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Are Elevations in ADHD Symptoms Associated with Physiological Reactivity and Emotion Dysregulation in Children?

Julia D. McQuade[1] **· Rosanna P. Breaux**[2]

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Abstract The present study examined whether children with elevated attention-deficit/hyperactivity disorder (ADHD) symptoms display a unique pattern of emotion dysregulation as indexed by both parent report and physiological reactivity during experiences of failure. A sample of 61 children (9 to 13 years; $M = 11.62$, $SD = 1.29$; 48 % male) with and without clinical elevations in ADHD symptoms participated. Parent and teacher report of ADHD and oppositional defiant disorder (ODD) symptoms and parent report of internalizing problems were collected. Parents also provided ratings of children's emotional negativity/lability and emotion regulation. Children's physiological reactivity, based on changes in respiratory sinus arrhythmia (RSA) and skin conductance level (SCL), were assessed while they completed a manipulated social rejection task and impossible puzzle task. Regression analyses indicated that ADHD symptoms were associated with higher parent-rated emotional negativity/lability and with blunted RSA withdrawal in response to social rejection; these effects were not accounted for by co-occurring ODD symptoms or internalizing problems. ODD symptoms also were uniquely associated with parent ratings of poor emotion regulation. Internalizing problems were uniquely associated with emotional negativity/lability, poor emotion regulation, and increased SCL activity in response to social rejection. Results suggest that there may be a pattern of emotion dysregulation that is specific to ADHD symptomatology. The importance of contextual factors when examining physiological reactivity to stress in youth with ADHD is discussed.

Keywords Emotion regulation · Respiratory sinus arrhythmia · Skin conductance level · ADHD · Co-morbidity

✉ Julia D. McQuade
jmcquade@amherst.edu

[1] Department of Psychology, Amherst College, Campus Box 2236, Amherst, MA 01002, USA

[2] Department of Psychological and Brain Sciences, University of Massachusetts Amherst, Tobin Hall, 135 Hicks Way, Amherst, MA, USA

There has been increasing acknowledgement that emotion dysregulation may play a critical role in the manifested functional impairments of children with attention-deficit/hyperactivity disorder (ADHD; Barkley 2015; Martel 2009; Steinberg and Drabick 2015). Children with ADHD display developmentally atypical levels of inattention, hyperactivity, and impulsivity, along with functional impairments in social, academic, and behavioral domains (American Psychiatric Association 2013). In the context of ADHD psychopathology, emotion dysregulation has been defined as the ineffective modulation of subjective, behavioral, or physiological emotional arousal and may include problems related to the escalation, expression, and /or subsequent de-escalation of an emotional response (Bunford et al. 2015a). A recent review (Bunford et al. 2015b) and meta-analysis (Graziano and Garcia 2016) suggest that youth with ADHD evidence the greatest impairments in their emotional reactivity (e.g., threshold, intensity, and duration of emotional responses) and emotion regulation skills (e.g., adaptive generation, modulation, or reduction of emotions).

Despite growing interest in characterizing the emotion dysregulation profile of youth with ADHD, one critical limitation has been a lack of research investigating physiological manifestations of emotional reactivity and regulation. Physiological measures can assist with the identification of biological markers of emotion dysregulation, which ultimately may provide a more fine-grained classification of such problems and more targeted treatment options. Physiological measures also may provide information that is distinct from behavioral and self-report measures, which may describe emotion dsyregulation more globally and are subject to rater bias. In addition, although emotion dysregulation is proposed to be a potential core deficit of ADHD (Barkley 2015; Martel 2009) it also is frequently described as a transdiagnostic risk factor (Bunford et al. 2015a). Thus it is also important for researchers to examine whether there are aspects of emotion dysregulation that are specific to ADHD symptomatology or whether certain emotional challenges result from symptoms that commonly co-occur with ADHD. Consequently, the present study examined whether ADHD symptomatology is uniquely associated with both parent ratings and physiological indicators of impaired emotional reactivity and regulation and whether effects were consistent when accounting for co-occurring oppositional defiant disorder (ODD) and internalizing symptoms.

