberg, 1995) and report *q*-values for all fNIRS analyses. Given changes in emotion regulation capacity and brain development that occur across the early childhood period (Thompson & Goodman, 2010), we examined associations between age and variables of interest for each set of analyses and, when appropriate, controlled for age effects.

3 | RESULTS

3.1 | Frequency of facial expressions

Means and standard deviations of facial expression frequency and parent-rated temperamental emotion regulation are shown in Table 1. We conducted a 2 (positive, negative) by 2 (presence, absence of eye constriction) repeated measures ANOVA to test whether frequencies of different facial expressions differed by valence and whether eye constriction was present or absent. There was a main effect of valence ($F(1, 64) = 89.12$, $p < .001$, $\eta_p^2 = .58$) such that children produced significantly more positive expressions than negative expressions during frustration, and a main effect of eye constriction ($F(1, 64) = 118.50$, $p < .001$, $\eta_p^2 = .65$) such that children produced more expressions without eye constriction than with eye constriction during frustration. There was also a significant valence × eye constriction interaction ($F(1, 64) = 63.53$, $p < .001$, $\eta_p^2 = .50$), such that negative expressions were more likely to involve eye constriction than positive expressions.

3.2 | Effects of child age

Bivariate correlations revealed that child age was unrelated to frequency of any facial expression, children's self-ratings of emotion during the task, or parent ratings of temperamental emotion regulation ($p > .05$). A mixed-effects model revealed that child age was inversely associated with LPFC activation at two channels in the left hemisphere ($t(64) = -3.39$, $p < .001$, $d = .85$, $q < .01$; $t(64) = -2.1$, $p < .05$, $d = .53$, $q > .05$),[1] such that younger children had greater activation during frustration than older peers. Therefore, we controlled for age in all subsequent fNIRS analyses.

TABLE 1 Descriptive statistics of study variables

Variable	Mean	*SD*	Range
Negative expressions (% during frustration)			
With orbicularis oculi	0.44	1.14	0–7.1
Without orbicularis oculi	3.29	6.25	0–42.48
Positive expressions (% during frustration)			
With orbicularis oculi	5.34	7.72	0–30.78
Without orbicularis oculi	26.68	18.75	1–75.56
CBQ falling reactivity	5.06	.91	2.67–6.83

3.3 | Self-report of frustration

One-hundred percent of children generally rated their emotion as less positive following frustration blocks ($M = 3.7$ on a 1–7 scale with 1 being most negative and 7 being most positive, $SD = 2.4$) compared to win blocks ($M = 6.2$, $SD = 1.1$). Distribution of self-ratings following frustration blocks showed that nearly half the sample chose either the most negative (1) or most positive (7) rating every time, suggesting largely bimodal responding consistent with previous studies in this age range (Chambers & Johnston, 2002; Grabell et al., 2017). Similarly, distribution of self-ratings following win blocks showed that half the sample chose the most positive rating every time. A paired-sample *t* test revealed that emotion ratings following frustration and win blocks were significantly different ($t(60) = -7.88$, $p < .001$, $d = 2.03$). Self-ratings of emotion were unrelated to parent-rated temperamental emotion regulation, frequency of facial expression, or child age. A mixed-effects model that controlled for age revealed that children's emotion ratings following frustration blocks was unrelated to LPFC activation during frustration blocks. After receiving their desired prize, children were asked open-ended questions about what emotions they felt during the FETCH task. One hundred percent of children reported negative emotions such as "angry" or "mad" when asked how they felt when Sparky was taking their bones away, consistent with other studies that have used this task (Perlman et al., 2014).

3.4 | Associations between facial expression and temperamental emotion regulation

Bivariate correlations were used to examine the association between different facial expressions during frustration and parent ratings of their child's temperamental emotion regulation. Frequency of negative expressions with eye constriction during frustration was significantly negatively associated with CBQ Falling Reactivity scale scores ($r = -.28$, $p < .05$), such that children who more frequently showed this expression during frustration were rated as having more difficulty recovering from an emotional challenge. Negative expressions without eye constriction ($r = -.077$, $p = .54$), and positive expressions with ($r = -.121$, $p = .34$) and without ($r = .07$, $p = .57$) eye constriction were unrelated to parent-rated temperamental emotion regulation.

3.5 | Associations between facial expression and frustration-related LPFC activation

As shown in Figure 3, generalized mixed-effects models revealed a negative association between negative expressions with eye

