Biological Psychology 142 (2019) 37–44

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

Children's sustained attention to emotional facial expressions and their autonomic nervous system reactivity during parent-child interactions☆

Mary L. Woody[a,*], Kiera James[b], Claire E. Foster[b], Max Owens[c], Cope Feurer[b], Anastacia Y. Kudinova[d], Brandon E. Gibb[b]

[a] *University of Pittsburgh, Department of Psychiatry, United States*
[b] *Center for Affective Science, Binghamton University (SUNY), United States*
[c] *University of South Florida St. Petersburg, United States*
[d] *Brown University, Department of Psychiatry, United States*

ARTICLE INFO

Keywords:
Research Domain Criteria
Attention bias
Late positive potential
Autonomic nervous system reactivity
Respiratory sinus arrhythmia
Childhood

ABSTRACT

The way individuals process socio-affective information is thought to impact their responses to social interactions, but research testing the relation between these processes is scarce, particularly among children. This study examined if children's attention to socio-affective stimuli was associated with their autonomic nervous system (ANS) reactivity during parent-child interactions. Children's sustained attention to facial expressions of emotion (afraid, happy, sad) was indexed using the late positive potential (LPP) event-related potential (ERP) component during a computer-based task. To measure ANS reactivity, children's respiratory sinus arrhythmia (RSA) was assessed at baseline and during positive and negative parent-child discussions. Enhanced LPP amplitudes in response to all emotional facial expressions, reflecting greater sustained attention to socio-affective stimuli, were associated with increased RSA reactivity during parent-child discussions. These results show correspondence between two psychophysiological substrates of emotion processing in healthy children and highlight how these systems may be synergistic forces contributing to emotion reactivity.

1. Introduction

The Research Domain Criteria (RDoC; https://www.nimh.nih.gov/research-priorities/rdoc/) initiative grew out of the 2008 National Institute of Mental Health (NIMH) Strategic Plan to link new classifications of psychiatric disorders to recent advances in neurobiology (Cuthbert, 2014; NIMH, 2008). Importantly, this initiative has provided researchers with opportunities to identify core processes that cut across traditional diagnostic boundaries and to examine the full range of functioning from normal to abnormal across human development (Cuthbert & Insel, 2013). To do so, the RDoC framework divides processes of human behavior into five domains of functioning (i.e., Negative Valence Systems, Positive Valence Systems, Cognitive Systems, Systems for Social Processes, and Arousal/Regulatory Systems), which form the rows of the RDoC matrix. The columns are used to represent units of analysis spanning genes, molecules, and cells to circuits, physiology, behavior, and self-report. A key focus of RDoC is to link findings across units of analysis within a given domain.

The processes implicated in processing and reacting to socio-affective information are largely highlighted within RDoC's Negative Valence Systems (e.g., Kujawa & Burkhouse, 2017; Woody & Gibb, 2015). A key component of the Negative Valence Systems is disruption in fronto-limbic circuitry responsible for processing of salient socio-affective stimuli. For children and adolescents, deficits in the ability of prefrontal cortex (PFC) regions to effectively regulate aberrant limbic and salience network reactivity are associated with disruptions in how individuals attend to socio-affective information and how they react to socio-affective stress (Ladouceur, 2012). Disruptions in these brain networks then have downstream effects on behavioral and peripheral responding.

At the behavioral level, disruptions in fronto-limbic circuitry shape children's attention to socio-affective stimuli. Initial allocation of attention toward salient socio-affective stimuli is directed by amygdala activation (Pourtois, Spinelli, Seeck, & Vuilleumier, 2010; Pourtois,

---

☆ This project was supported by the National Institute of Mental Health grant MH098060 awarded to B.E.G., and M.L.W. is supported by an Institutional NRSA from NIMH (T32 MH018269). We would like to thank Katie Burkhouse, Aliona Tsypes, Sydney Meadows, Michael Van Wie, Devra Alper, Eric Funk, Effua Sosoo, and Nathan Hall for their help in conducting assessments for this project.

* Corresponding author at: Department of Psychiatry, University of Pittsburgh, Pittsburgh, PA 15213, United States.
E-mail address: woodyml@upmc.edu (M.L. Woody).

https://doi.org/10.1016/j.biopsycho.2019.01.005
Received 17 May 2018; Received in revised form 4 January 2019; Accepted 12 January 2019

Schettino, & Vuilleumier, 2013) as the amygdala has the propensity to prioritize processing of a variety of salient stimuli. Specifically, amygdala reactivity is elicited not only by threat-relevant stimuli but by a wider variety of stimuli than previously believed (e.g. afraid, happy, and sad stimuli; Fusar-Poli et al., 2009). Sustained attention to socio-affective stimuli, however, has been associated with activity in the lateral prefrontal cortex and a broader attention control network, consisting of the right inferior frontal gyrus, right middle frontal gyrus, dorsal anterior cingulate gyrus, left middle frontal gyrus, right supramarginal gyrus, left supramarginal gyrus, and a node within the precuneus region of the occipital lobe (Beevers, Clasen, Stice, & Schyner, 2010; Nee, Wager, & Jonides, 2007; Wager, Davidson, Hughes, Lindquist, & Ochsner, 2008). In general, these prefrontal regions are responsible for allocating attention either toward or away from the socio-affective stimuli that is prioritized by limbic regions. Further, connectivity between fronto-limbic regions is responsible for resolving competition between limbic-generated "bottom-up" attention to salient socio-affective stimuli and prefrontal-associated "top-down" attention to goal-relevant stimuli (for a review, see Carretié, 2014). In youth, limbic regions increasingly prioritize attention to affectively-salient stimuli, which overrides the influence of still-developing PFC regions and fronto-limbic connectivity. For some youth, these neurodevelopmental changes lead to excessive attention to socio-affective stimuli, at the expense of attention to goal-relevant information, which can increase risk for internalizing problems and other adverse outcomes (Casey, Heller, Gee, & Cohen, 2018; Ladouceur, 2012).

At the level of the central nervous system (CNS), one promising method of indexing the influence of fronto-limbic networks on sustained attention comes from the late positive potential (LPP) event-related potential (ERP) component. The LPP is a posterior slow wave ERP with amplitudes that are modulated by sustained attention to, and processing of, an emotional stimulus (Proudfit, Bress, Foti, Kujawa, & Klein, 2015). In healthy adults and children, emotional stimuli elicit greater LPP amplitudes than neutral stimuli, indicating increased neural processing of emotionally-salient visual information (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Hajcak & Dennis, 2009). In adults, studies utilizing concurrent fMRI and EEG have demonstrated that the LPP is related to neural activity in limbic, prefrontal, parietal, and occipital regions, which are key regions involved in attention networks (Bradley et al., 2003; Keil et al., 2002; Liu, Huang, McGinnis-Deweese, Keil, & Ding, 2012; Sabatinelli, Lang, Keil, & Bradley, 2007; Sabatinelli, Keil, Frank, & Lang, 2013). Similarly, in youth, LPPs correspond with simultaneous parietal, orbitofrontal, and amygdala activation while viewing emotional faces (Bunford, Kujawa, Fitzgerald, Monk, & Phan, 2018), and reappraisal-induced reductions in LPPs appear to be modulated by activation in the dorsolateral prefrontal cortex and right parietal cortex (Wessing et al., 2015).