The majority of evidence suggesting that youth with ADHD suffer from emotion dysregulation comes from laboratory studies that observe children's behavior and from parent report of children's daily functioning (Graziano and Garcia 2016). Coded behavior during laboratory tasks that elicit frustration or emotional reactions suggest that, relative to children without ADHD, children with ADHD are more emotionally intense, display more frequent negative and positive emotions, and use less effective emotion management strategies (Maedgen and Carlson 2000; Melnick and Hinshaw 2000; Walcott and Landau 2004). Parent ratings of emotion dysregulation also suggest that children with elevated ADHD symptoms are characterized by high negative emotionality (Martel et al. 2009), greater emotional lability (Anastopoulos et al. 2011; Seymour et al. 2014; Sobanski et al. 2010), and poorer modulation of emotions (Sjöwall et al. 2013).

As noted above, emotional reactivity and regulation also is reflected in physiological changes, such as changes in sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) functioning. The SNS is involved in the "fight or flight" response whereas the PNS is involved in "rest and digest" functions. During a threatening or stressful situation, individuals typically respond with an increase in SNS and a decrease in PNS functioning. Polyvagal theory argues that the PNS plays a critical biological role in an individual's ability to regulate emotions (Porges 2001, 2003). A common measure of PNS influence is respiratory sinus arrhythmia (RSA), a measure of vagal input on the heart that is based on rhythmic heart rate fluctuations associated with the respiratory cycle (Berntson et al. 1997). A decrease in RSA (i.e., RSA withdrawal), via the vagus nerve, serves to increase heart rate and the mobilization of metabolic resources. In threatening or stressful situations, RSA withdrawal is proposed to support effective emotion regulation (Porges 2001, 2003); however, in non-threatening contexts RSA withdrawal may be maladaptive and indicative of an exaggerated and unfounded emotional response (Beauchaine 2001; Hastings et al. 2008). Interestingly, youth with ADHD display a pattern of inflexible RSA activation during the induction and suppression of positive and negative emotions (Musser et al. 2011), especially when they also show a lack of prosocial behavior (Musser et al. 2013) or an irritable/aggressive temperament (Karalunas et al. 2014). Yet during cognitively challenging tasks, some evidence suggests that ADHD symptoms are associated with exaggerated RSA withdrawal (Beauchaine et al. 2013; Ward et al. 2015); though others do not find ADHD-specific effects (Beauchaine et al. 2001).

Some researchers also argue that SNS reactivity during threatening or stressful situations may reflect emotional reactivity (El-Sheikh 2005; Hubbard et al. 2002). One measure of SNS reactivity is skin conductance level (SCL), which measures activity of the sweat glands (Dawson et al. 2007). In the context of negative stressors, exaggerated SCL reactivity may suggest a more extreme internal negative emotional reaction (Beauchaine 2001; Hubbard et al. 2002) whereas a lack of SCL reactivity may suggest a failure to experience normative levels of fear (Ortiz and Raine 2004). Mixed findings regarding SNS reactivity also exist in the ADHD literature. On a task that included induction and suppression of emotions, SNS reactivity (measured based on cardiac pre-ejection period) did not differ as a function of ADHD status (Karalunas et al. 2014; Musser et al. 2011, 2013). Yet on a cognitively challenging reward and punishment task, preschool children with high levels of ADHD and ODD symptoms displayed less change in SNS arousal than control children (Crowell et al. 2006); other work suggests that this lack of SNS reactivity to reward and punishment may result from co-morbid conduct disorder (CD) rather than ADHD symptoms (Beauchaine et al. 2001).

One critical factor when examining physiological indicators of emotional reactivity and regulation is the specific task used to evoke changes in PNS and SNS functioning (Obradović et al. 2011). Theoretical discussions suggest that reactivity to negative and threatening contexts may have the greatest implications for understanding physiological indicators of emotional reactivity and regulation (Hubbard et al. 2002; Porges 2001, 2003). However, prior ADHD research in this area has used relatively non-threatening tasks (Karalunas et al. 2014; Musser et al. 2011, 2013) or tasks in which perceptions of negativity may vary as a function of children's performance (Beauchaine et al. 2001, 2013; Crowell et al. 2006; Ward et al. 2015). Consequently, the present study examined children's physiological reactivity in response to two different standardized failure experiences that should be perceived as negative: social rejection and attempts to complete impossible puzzles. Youth with ADHD are frequently described as dysregulated and highly reactive in social interactions and in cognitively demanding settings (Abikoff et al. 2002; McQuade and Hoza 2014), suggesting these are contexts in which their emotion regulation capacities are compromised. These are also domains in which children with ADHD evidence functional impairments (e.g., Loe and Feldman 2007; McQuade and Hoza 2014), which could stem in part from physiological dysregulation (e.g., Graziano and Derefinko 2013). However, to our knowledge researchers have not considered whether ADHD symptomatology is associated with a distinct pattern of physiological reactivity in response to social or cognitive challenges.