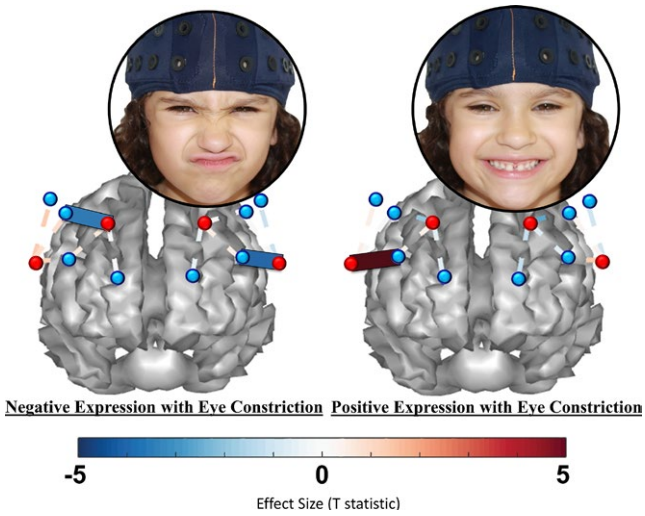

FIGURE 3 Source-detector pairs comprising the fNIRS probe superimposed on a 3D mesh brain with solid lines indicating significant associations between oxygenated-hemoglobin levels during frustration and frequency of negative and positive facial expressions during frustration [The author(s) have obtained the individual's or parent's/guardian's free prior informed consent to publish this image.]

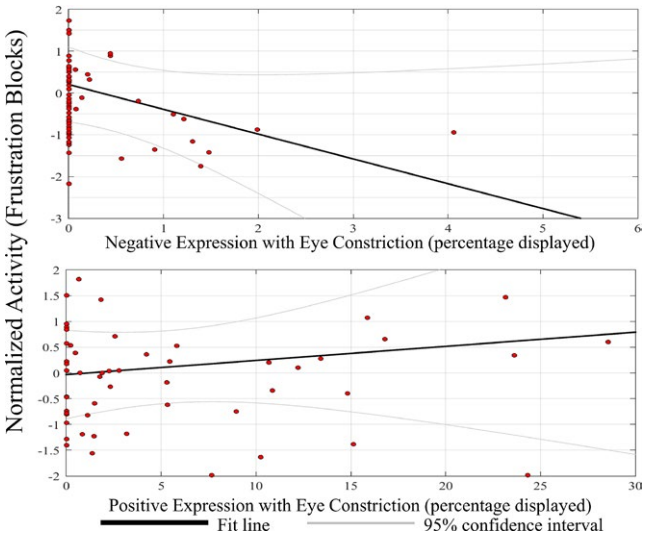

FIGURE 4 Scatterplot showing the between-subjects association between the percentage subjects displayed negative (top) and positive (bottom) expressions with eye constriction and hemodynamic activation during frustration, controlling for child age

constriction and frustration-related LPFC activation at two channels, one in the left ($t(64) = -3.42$, $q < .05$, $d = .85$) and one in the right ($t(64) = -3.09$, $q < .05$, $d = .77$) hemisphere controlling for age. The R^2 associated with these channel models were .16 and .15, respectively. The association was such that children who exhibited a lower frequency of this expression had a stronger frustration-related LPFC response relative to their peers (see Figure 4). Negative expressions without eye constriction were unrelated to frustration-related LPFC activation. In addition, positive expressions with eye constriction were positively associated with frustration-related LPFC at another channel in the right hemisphere ($t(64) = 5.74$, $q < .001$, $d = 1.43$) controlling for age. The R^2 associated with the channel model was .47. The association was such that children who made this expression more often had a stronger LPFC response than children who made this expression less often. Positive expressions without eye constriction were unrelated to frustration-related LPFC activation.

4 | DISCUSSION

The present study was, to our knowledge, the first to examine individual facial muscular movements, simultaneous LPFC activation, and parent ratings of emotion regulation in an early childhood population. We found evidence that young children were more likely to exhibit eye constriction in the context of negative faces versus positive faces during frustration. Moreover, individual differences in the frequency of negative expressions with eye constriction during frustration related to children's simultaneous LPFC activation and how their parents rated their temperamental emotion regulation. Consistent with our hypotheses, frequency of negative expression with eye constriction was inversely associated with both concurrent LPFC response and parent ratings of temperamental emotion regulation. We also found evidence that frequency of positive expressions with eye constriction during frustration was associated with a stronger LPFC response. Facial expressions that did not include eye constriction were unrelated to frustration-related LPFC activation or parent ratings of temperamental emotion regulation.

We utilized a multi-modal strategy to address two major gaps in the emotion regulation literature: discriminating whether facial expressions indicate emotion regulation versus low emotional reactivity, and testing how brain regions hypothesized to underpin emotion regulation relate to facial display (Gross, 2013; Simonds et al., 2007). Without knowing whether children who appear calm during frustration are excellent emotion regulators or just experience lower levels of frustration than peers (Gross, 2013), we are left with two different interpretations of the literature showing links between early frustration tolerance and later functioning (Mischel, Shoda, & Rodriguez, 1989). We detected a consistent pattern such that a heightened LPFC response occurred in children who had infrequent negative expressions, suggesting that the LPFC supports emotion regulation through modulating frustration at its onset, as evidenced by control of facial display. Given the LPFC's role in executive function (D'Esposito et al., 1995), this contention supports several influential theoretical models arguing that early emotion regulation results from brain development important for cognitive control (Kopp, 1989; Zelazo & Cunningham, 2007) that to date had not been directly tested *in vivo* due to practical limitations. That negative facial expressions were only associated with concurrent LPFC activation if the expression included eye constriction is consistent with previous literature showing that this muscle signals emotion intensification in infants and adults (Messinger et al., 2012). Here, we present novel evidence that controlling salient expressions

of "true" distress may be more difficult, requires greater cognitive control, and indicates better overall emotion regulation in the early childhood period. Our findings further suggest that measuring children's facial expressions at the muscular level, and in particular noting the presence or absence of eye constriction, may be critical to making inferences about both underlying regulatory processes during experimental paradigms and general emotion regulation ability outside of the lab. Associations were robust and comparable to reported associations between amygdala activation and corrugator contraction in a study of healthy adults (Heller et al., 2014).