At the level of the autonomic nervous system (ANS), respiratory sinus arrhythmia (RSA) may be particularly sensitive to the influence of fronto-limbic circuitry (for a review, see Thayer, Åhs, Fredrikson, Sollers, & Wager, 2012). RSA (i.e., temporal variability in heart rate) is a peripheral measure of parasympathetic regulation and autonomic arousal in social contexts (Appelhans & Luecken, 2006; Porges, 2007). Specifically, the parasympathetic nervous system exerts influence on the heart through modulation of the vagus nerve, and measures of RSA provide a peripheral measure of this activity (Berntson et al., 1997). Because the vagus nerve communicates bidirectionally with the PFC and amygdala (Thayer et al., 2012), RSA is thought to serve as a marker of the ease with which individuals are able to effectively engage and regulate their physiological responses. Specifically, studies have shown that higher levels of RSA at rest are associated with better capacity to self-regulate physiological responses and greater prefrontal cognitive control over limbic-driven emotional responding (Thayer et al., 2012). During challenge and stress, RSA levels typically decrease, reflecting an autonomic response to stress as cardiac vagal control is withdrawn and sympathetic nervous system is activated. Increased limbic reactivity to stress that is not regulated by prefrontal regions is thought to precede and influence the withdrawal of cardiac vagal control (Thayer et al., 2012). In youth, resting RSA and RSA reactivity are thought to increase through 4 years of age (Bar-Haim, Marshall, & Fox, 2000), stabilize during middle childhood and pre-adolescence (El-Sheikh, 2005; Hinnant, Elmore-Staton, & El-Sheikh, 2011), and then decline through adolescence and early adulthood (Hollenstein, McNeely, Eastabrook, Mackey, & Flynn, 2012). Despite these broad developmental patterns, research has also shown that there are individual differences in whether youth exhibit increases or decreases in RSA in response to challenge or stress (Hinnant et al., 2011; Pang & Beauchaine, 2013), suggesting that there may be identifiable factors that moderate ANS reactivity, consistent with the RDoC framework.

Notably, the brain circuitry underlying sustained attention to emotional stimuli and RSA response are similar (i.e., both driven by disruptions in fronto-limbic circuits) and both are highlighted as separate units of analysis within the RDoC Negative Valence Systems. Although it is yet to be tested, it is possible that sustained attention to socio-affective stimuli and increased RSA reactivity to stress both reflect a hyperreactive response style to salient socio-affective information. Despite the common underlying neural circuitry and theoretical foundations, no study of which we are aware has examined the link between sustained attention to socio-affective stimuli and RSA reactivity in youth. However, several studies provide important clues to how these systems may be related. For example, Sanchez, Vazquez, Marker, LeMoult, and Joormann (2013) found evidence for a link between attention to socio-affective stimuli and stress reactivity among depressed adults, such that individual differences in ability to disengage from sad facial expressions of emotion was predictive of slower mood recovery following a stress induction (Sanchez et al., 2013). In healthy adults, there is also evidence for a link between resting cardiac vagal tone, as indexed by heart rate variability (HRV), and attention to socio-affective stimuli. Specifically, a recent review found that individuals with lower resting HRV, relative to individuals with higher resting HRV, exhibit attentional hypervigilance to threat-relevant socio-affective stimuli and difficulty disengaging and inhibiting attention to socio-affective stimuli (for review, see Park & Thayer, 2014). Finally, in children, a series of studies have shown that attentional biases to threat-relevant socio-affective stimuli moderate concurrent and predictive relations between early socio-affective reactivity (e.g. temperamental negative affect and behavioral inhibition) and anxiety symptoms in later childhood and adolescence (Cole, Zapp, Fettig, & Perez-Edgar, 2016; Perez-Edgar et al., 2010, 2011). Together, these studies suggest that attention to socio-affective stimuli and stress responses may be synergistic forces underlying emotion reactivity in both youth and adults. However, future research is needed to directly test the links between sustained attention to socio-affective stimuli and physiological stress response during interpersonal stress in youth.

To develop a fine-grained, integrated understanding of constructs across units of analysis within the RDoC Negative Valence Systems domains, the current study examined the association between children's sustained attention to emotional facial expressions (afraid, happy, sad) and their ANS reactivity to a positive and negative parent-child discussion in a sample of community youth aged 7–11 years. We chose to study children in this age range because biases in attention to and memory for affective information begin to stabilize during late childhood (Gibb & Coles, 2005; Hankin et al., 2009) and thus mark a critical developmental period in which to examine constructs relevant to RDoC Negative Valence Systems. Further, because adolescence is marked by an increasing influence of peer rather than parental relationships (Bokhorst, Sumter, & Westenberg, 2010), we chose to focus on the relation between sustained attention and ANS reactivity to parent-child interaction during pre-adolescence.

In the current study, we used the LPP ERP component as an index of sustained attention to facial expressions of emotion that ranged in emotional intensity. We chose this approach as previous research suggests that measuring responses solely to full-intensity facial expressions of emotion may suffer from reduced ecological validity because facial expressions exhibited in real life are often not displayed at full emotional intensity (Joormann & Gotlib, 2006; Vanhalst, Gibb, & Prinstein, 2017). To measure children's ANS responses, we collected RSA during a resting baseline and during a positive and negative parent-child discussion. We predicted that children who exhibited increased sustained attention (i.e., larger LPP amplitudes) to emotional facial expressions would also be more likely to display greater ANS reactivity (i.e., decreases in RSA from baseline) during both the positive and negative parent-child discussion. Given prior-established links between attention to negative socio-affective stimuli and increased reactivity to laboratory-based stressors (Sanchez et al., 2013), we hypothesized that the emotional valence of the facial expressions would moderate the link between RSA and LPP indices, such that the positive relation between sustained attention to negative socio-affective stimuli (sad, afraid faces) and ANS reactivity to the negative parent-child discussion would be stronger than links between attention to positive socio-affective stimuli (happy faces) and ANS reactivity to the negative parent-child discussion. Finally, because the majority of prior research has not examined facial expressions that vary in emotional intensity, we examined the intensity of facial expressions as an exploratory moderator of the hypothesized relations.

2. Method

2.1. Participants

Participants in this study were 37 children ages 7–11 and their parent recruited from the community. See Table 1 for demographic characteristics about the children in our sample. For parents, the average age was 38.89 years (*SD* = 8.47), 89% were women, 97% were Caucasian, and the median annual family income was $35,001–40,000.