An additional critical consideration in research examining emotion dysregulation in children with ADHD is the presence of comorbid symptomatology. Although a recent meta-analysis and literature review suggest that emotion dysregulation in youth with ADHD is not fully a function of comorbid symptomatology (Bunford et al. 2015b; Graziano and Garcia 2016), problems with emotion regulation are not unique to children with ADHD (e.g., Eisenberg et al. 2010; Graziano and Derefinko 2013). Co-occurring ODD and internalizing problems are two symptom domains that may be particularly critical to consider (Bunford et al. 2015a). ODD and internalizing psychopathology are both predictive of greater parent-rated emotion dysregulation (e.g., Dunsmore et al. 2013; Kim-Spoon et al. 2013; Rydell et al. 2003) and frequently co-occur with ADHD symptoms (Willcutt et al. 2012). Co-occurring CD symptoms, particularly aggression, also may have implications for emotion dysregulation (e.g., Melnick and Hinshaw 2000); however given evidence that children with CD can either be highly emotionally reactive or callous and unemotional (Herpers et al. 2012), the present study focused exclusively on ODD symptoms.

Some evidence suggests that ADHD is associated with emotion dysregulation above and beyond the effects of internalizing and externalizing symptoms (Bunford et al. 2015b; Seymour et al. 2014). However, other work suggests that ODD or internalizing problems may exacerbate (Melnick and Hinshaw 2000; Sobanski et al. 2010; Sørensen et al. 2011) or even account for emotion dysregulation in youth with ADHD (Factor et al. 2014; Rosen and Factor 2015; Sobanski et al. 2010). Comorbid symptoms may also help to differentiate profiles of physiological reactivity in ADHD samples. Comorbid ODD may contribute to inflexible RSA responding (Karalunas et al. 2014) and to blunted SCL reactivity (Crowell et al. 2006). Internalizing problems also are associated with blunted RSA withdrawal (Graziano and Derefinko 2013), which may be coupled with exaggerated SCL activation (El-Sheikh et al. 2013).

Consequently, the present study examined the extent to which multiple parent-rated and physiological measures of emotional reactivity and emotion regulation were uniquely associated with ADHD symptomatology and considered how effects differed when accounting for co-occurring ODD and internalizing symptoms. Consistent with growing acknowledgement that ADHD symptoms exist along a continuum (e.g., Marcus and Barry 2011) and that diagnostic boundaries often fail to create meaningful distinctions between groups of children (Sanislow et al. 2010), ADHD symptoms were examined dimensionally. RSA and SCL reactivity were examined during an experience of social rejection and while trying to complete impossible puzzles. In order to disentangle the effects of task performance from physiological reactivity, performance during these tasks was fully standardized. We examined whether ADHD symptoms were independently associated with each emotion dysregulation measure, and whether there were unique effects when accounting for overlap between ADHD symptoms, ODD symptoms, and internalizing problems. We hypothesized that all three symptom domains would be independently associated with parent reports of emotion dysregulation and, consistent with polyvagal theory (Porges 2003) and meta-analysis results (Graziano and Derefinko 2013), with blunted RSA withdrawal during the standardized failure tasks. Based on prior research (e.g., Beauchaine et al. 2001; Musser et al. 2011), we did not expect SCL reactivity to be specifically associated with ADHD symptoms but explored whether other symptom domains may be predictive of differences in SCL reactivity. Given limited and mixed prior research, additional hypotheses regarding unique ADHD effects were not made.