We found that children showed more positive than negative expressions during frustration. In addition, frequency of positive expressions with eye constriction during frustration was associated with greater concurrent LPFC activation. Displaying more positive than negative expressions during an emotional challenge has been consistently reported in the child literature over the past 30 years in studies using various disappointment (Cole, 1986; Saarni, 1979), frustration (Dennis, Cole, Wiggins, Cohen, & Zalewski, 2009), and disgust (Soussignan & Schall, 1996) paradigms. Children's positive expressions during negative emotion challenges are postulated to reflect a masking or display rules-related behavior to cope or adapt to the stressor, as opposed to a genuine expression of joy (Cole, 1986; Saarni, 1984). Indeed, in the present study children consistently reported experiencing negative affect during frustration via their self-rated and open-ended responses. The masking literature suggests that in certain cases both negative and positive expressions may be valid indicators of young children's frustration, a phenomenon that makes inferring underlying emotion regulation, based merely on the gross valence of an expression, problematic. To our knowledge, the present study is the first to examine masking expressions at the individual muscular movement level and how this expression relates to concurrent LPFC activation during frustration. The present study potentially advances an understanding of the key characteristics of young children's masking expressions and the underlying neural mechanisms involved in their production. Specifically, when children are frustrated, positive expressions indicating masking may be defined by the presence of eye constriction, and the process of producing these expressions in lieu of negative expressions may require cognitive control supported by brain regions important for executive function (Simonds et al., 2007). Clearly, future research is needed to replicate and further explore the meaning of young children's masking expressions in response to frustration.

The present study demonstrates the feasibility of inferring children's emotion regulation-related brain activation from their facial expressions, a finding with potential practical and clinical implications. Children's non-verbal behaviors are constantly observed by parents, teachers, and other professionals, and inform assessments of varying importance. Consider a mother noticing that her child is becoming frustrated waiting in line, a school psychologist observing a child's angry outbursts to determine if they require services, or a psychiatrist assessing a 5-year-old for depression. Indeed, operationalizing and measuring specific non-verbal behaviors in response to challenges are becoming integrated into many cutting-edge standardized diagnostic techniques (e.g., Lord et al., 2000; Wakschlag et al., 2008). Our findings raise the possibility that specific facial expressions may help caregivers and professionals more accurately assess children's emotion regulation abilities and related dysfunction, using a brain-based rationale. Using facial muscular movements to further elucidate emerging emotion regulation, and potentially develop clinical applications, will require rigorous replication and advanced classification techniques (e.g., Sato et al., 2011). Future work mapping how children's facial expressions reflect underlying neural functioning may lead to novel clinical tools informing better decision-making, which will require testing in clinical populations.

4.1 | Limitations, future directions, and conclusions

Our current findings potentially represent a significant advancement in our understanding of early emotion regulation, and address long-standing methodological challenges to measuring it, but limitations must be acknowledged. It is unknown whether strong facial muscle contractions affect fNIRS recording via stretching and pulling the scalp. In the present study, only facial expressions with eye constriction were related to neural activation, but the direction of the finding contrasted depending on whether the expression was positive or negative, suggesting that neural activation associated with eye constriction was not due to artifact related to movement of muscles beneath the fNIRS probe. Experiencing and regulating frustration involves complex and dynamic activation of multiple cortical and sub-cortical structures, yet fNIRS is limited to measuring the outer cortex in a priori regions of interest (e.g., the LPFC). Future studies adopting a similar multi-modal strategy may be able to infer activation of both cortical and sub-cortical structures, such as the amygdala, by collecting proxy data such as galvanic skin response with fNIRS (Critchley, Elliott, Mathias, & Dolan, 2000). Overall, multi-modal approaches connecting facial expressions with concurrent brain activation represent an innovative strategy with the potential to make new headway in understanding emotion regulation and how it supports healthy development.

CONFLICTS OF INTEREST

Drs Grabell, Barker, Huppert, Fishman, and Perlman, and Mss Li, Jones, Wilett, and Bemis report no competing interests.

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ENDNOTE

[1] As in our previous fNIRS investigations (Grabell et al., 2017; Li et al., 2016; Perlman et al., 2015), the entire second-level data set (subjects by channels by {oxy-/deoxy-hemoglobin} by conditions) was analyzed concurrently in a single model such that the non-independence of spatial channels and task conditions can be whitened using the first-level error-covariance. Therefore, in previous investigations, the effective degrees of freedom was estimated as described by Satterthwaite (1946) and Welch (1947). In the present study, however, we estimated degrees of freedom based on the sample size.

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