2.2. Measures

2.2.1. Morphed faces task

Children completed a morphed faces task (cf. Burkhouse, Gibb, & Siegle, 2014) in which they viewed grey-scaled faces displaying a variety of emotional expressions (afraid, happy, sad, neutral) from a standardized stimulus set of child actors aged 10 to 17 years old from the NIMH Child Emotional Faces Picture Set (Egger et al., 2011). The stimuli consisted of emotional and neutral photographs from each actor, morphed to form a continuum of 10% increments between the two photographs. Each emotion is represented by 4 continua (2 male and 2 female actors), for a total of 12 continua. Eleven morphed images were used from each continuum, representing 10% increments of the two emotions ranging from 100% neutral (0% target emotion) to 100% target emotion (e.g., 90% Neutral, 10% Sad; 80% Neutral, 20% Sad; and so on). The pictures were presented, one at a time in the middle of the screen for three seconds, after which they disappeared and the participant was asked to indicate which emotion was presented using four response options: afraid, happy, sad, calm/relaxed. Each face was 26.5 cm tall (16° visual angle) × 16.5 cm wide (10° visual angle). The inter-trial interval varied randomly between 500 and 750 ms. The stimuli were presented in semi-random order with the condition that no two images from the same actor were presented consecutively. Each of the 132 images was presented twice for a total of 264 trials, with 8 trials for each emotion type per morph level. Within the task, children were given the chance to rest after every 55 trials.

Consistent with previous research (Burkhouse et al., 2014; Burkhouse, Siegle, Woody, Kudinova, & Gibb, 2015), responses were binned into three separate morph conditions for analyses: low (10%, 20% and 30%), medium (40%, 50%, 60% and 70%) and high (80%, 90% and 100%). Information about children's behavioral performance during the Morphed Faces Task has been previously published (James, Owens, Woody, Hall, & Gibb, 2018) and showed that children are more accurate in detecting the target emotion (i.e., afraid, happy, or sad faces) at each subsequent morph level and that children display higher accuracy in detecting afraid and happy faces compared to sad faces.

2.2.2. EEG data recording and processing

Continuous EEG was recorded during the morphed faces task using a custom cap and the BioSemi ActiveTwo system. The signal was preamplified at the electrode with a gain of 16 × . The EEG was digitized at 24-bit resolution with a sampling rate of 512 Hz using a low-pass fifth-order sinc filter with a half-power cutoff of 104 Hz. Recordings were taken from 34 scalp electrodes based on the 10/20 system. Two additional electrodes, an active (Common Mode Sense (CMS) and a passive Driven Right Leg (DRL) electrode were used in the study. Raw EEG was recorded relative to CMS. The CMS/DRL electrodes replaced the ground for recordings through a feedback loop which drove the average potential of the subject (i.e. the Common Mode voltage) as close as possible to the "zero" ADC reference voltage in the AD-box (please see http://www.biosemi.com/faq/cms&drl.htm for further details). In addition, the electrooculogram was recorded from four facial electrodes.

Off-line EEG analysis was performed using the MATLAB extension EEGLAB (Delorme & Makeig, 2004) and the EEGLAB plug-in ERPLAB (Lopez-Calderon & Luck, 2014). All data were band-pass filtered with cutoffs of 0.1 Hz and 30 Hz and re-referenced to the average of the left and right mastoid electrodes. EEG data were processed using both artifact rejection and correction. First, large and stereotypical ocular components were identified and removed using independent component analysis (ICA) scalp maps (Jung et al., 2001). Epochs were then extracted from raw EEG with the interval from −200 ms to 0 ms serving as the baseline for each trial. Epochs with large artifacts (greater than 200 μV) were excluded from analysis. Participants' trial rejection, as determined by the above artifact detection criteria, did not exceed 50% [*M* = 22.27% (*SD* = 13.78%)].

Table 1
Descriptive Statistics and Intercorrelations.

	M (*SD*) / %	1	2	3	4	5	6	7	8
1. Age	10.19 (1.28)	–							
2. % Female	54%	−.09	–						
3. % Caucasian	75%	−.26	.04	–					
4. LPPs (averaged across conditions)	13.70 (6.85)	−.27	−.02	.20	–				
5. Resting RSA	7.72 (1.02)	−.12	−.13	.01	.10	–			
6. Vacation Planning RSA	7.55 (0.88)	.10	−.16	−.15	-.33*	.68**	–		
7. Vacation Planning RSA Residual	0.00 (0.99)	.25	−.10	−.21	-.54**	.00	.74**	–	
8. Issues Discussion RSA	7.51 (0.92)	.05	−.12	−.07	-.33*	.62**	.91**	.66**	–
9. Issues Discussion RSA Residual	0.00 (0.99)	.16	−.05	−.09	-.50**	.00	.62**	.85**	.78**

Note. RSA = Respiratory sinus arrhythmia.
* $p < .05$.
** $p < .01$.