Methods

Participants

A sample of 61 children, ages 9 to 13 ($M = 11.62$, $SD = 1.29$), with and without clinical elevations in ADHD symptoms participated in the study. All children had previously participated in a research study that included an ADHD assessment approximately 12 months earlier ($N = 124$; see McQuade et al. 2016 for additional details), enabling us to recruit subjects with a range of ADHD symptom profiles. The ADHD assessment included a structured and semi-structured interview with the parent, parent and teacher report on symptom rating scales, and parent report on a broadband rating scale of psychopathology. To support the dimensional examination of symptoms in the present study, children with ADHD, with subthreshold clinical elevations in ADHD symptoms, and children without ADHD were recruited from the larger sample. However, due to theories that youth with a sluggish cognitive tempo presentation of ADHD do not display emotion dysregulation deficits (Barkley 2015), children with full or subthreshold ADHD were only re-recruited if they displayed at least three symptoms of hyperactivity-impulsivity. In addition, only subjects of parents who had provided contact information for participation in future research were re-contacted. This resulted in 101 eligible subjects, with 61 participating. The final sample was comprised of 23 children previously assigned a diagnosis of ADHD (13 combined, 8 predominantly inattentive, and 2 predominantly hyperactive-impulsive), seven previously classified as subthreshold ADHD (demonstrating at least four symptoms of ADHD in addition to cross-domain impairment), and 31 previously classified as typically developing. In the previous study, children were excluded if they had a history of autism spectrum disorder, bipolar disorder, or a neurologic condition or if their estimated IQ was below 80 on the Kaufman Brief Intelligence Test, Second Edition (Kaufman and Kaufman 2004); however, participants could meet criteria for other disorders. The current sample was 48 % male. Racial distribution was 85 % Caucasian, 5 % Asian, and 7 % other or mixed race; 8 % identified as Hispanic or Latino. The median household income was $100,000, the average parent education level was 16 years ($SD = 1.28$), and 77 % of parents were married or cohabitating.

Procedure

The Amherst College institutional review board approved all study procedures. Parents provided consent and children provided assent prior to participation. A primary caretaker and the child attended two study visits that occurred within the same month ($M = 4$ days apart). To minimize medication effects, participants taking stimulant medication ($n = 10$) discontinued medication on the assessment days. However, three participants taking selective serotonin reuptake inhibitors (SSRI) remained on their medication. During the first study visit children completed initial information used during the social rejection task (e.g., creating a profile) in addition to measures not considered in the present study. At the second study visit children completed the two failure tasks and physiological reactivity was assessed. One research assistant administered the tasks while a second research assistant monitored the physiology equipment. Rating scales were completed by parents during the study visits and by teachers via an online survey system. Families were compensated $100 and teachers were compensated $25.

Measures

ADHD and ODD Symptoms A parent and a primary teacher completed the Disruptive Behavior Disorder Rating Scale (DBD; Pelham et al. 1992), which includes DSM-IV symptoms of ADHD and ODD. Parents rated how often the child displayed each of the DSM-IV symptoms on a scale from 0 (*not at all*) to 3 (*very much*). Consistent with standard scoring recommendations (Pelham et al. 1992), symptoms were considered as present if endorsed as *pretty much* (2) or *very much* (3) present by either the parent or teacher. If teacher data was unavailable ($n = 13$), symptom counts were based on parent report alone. To index symptom levels dimensionally, sums of ADHD and ODD symptoms were each computed. Parent-reported conduct disorder symptoms on the DBD also were collected; however, 93 % of the sample did not display symptoms of conduct disorder, suggesting insufficient variability to examine this symptom domain further. The DBD has good reliability and is able to distinguish between clinical and non-clinical groups of children (Pelham et al. 2005). Cronbach's alphas ranged from 0.85 to 0.95 for parent and teacher reports.

Internalizing Problems Parents completed the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), a broadband measure of behavioral impairments and competencies that includes empirically derived subscales of psychopathology. Parents rated how true a series of behaviors were for their child on a 0 (*not true*) to 2 (*very true or often true*) scale. The empirically derived internalizing problems subscale was used to index broadband internalizing psychopathology. This scale includes items assessing anxious behavior (e.g., "fears certain animals, situations, or places", "nervous, high-strung, tense"), withdrawn behavior (e.g., "would rather be alone than with others", "withdrawn, doesn't get involved with others"), depressed mood (e.g., "cries a lot", "there is very little he/she enjoys"), and somatic complaints (e.g., "feels dizzy or lightheaded", "overtired without good reason"). Raw subscale scores were computed into a standardized *T*-score based on age and gender norms. The internalizing subscale evidences good reliability and is able to discriminate between referred and non-referred children (Achenbach and Rescorla 2001). Cronbach's alpha in the present sample was 0.92.