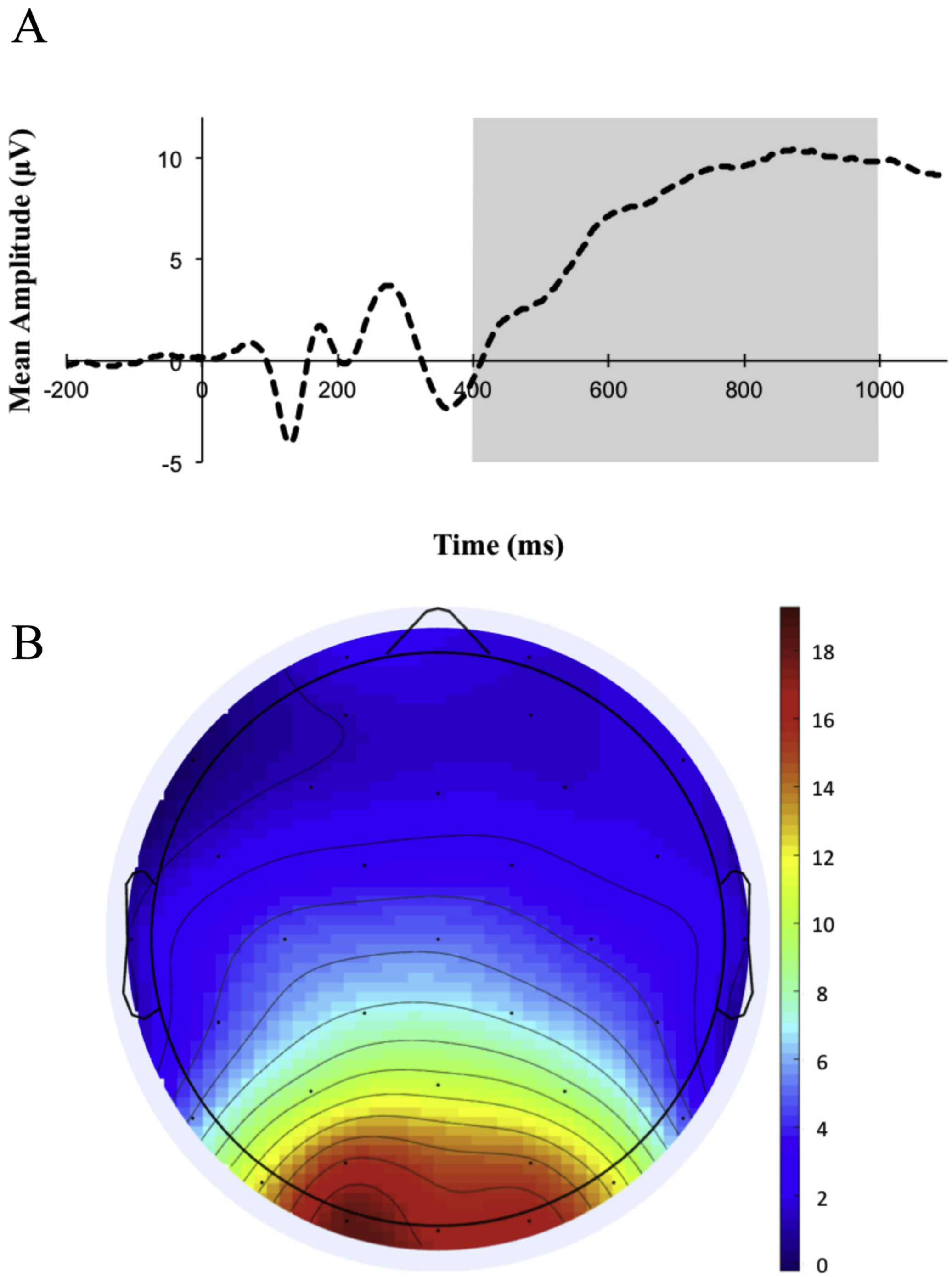

Fig. 1. Grand-averaged late positive potential (LPP) waveform time-locked to stimulus-onset (collapsed across emotion and morph conditions) is depicted in (A). The highlighted region shows the measurement window for the LPP (400–1000 ms). The waveform is averaged across electrode sites (O1, O2, Oz, P3, P4, PO3, PO4, Pz). Mean scalp topography depicting the LPP in response to emotional facial expressions (collapsed across emotion and morph conditions) from 400 to 1000 ms following stimulus-onset is depicted in (B).

Given that the LPP is localized more occipitally in children than in adults and consistent with previous studies measuring LPP responses in youth (Dennis & Hajcak, 2009; Kujawa, Klein, & Hajcak, 2012), the LPP was scored as the mean activity from 400-1000 ms after stimulus onset at a cluster of occipital (O1, O2, Oz) and parietal (P3, P4, PO3, PO4, Pz) electrode sites (e.g., Kujawa et al., 2015, 2016). Grand-averaged LPP waveforms time-locked to face onset and the corresponding scalp topography are illustrated in Fig. 1. Supplementary materials contain additional waveforms and scalp maps for each Emotion × Morph condition in addition to simple tests of Morph and Emotion effects on LPP amplitudes. Split-half reliability for LPP indices was good (Guttman split-half coefficient = .86).

2.2.3. *Parent-child interaction task*

Children and their parents completed a standardized Discussion Paradigm, which included positive and negative discussions (Robin & Foster, 1989). Before the Parent-Child Interaction Task, each parent and child separately completed an Issues Checklist, which lists several common topics of disagreement (homework, bedtime, chores, etc.) and were asked to endorse the frequency and intensity of their conflicts over each topic. Then, parent-child dyads engaged in a 2-min rest period in which they watched a nature video featuring landscape scenes from

Olympic National Park. Next, they completed a 4-min Vacation Planning task, for which they were asked to plan a “dream vacation” for the two of them. Following this conversation, the issue from the checklist that was mutually endorsed with the highest frequency and intensity ratings was be selected for a 6-min Issues Discussion, during which they were asked to talk about the issue, describe a recent disagreement, and attempt to come up with a resolution.

2.2.4. ECG data recording and processing

During each phase of the Parent-Child Interaction Task, electrocardiogram (ECG) and respiration (RSP) data were obtained using Biopac BioNomadix wireless systems and recorded with Acqknowledge v4.2 software. ECG was recorded via a standard 3-electrode (lead II) set-up and respiration was assessed with a respiratory belt around the child’s chest. ECG and RSP data were sampled at 1000 Hz. MindWare HRV 3.0.12 was used to inspect, transform, and analyze the ECG and RSP signals. ECG data were visually inspected for artifacts (e.g., temporary equipment failure, large movements, or an unusual R-R interval), and artifacts were corrected manually. Consistent with previous research (James, Woody, Feurer, Kudinova, & Gibb, 2017; Woody, Feurer, Sosoo, Hastings, & Gibb, 2016), epochs with more than 10% artifacts (i.e., 10% of R-waves estimated within an epoch) were excluded, and tasks (i.e., rest, vacation planning, or issues discussion) with more than 50% missing epochs were marked as missing data. RSA values for children were calculated for each 30 s epoch of the 2-min rest period, 4-min Vacation Planning task, and 6-min Issues Discussion. To calculate RSA, spectral power analyses were performed with a fast Fourier transformation in the .12–1.00 Hz frequency band, consistent with recommendations by the Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology (Camm et al., 1996). To measure resting RSA, mean levels of RSA across the 2-min resting baseline task was calculated. To measure RSA reactivity during the vacation-planning and issues task, RSA residuals were created by taking the standardized residual of mean RSA levels during each interaction task after accounting for mean baseline RSA levels. Of note, more negative RSA residuals indicate greater RSA reactivity (i.e., RSA reduction from baseline to the task) whereas more positive RSA residuals represent reduced RSA reactivity (or even an increase in RSA levels from baseline to task).

2.3. Procedure

Parent-child dyads were recruited from the community through a variety of means (e.g., television, social media, newspaper, and flyers) to participate in a larger study examining the Research Domain Criteria (RDoC) domain of Negative Valence Systems among community youth ages 7–11. Upon arrival at the laboratory, parents were asked to provide informed consent and children were asked to provide assent to be in the study. Next, children completed the Morphed Faces Task. Finally, parent-child dyads participated in the Parent-Child Interaction Task. As part of the larger study, parents were compensated $80 and children received a $10 gift card to a local store. All study procedures were approved by the University’s Institutional Review Board.

3. Results

A preliminary inspection of the data revealed the presence of some missing data with up to 8.10% missing for any given variable. Given the presence of missing data, we examined whether the data were missing at random, thereby justifying the use of data imputation methods for estimating missing values (cf. Schafer & Graham, 2002). Little’s missing completely at random (MCAR) test, for which the null hypothesis is that the data are MCAR (Little & Rubin, 1987) was nonsignificant, $\chi^2(332) = 292.71$, $p = .94$, providing support for the imputation of missing values. Given this, maximum likelihood estimates of missing values were created and used in all subsequent analyses (see Schafer & Graham, 2002). See Table 1 for descriptive statistics and intercorrelations of the primary study variables.