Parent-Rated Emotion Regulation Parents completed the Emotion Regulation Checklist (Shields and Cicchetti 1997), which assesses the parent's perception of the child's emotionality and regulation. Parents rated how often their child exhibited a series of behaviors on a 1 (*rarely/never*) to 4 (*almost always*) scale. Items were averaged to create two subscale scores: negativity/lability and emotion regulation. The negativity/lability subscale includes 15 items that describe the extent to which the child displays labile and intense emotions (e.g., "has wild mood swings", "can keep his/her excitement under control"); lower scores are more adaptive. Although some items on this scale describe behaviors that overlap with symptoms of ADHD (e.g., "is able to wait for what he/she wants") or ODD (e.g., "is likely to have an angry outburst or easily throws tantrums") results were consistent with these overlapping items deleted from the scale; hence the original scale was used. The emotion regulation subscale includes eight items that describe the extent to which the child understands and responds appropriately to emotions (e.g., "responds positively when another child approaches him/her in a friendly or neutral manner", "is able to say when he/she is feeling sad, angry or mad, fearful or afraid"); higher scores are more adaptive. Cronbach's alphas were 0.90 for the negativity/lability scale and 0.72 for the emotion regulation scale.

Physiological Reactivity Participants completed two standardized failure tasks, in counterbalanced order, while measures of RSA and SCL were collected. Prior to the introduction of each task, a 3 minute resting baseline of RSA and SCL arousal was collected while participants viewed a silent video of fish swimming. After each task, participants completed post-task performance evaluation questions as a manipulation check, followed by an additional 3 minute period of rest. To minimize continued negative emotions after the completion of the first failure task, children were provided with an external excuse for why they had failed (due to a research assistant mistake); they then completed a 3 minute distractor task. This was followed by the second baseline and then the introduction of the second failure task. At the end of the assessment children were debriefed with a parent present.

Social Rejection Task Participants completed a modified version of the Chatroom Interact Task, which manipulates peer acceptance and rejection (Silk et al. 2012). Responses to computerized social rejection experiences have been used successfully by researchers to assess physiological reactivity in middle childhood (e.g., Sijtsema et al. 2011). Evidence also suggests that children's behavior during a chatroom task is consistent with adult ratings of their social behavior more globally (e.g., Mikami et al. 2007). During this task, participants were led to believe that they would be interacting with other peers online; however, in reality the task is computer programmed. At their first study visit, participants answered questions and had their picture taken to create a profile for the task. Participants also viewed photos and profiles of age- and gender-matched fictitious virtual peers and made selections of the peers that they were most interested in chatting with. At the second study visit, participants completed the task on a laptop computer. They were informed that they had been matched with two of the peers they had selected during their first study visit and would have a chance to chat with them online. Participants were then told that each player would first have an opportunity to choose who they would like to chat with about 15 different topics (e.g., friends, music). The order was rigged such that the other two virtual peers always made their choices first. To manipulate peer rejection, the task was programmed so that the participant was not chosen for 12 of the 15 topics (80 % of the time) by each virtual player in consecutive rounds. A large X appeared on the picture of the player who was not chosen. Children's physiological reactivity was measured while the virtual peers made their choices (4.5 min). After the virtual peers had made their choices, children rated how much they thought the peers liked them on a 1 (*not at all*) to 5 (*very much*) scale and how often they were chosen by the peers on a 1 (*never*) to 7 (*all the time*) scale. If the social rejection task was completed first, the research assistant then told the participant that an error had occurred and their profile had not been uploaded correctly, preventing the other players from viewing their profile; the research assistant speculated that this was why the participant was not chosen by the other players.

Impossible Puzzles Participants also completed a cognitive puzzle task that was modified from prior research (Hoza et al. 2001). Impossible puzzle tasks have been successfully used by other researchers to examine physiological reactivity in middle childhood (e.g., Somers et al. 2015). Children were told that they would be completing a timed word search task on a laptop computer. For each of three puzzles, participants were presented with a 15 x 15 matrix of random letters and three nonsense words that they needed to find. Only the first word in the first puzzle was actually hidden in the puzzle; the eight remaining words were not hidden in the puzzle and were therefore impossible to find. Participants were told that they had two minutes to search for the words in each puzzle and that they should continue to search until the research assistant told them the time was up. When time was up, the research assistant provided verbal feedback regarding the child's success (i.e., "you found zero words on that puzzle"). Given that children had some success in the first puzzle, reactivity to the impossible puzzle task was assessed during the second and third puzzles, when failure was fully standardized (4 min). After the task children rated how hard they thought the puzzles were on a 1 (*not at all*) to 5 (*very much*) scale and how many words they were able to find on a 1 (*none*) to 7 (*all*) scale. If the puzzle task was completed first, the research assistant told the participant that she had made an error and had given the participant puzzles that were meant for college students, which have different rules for finding the words; the research assistant speculated that this was why the participant was unable to find the words.