To test the hypothesis that children’s LPP responses to emotional faces (afraid, happy, sad) during the Morphed Faces Task would be associated with children’s RSA during the Parent-Child Interaction Task, we conducted three separate 3 (Emotion) × 3 (Morph) general linear models with mean RSA levels during the resting baseline and RSA residual scores during vacation-planning or issues discussion tasks added as a continuous predictor variable within each respective model. Again, these RSA residuals were created by taking the standardized residual of mean RSA levels during each interaction task after accounting for mean baseline RSA levels with more negative RSA residuals representing greater RSA reactivity.

During the resting task, the main effect of RSA was nonsignificant, $F(1, 35) = 0.34$, $p = .56$, $\eta_p^2 = .01$, $r = .10$, and there was no significant interactions between RSA and either Emotion or Morph (lowest $p = .15$). During the vacation-planning task, there was a significant main effect of RSA reactivity, $F(1, 35) = 14.13$, $p = .001$, $\eta_p^2 = .29$ (large effect), which was not moderated by Emotion or Morph (lowest $p = .36$). To examine this main effect, we conducted follow-up analyses examining the correlation between mean LPP amplitudes (collapsed across Emotion and Morph conditions) and RSA reactivity from baseline to vacation-planning task. We found that LPP amplitudes were significantly correlated with children’s RSA reactivity during the task, $r = -.54$, $p = .001$ (large effect), showing that children who displayed larger LPP amplitudes to emotional facial expressions exhibited greater RSA reactivity during the vacation-planning task.

During the issues discussion, there was also a significant main effect of RSA reactivity, $F(1, 35) = 11.85$, $p = .002$, $\eta_p^2 = .25$ (large effect), which was not moderated by Emotion or Morph (lowest $p = .28$). In examining the correlation between LPP response and RSA during the task, we found that LPP amplitudes were significantly correlated with children’s RSA reactivity during the task, $r = -.50$, $p = .002$ (large effect). Similar to the vacation-planning task, this demonstrates that children who displayed larger LPP amplitudes to emotional facial expressions exhibited greater RSA reactivity during the issues discussion. Scatterplots between average LPP responses to emotional facial expressions and RSA levels during the resting baseline and reactivity during the vacation-planning, and issues discussion tasks are presented in Fig. 2.

4. Discussion

The current study investigated the link between children’s sustained attention to emotional facial expression, as indexed by the LPP, and their ANS responses, as indexed by RSA levels during rest and RSA reactivity during a positive and negative discussion with their parent. This type of investigation is important because both sustained attention to emotional facial expressions and autonomic response are highlighted at different units of analyses in the RDoC Negative Valence Systems domains and should, therefore, be related. Building theoretically from our understanding of the similar neural circuitry underlying these processes (i.e., disruptions in fronto-limbic circuitry), we hypothesized that youth exhibiting sustained attention to emotional facial expressions would exhibit lower levels of RSA during rest and heightened ANS reactivity (i.e., reductions in RSA levels) during parent-child interaction. Further, based on previous research (Park & Thayer, 2014; Sanchez et al., 2013), we predicted that the relations between attention to negative socio-affective stimuli and RSA reactivity to negative parent-child discussions would be stronger than for attention to positive stimuli and reactivity to negative discussions. Our hypotheses were partially supported. Specifically, findings show that higher LPP amplitudes to all emotional facial expressions were related to greater RSA reactivity during positive and negative parent-child discussions but not at rest. Further, these findings were not moderated by the valence of the discussion or the emotional intensity of the socio-affective stimuli.

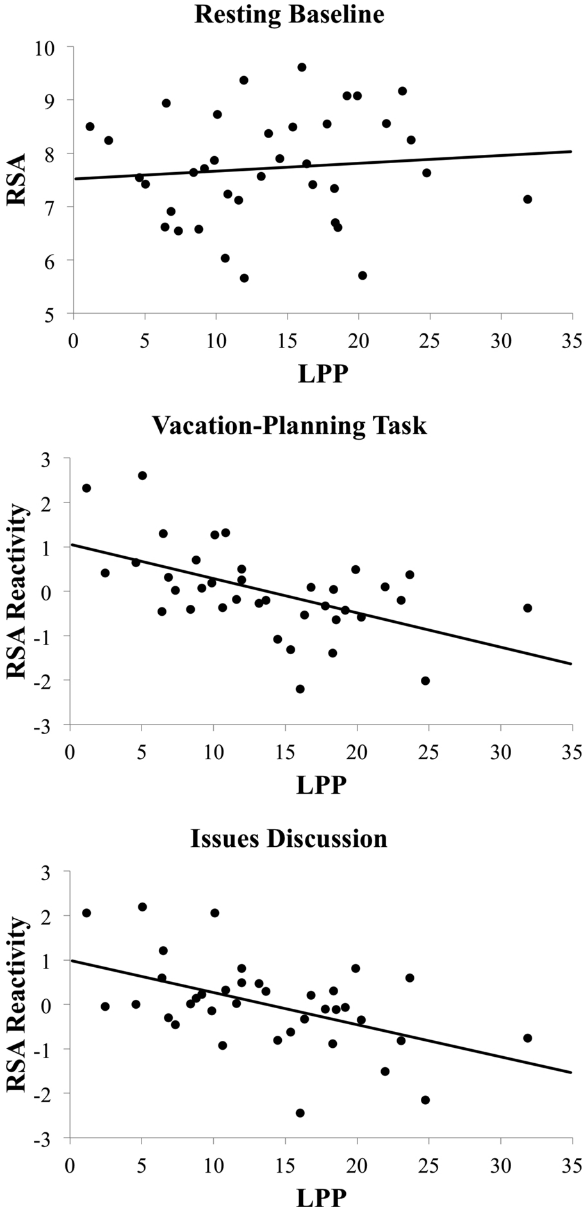

Fig. 2. Scatterplots between mean LPP amplitudes to emotional facial expressions (collapsed across emotion and morph conditions) and respiratory sinus arrhythmia (RSA) during the resting baseline (top), RSA reactivity from baseline to vacation-planning (middle), and RSA reactivity from baseline to issues discussion (bottom). Note that RSA reactivity was calculated by taking the standardized residual of mean RSA levels during each interaction task after accounting for baseline mean RSA levels. Negative RSA residual scores represent greater RSA reactivity (i.e., reductions in RSA from baseline to the task).

These results suggest that children who exhibit greater sustained attention to emotional faces are also more likely to exhibit heightened ANS reactivity during parent-child interactions. This said, because our findings did not differ significantly for high versus medium or low intensity emotional faces, an alternative explanation is that our results reflect a link between ANS reactivity and a biases in interpreting the valence of facial expressions (e.g., interpreting neutral faces as emotional; Widen, 2013) or simply increased attention to interpersonal stimuli more broadly, regardless of emotional context. Future studies are needed to test these possibilities.

The current findings provide preliminary evidence of construct validity for two processes implicated in the RDoC Negative Valence Systems among community youth. This is notable as there have long been calls within cognitive neuroscience to further develop and understand the validity of biological "constructs" and show how these constructs map onto a biological system across multiple levels (Cuthbert & Insel, 2013). Our findings support the link between sustained attention to emotional stimuli and ANS reactivity highlighted within the RDoC matrix in a community sample of children. Future work will be needed to extend these findings to clinical samples. For example, cognitive theories of psychopathology posit that information processing biases serve to predict divergent paths of psychopathology (Gibb, McGeary, & Beevers, 2016), though less is known about how information processing biases hang together across multiple levels of analysis and how these relations may differ by disorder. There is some evidence for divergent paths, with research suggesting that anxious youth display heightened initial attention ($<$ 500 ms) to threat-relevant stimuli (e.g., afraid or angry faces) whereas depressed youth display sustained attention biases for depressogenic stimuli (e.g., sad faces) (for a review, see Gibb et al., 2016). Similarly, at the physiological level, there is some evidence that anxious youth display hyperreactive ANS reactivity to stress (Rozenman, Sturm, McCracken, & Piacentini, 2017) whereas depressed youth show blunted physiological reactivity (for a review, see Hamilton & Alloy, 2016). Future work will be needed to establish if early attention biases for threat-relevant socio-affective stimuli may be more closely related to increased ANS reactivity to stress in anxious youth whereas attention for sad faces is related to blunted physiological reactivity in depressed youth. Further, exploratory research is needed to examine how depression and anxiety may disrupt biological systems that respond to positive socio-affective information (Kujawa & Burkhouse, 2017). Critically, the current findings serve as a preliminary step in establishing a link between attention biases and ANS reactivity in community youth, but future research will be needed to establish how these links may diverge among youth with internalizing problems and help explain how these biological systems work synergistically to confer risk for psychopathology.

Although the neurobiological processes underlying both LPP and RSA responses share commonalities (i.e., similar underlying fronto-limbic circuitry), they also represent distinct biological processes (i.e., CNS vs. ANS response). Therefore, future studies will be imperative to examine communication between CNS and ANS systems during emotion responding in youth. For example, one possibility is that during social interaction, increased attention to and processing of emotional facial expressions of a social partner may increase the perceived salience of the interaction (Ekman, 1993; Monk et al., 2003), which can lead to enhanced ANS reactivity. However, because the vagus nerve communicates bi-directionally with prefrontal and limbic regions (Thayer et al., 2012), afferent feedback to the CNS regarding ANS reactivity could maintain subsequent sustained attention to specific types of socio-affective stimuli. Future research will be essential to identify and understand potential feedback loops across CNS and ANS systems and how they contribute to emotion reactivity.

Notably, the current findings indicate that sustained attention to emotional faces was only related to levels of RSA during the parent-child interactions and not at rest. Divergent findings for resting versus reactive RSA is consistent with theory and prior work suggesting that levels of RSA during rest and during stress or social interaction are thought to represent distinct biological processes (2007, Porges, 1995; Thayer & Lane, 2000). Specifically, this work suggests that resting RSA represents a more stable and "trait-like" marker of how well an individual is able to regulate their physiological responses in general. In contrast, RSA reactivity is a state response to stress or social interaction. Although some prior research has linked trait levels of resting RSA to increased attention to threat-relevant stimuli in adults (Park & Thayer, 2014), it may be that trait-like physiological vulnerabilities have not yet stabilized in 7–11 year old children. This is consistent with prior work suggesting that cognitive response styles are still stabilizing during childhood before becoming more reliable in adolescence and adulthood (Gibb & Coles, 2005; Hankin et al., 2009). Future work with a broader age range will be needed to determine if links between sustained attention to socio-affective stimuli and resting RSA are stronger for adolescents and adults than children.

This study demonstrated several strengths including the focus on the link between two units of analysis within the RDoC Negative Valence Systems. Furthermore, these findings demonstrate the generalizability of a CNS index of sustained attention to socio-affective stimuli measured via a computer-based task to ANS reactivity during "real-world" parent-child interactions. Despite the strengths of the study, there were limitations that highlight areas for future research. For example, the current study was conducted in a community sample of youth, and, thus, can only inform models of emotion processing in typically-developing youth. Future efforts to replicate and extend the current findings would benefit from the inclusion of youth with psychopathology as well as a comparison group. Additionally, our study measured sustained attention to emotional facial expressions using the LPP, and future studies may benefit from the inclusion of functional neuroimaging to better understand the specific brain regions, and their connectivity, that are implicated in the link between sustained attention to emotional stimuli and children's ANS reactivity during parent-child interaction. Further, future research could extend the current findings through tasks that separate "bottom-up" and "top-down" attention using the LPPs (e.g., Hajcak, MacNamara, Foti, Ferri, & Keil, 2013) in order to determine which components of sustained attention are most closely related to ANS reactivity during social interaction. Relatedly, the inclusion of behavioral measures of parent-child interaction, such as parental emotional tone, would be beneficial to provide a more nuanced picture of parent-child dynamics during positive and negative discussions. Finally, the sample size of the study was moderate in size and may have reduced the likelihood that significant interactions would be observed, especially for relations with small effect sizes. Specifically, although the study was adequately powered (.80) to detect medium-sized effects (and all of the significant relations were large in magnitude), future research with larger samples may uncover potentially interesting moderating effects of emotional valence and intensity of facial expressions within the Morphed Faces Task. Finally, the sample was relatively homogenous (84% Caucasian), so future research will be essential to replicate these findings in larger and more diverse samples.

In summary, the current study provides evidence that children who display higher levels of sustained attention to all emotional facial expressions are more likely to exhibit heightened ANS reactivity during both positive and negative parent-child discussions. These findings begin to provide construct validity for links between units of analysis within the Negative Valence Systems and also demonstrate the generalizability of sustained attention measured during a computer-based task to children's ANS reactivity during parent-child interaction. These findings provide important preliminary evidence for a link between two psychophysiological substrates of emotion processing in healthy children and, pending replication, this information could be leveraged by future work to understand how these processes may synergistically contribute to emotional reactivity biases in psychopathology.

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.biopsycho.2019.01.005.

References

Appelhans, B. M., & Luecken, L. J. (2006). Heart rate variability as an index of regulated emotional responding. *Review of General Psychology, 10*, 229–240.

Bar-Haim, Y., Marshall, P. J., & Fox, N. A. (2000). Developmental changes in heart period and high-frequency heart period variability from 4 months to 4 years of age. *Developmental Psychobiology, 37*, 44–56.

Beevers, C. G., Clasen, P., Stice, E., & Schyner, D. (2010). Depression symptoms and cognitive control of emotion cues: An fMRI study. *Neuroscience, 167*, 97–103.

Berntson, G. G., Bigger, J. T., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., ... van der Molen, M. (1997). Heart rate variability: Origins, methods, and interpretative caveats. *Psychophysiology, 34*, 623–648.

Bokhorst, C. L., Sumter, S. R., & Westenberg, P. (2010). Social support from parents, friends, classmates, and teachers in children and adolescents aged 9 to 18 years: Who is perceived as most supportive? *Social Development, 19*, 417–426.

Bradley, M. M., Sabatinelli, D., Lang, P. J., Fitzsimmons, J. R., King, W., & Desai, P. (2003). Activation of the visual cortex in motivated attention. *Behavioral Neuroscience, 117*, 369–380.

Bunford, N., Kujawa, A., Fitzgerald, K. D., Monk, C. S., & Phan, K. L. (2018). Convergence of BOLD and ERP measures of neural reactivity to emotional faces in children and adolescents with and without anxiety disorders. *Biological Psychology, 134*, 9–19.

Burkhouse, K. L., Gibb, B. E., & Siegle, G. J. (2014). Pupillary reactivity to emotional stimuli in children of depressed and anxious mothers. *Journal of Child Psychology and Psychiatry, 55*, 1009–1016.

Burkhouse, K. L., Siegle, G. J., Woody, M. L., Kudinova, A. Y., & Gibb, B. E. (2015). Pupillary reactivity to sad stimuli as a biomarker of depression risk: Evidence from a prospective study of children. *Journal of Abnormal Psychology, 124*, 498–506.

Camm, A. J., Malik, M., Bigger, J. T., Gunter, B., Cerutti, S., & Choen, R. (1996). Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology. Heart rate variability: standards of measurement, physiological interpretation and clinical use. *Circulation, 93*(5), 1043–1065.

Carretié, L. (2014). Exogenous (automatic) attention to emotional stimuli: A review. *Cognitive, Affective & Behavioral Neuroscience, 14*, 1228–1258.

Casey, B. J., Heller, A. S., Gee, D. G., & Cohen, A. O. (2018). Development of the emotional brain. *Neuroscience Letters*.

Cole, C. E., Zapp, D. J., Fettig, N. B., & Perez-Edgar, K. (2016). Impact of attention biases to threat and effortful control on individual variations in negative affect and social withdrawal in very young children. *Journal of Experimental Child Psychology, 141*, 210–221.

Cuthbert, B. N. (2014). The RDoC framework: Facilitating transition from ICD/DSM to dimensional approaches that integrate neuroscience and psychopathology. *World Psychiatry, 13*, 28–35.

Cuthbert, B. N., & Insel, T. R. (2013). Toward the future of psyciatric diagnosis: The seven pillars of RDoC. *BMC Medicine, 11*, 1–8.

Cuthbert, B. N., Schupp, H. T., Bradley, M. M., Birbaumer, N., & Lang, P. J. (2000). Brain potentials in affective picture processing: Covariation with autonomic arousal and affective report. *Biological Psychology, 52*, 95–111.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics. *Journal of Neuroscience Methods, 134*, 9–21.

Dennis, T. A., & Hajcak, G. (2009). The late positive potential: A neurophysiological marker for emotion regulation in children. *Journal of Child Psychology and Psychiatry, 50*, 1373–1383.

Egger, H. L., Pine, D. S., Nelson, E., Leibenluft, E., Ernst, M., Towbin, K. E., ... Angold, A. (2011). The NIMH child emotional faces picture set (NIMH-ChEFS): A new set of children's facial emotion stimuli. *International Journal of Methods in Psychiatric Research, 20*, 145–156.

Ekman, P. (1993). Facial expression and emotion. *The American Psychologist, 48*, 384–392.

El-Sheikh, M. (2005). Stability of respiratory sinus arrhythmia in children and young adolescents: A longitudinal examination. *Developmental Psychobiology, 46*, 66–74.

Fusar-Poli, P., Placentino, A., Carletti, F., Landi, P., Allen, P., Surguladze, S., ... Politi, P. L. (2009). Functional atlas of emotional faces processing: A voxel-based meta-analysis of 105 functional magnetic resonance imaging studies. *Journal of Psychiatry and Neuroscience, 34*, 418–432.

Gibb, B., & Coles, M. E. (2005). Cognitive vulnerability-stress models of psychopathology: A developmental perspective. In B. L. Hankin, & J. R. Z. Abela (Eds.). *Development of psychopathology: A vulnerability-stress perspective* (pp. 104–135). Thousand Oaks, CA: Sage.

Gibb, B. E., McGeary, J. E., & Beevers, C. G. (2016). Attentional biases to emotional stimuli: Key components of the RDoC constructs of sustained threat and loss. *American Journal of Medical Genetics Part B Neuropsychiatric Genetics, 171*, 65–80.

Hajcak, G., & Dennis, T. A. (2009). Brain potentials during affective picture processing in children. *Biological Psychology, 80*, 333–338.

Hajcak, G., MacNamara, A., Foti, D., Ferri, J., & Keil, A. (2013). The dynamic allocation of attention to emotion: Simultaneous and independent evidence from the late positive potential and steady state visual evoked potentials. *Biological Psychology, 92*, 447–455.

Hamilton, J. L., & Alloy, L. B. (2016). Atypical reactivity of heart rate variability to stress and depression across development: Systematic review of the literature and directions for future research. *Clinical Psychology Review, 50*, 67–79.

Hankin, B. L., Oppenheimer, C., Jenness, J., Barrocas, A., Shapero, B. G., & Goldband, J. (2009). Developmental origins of cognitive vulnerabilities to depression: Review of processes contributing to stability and change across time. *Journal of Clinical Psychology, 65*, 1327–1338.

Hinnant, J. B., Elmore-Staton, L., & El-Sheikh, M. (2011). Developmental trajectories of respiratory sinus arrhythmia and preejection period in middle childhood. *Developmental Psychobiology, 53*, 59–68.

Hollenstein, T., McNeely, A., Eastabrook, J., Mackey, A., & Flynn, J. (2012). Sympathetic and parasympathetic responses to social stress across adolescence. *Developmental Psychobiology, 54*, 207–214.

James, K. M., Owens, M., Woody, M. L., Hall, N. T., & Gibb, B. E. (2018). Parental expressed emotion-criticism impacts children's neural reactivity to facial expressions of emotion. *Journal of Clinical Child and Adolescent Psychology*.

James, K. M., Woody, M. L., Feurer, C., Kudinova, A. Y., & Gibb, B. E. (2017). Disrupted physiological reactivity among children with a history of suicidal ideation:

Moderation by parental expressed emotion-criticism. *Biological Psychology, 130*, 22–29.

Joormann, J., & Gotlib, I. H. (2006). Is this happiness I see? Biases in the identification of emotional facial expressions in depression and social phobia. *Journal of Abnormal Psychology, 115*, 705–714.

Jung, T.-P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2001). Analysis and visualization of single-trial event-related potentials. *Human Brain Mapping, 14*, 166–185.

Keil, A., Bradley, M. M., Hauk, O., Rockstroh, B., Elbert, T., & Lang, P. J. (2002). Large-scale neural correlates or affective picture processing. *Psychophysiology, 39*, 641–649.

Kujawa, A., & Burkhouse, K. L. (2017). Vulnerability to depression in youth: Advances from affective neuroscience. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging, 2*, 28–37.

Kujawa, A., Hajcak, G., Danzig, A. P., Black, S. R., Bromet, E. J., Carlson, G. A., ... Klein, D. N. (2016). Neural reactivity to emotional stimuli prospectively predicts the impact of a natural disaster on psychiatric symptoms in children. *Biological Psychiatry, 80*, 381–389.

Kujawa, A., Klein, D. N., & Hajcak, G. (2012). Electrocortical reactivity to emotional images and faces in middle childhood to early adolescence. *Developmental Cognitive Neuroscience, 2*, 458–467.

Kujawa, A., MacNamara, A., Fitzgerald, K. D., Monk, C. S., & Phan, K. L. (2015). Enhanced neural reactivity to threatening faces in anxious youth: Evidence from the event-related potentials. *Journal of Abnormal Child Psychology, 43*, 1493–1501.

Ladouceur, C. D. (2012). Neural systems supporting cognitive-affective interactions in adolescence: The role of puberty and implications for affective disorders. *Frontiers in Integrative Neuroscience, 6*, 1–11.

Little, R., & Rubin, D. (1987). *Statistical analysis with missing data.* New York, NY: Wiley.

Liu, Y., Huang, H., McGinnis-Deweese, M., Keil, A., & Ding, M. (2012). Neural substrate of the late positive potential in emotional processing. *Journal of Neuroscience, 32*, 14563–14572.

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience, 8*, 1–14.

Monk, C. S., McClure, E. B., Nelson, E. E., Zarahn, E., Bilder, R. M., Leibenluft, E., ... Pine, D. S. (2003). Adolescent immaturity in attention-related brain engagement to emotional facial expressions. *NeuroImage, 20*, 420–428.

Nee, D. E., Wager, T. D., & Jonides, J. (2007). Interference resolution: Insights from a meta-analysis of neuroimaging tasks. *Cognitive, Affective & Behavioral Neuroscience, 7*, 1–17.

Pang, K. C., & Beauchaine, T. P. (2013). Longitudinal patterns of autonomic nervous system responding to emotion evocation among children with conduct problems and/or depression. *Developmental Psychobiology, 55*, 698–706.

Park, G., & Thayer, J. F. (2014). From the heart to the mind: Cardiac vagal tone modulates top-down and bottom-up visual perception and attention to emotional stimuli. *Frontiers in Psychology, 5*, 1–8.

Perez-Edgar, K., Bar-Haim, Y., McDermott, J. M., Chronis-Tuscano, A., Pine, D. S., & Fox, N. A. (2010). Attention biases to threat and behavioral inhibition in early childhood shape adolescent social withdrawal. *Emotion, 10*, 349–357.

Perez-Edgar, K., Reeb-Sutherland, B. C., McDermott, J. M., White, L. K., Henderson, H. A., Degnan, K. A., ... Fox, N. A. (2011). Attention biases to threat link behavioral inhibition to social withdrawal over time in very young children. *Journal of Abnormal Child Psychology, 39*, 885–895.

Porges, S. W. (1995). Orienting in a defensive world: Mammalian modifications of our evolutionary heritage. A polyvagal theory. *Psychophysiology, 32*, 301–318.

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74*, 116–143.

Pourtois, G., Schettino, A., & Vuilleumier, P. (2013). Brain mechanisms for emotional influences on perception and attention: What is magic and what is not. *Biological Psychology, 92*, 492–512.

Pourtois, G., Spinelli, L., Seeck, M., & Vuilleumier, P. (2010). Temporal precedence of emotion over attention modulations in the lateral amygdala: Intra-cranial ERP evidence from a patient with temporal lobe epilepsy. *Cognitive, Affective & Behavioral Neuroscience, 10*, 83–93.

Proudfit, G. H., Bress, J. N., Foti, D., Kujawa, A., & Klein, D. N. (2015). Depression and Event-related Potentials: Emotional disengagement and reward insensitivity. *Current Opinion in Psychology, 4*, 110–113.

Robin, A. L., & Foster, S. L. (1989). *Negotiating parents-adolescent conflict: A behavioral-family systems approach.* New York, NY: Guilford Press.

Rozenman, M., Sturm, A., McCracken, J. T., & Piacentini, J. (2017). Autonomic arousal in anxious and typically developing youth during a stressor involving error feedback. *European Child & Adolescent Psychiatry, 26*, 1423–1432.

Sabatinelli, D., Keil, A., Frank, D. W., & Lang, P. J. (2013). Emotion perception: Correspondence of eraly and late event-related potentials with cortical and subcortical functional MRI. *Biological Psychology, 92*, 513–519.

Sabatinelli, D., Lang, P. J., Keil, A., & Bradley, M. M. (2007). Emotional perception: Correlation of functional MRI and event-related potentials. *Cerebral Cortex, 17*, 1085–1091.

Sanchez, A., Vazquez, C., Marker, C., LeMoult, J., & Joormann, J. (2013). Attentional disengagement predicts stress recovery in depression: An eye-tracking study. *Journal of Abnormal Psychology, 122*, 303–313.

Schafer, J. L., & Graham, J. W. (2002). Missing data: Our view of the state of the art. *Psychological Methods, 7*, 147–177.

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in ER and dysregulation. *Journal of Affective Disorders, 61*, 201–216.

Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience and Biobehavioral Reviews, 36*, 747–756.

Vanhalst, J., Gibb, B. E., & Prinstein, M. J. (2017). Lonely adolescents exhibit heightened sensitivity for facial cues of emotion. *Cognition & Emotion, 31*, 377–383.

Wager, T. D., Davidson, M. L., Hughes, B. L., Lindquist, M. A., & Ochsner, K. N. (2008). Prefrontal-subcortical pathways mediating successful emotion regulation. *Neuron, 59*, 1037–1050.

Wessing, I., Rehbein, M. A., Romer, G., Achtergarde, S., Dobel, C., Zwitserlood, P., ... Junghofer, M. (2015). Cognitive emotion regulation in children: Reappraisal of emotional faces modulates neural source activity in a frontoparietal network. *Developmental Cognitive Neuroscience, 13*, 1–10.

Widen, S. C. (2013). Children's interpretation of facial expressions: The long path from valence-based to specific discrete categories. *Emotion Review, 5*, 72–77.

Woody, M. L., & Gibb, B. E. (2015). Integrating NIMH Research Domain Criteria (RDoC) into depression research. *Current Opinion in Psychology, 4*, 6–12.

Woody, M. L., Feurer, C., Sosoo, E. E., Hastings, P. D., & Gibb, B. E. (2016). Synchrony of physiological activity during mother–Child interaction: Moderation by maternal history of major depressive disorder. *Journal of Child Psychology and Psychiatry, 57*, 843–850.