Physiological Measures An ambulatory physiology system (Biolog UFI 3991) was used to measure RSA and SCL arousal. An EKG assessed RSA, with electrodes placed on the left rib cage and sternum and a ground lead placed on the right rib cage. Interbeat intervals were extracted and data was visually inspected and edited using CardioEdit software to correct for outliers (Brain-Body Center 2007). RSA was calculated in CardioBatch based on procedures outlined by Porges (1985). Spontaneous breathing frequency was controlled using a frequency band consistent with the spontaneous respiration of adolescents (0.12 to 1.00 Hz). Amplitude of RSA was calculated based on the natural logarithm of the variances of 30-second epochs, which were averaged. RSA is reported in $\ln(\text{ms})^2$ units. SCL was measured with two Ag/AgCl electrodes attached to the palmer surface of the middle phalanges of the second and third fingers on the non-dominant hand. SCL was quantified as the average electrical conductance in microsiemens. RSA reactivity (RSA-R) and SCL reactivity (SCL-R) during each task were calculated as the difference between average baseline arousal prior to the task and average arousal during the task (reactivity = task arousal—baseline arousal). Positive RSA-R values indicate an increase in PNS activity (termed RSA activation) and negative values indicate a decrease in PNS activity (termed RSA withdrawal). Positive SCL-R values indicate an increase in SNS activity whereas negative values indicate a decrease in SNS activity.

Data Analytic Plan

The primary multiple regression analyses were conducted in MPLUS version 6 (Muthén and Muthén 2010) using maximum likelihood with robust estimators to address missing data and variable skew. Because the models were saturated, fit indices were not interpreted. Reactivity data on both tasks was treated as missing for one child because of extreme non-compliance during the task. Reactivity data on the social task was treated as missing for one additional subject who failed to understand the task. Due to equipment failure, RSA data was missing for four participants on the impossible puzzle task and three participants on the social rejection task. Given evidence that baseline arousal is systematically related to reactivity during challenge tasks (Graziano and Derefinko 2013), the relevant baseline physiological arousal level (RSA or SCL) was included as a covariate when predicting physiological reactivity. Coefficients based on standardized independent and dependent variables were interpreted. A priori power analyses conducted in G*Power (Faul et al. 2007) indicated that a sample size of 55 was sufficient to detect a medium magnitude effect in primary regression analyses.

Results

Preliminary Analyses

Descriptive statistics and correlations of primary study variables are presented in Table 1. ADHD symptoms and internalizing symptoms did not evidence significant skew in this dataset; however, ODD symptoms were significantly positively skewed (Tabachnick and Fidell 2007). Preliminary analyses examined the correlation between dependent variables and demographic variables (child age, gender, non-Caucasian status, non-Hispanic/Latino status, household income, and parent education). Negativity/lability was significantly associated with lower log10 transformed household income, $r = -0.32$, $p = 0.014$, but was unrelated to other demographic variables, $|rs|$ 0.04–0.16, $ps > 0.231$. Emotion regulation was not associated with any demographic variable, $|rs|$ 0.05–0.15, $ps > 0.269$, nor was RSA-R to social rejection, $|rs|$ 0.01–0.18, $ps > 0.188$. SCL-R to social rejection was significantly associated with younger age, $r = -0.36$, $p = 0.005$, but was unrelated to other variables, $|rs|$ 0.02–0.17, $ps > 0.204$. Greater RSA-R to the puzzle task was marginally associated with non-Caucasian status, $r = 0.24$, $p = 0.082$, but was unrelated to other variables, $|rs|$ 0.09–0.21, ps > 0.356. Lower SCL-R to the puzzle task also was marginally associated with non-Caucasian status, $r = 0.25$, $p = 0.055$, but was unrelated to other demographic variables, $|rs|$ 0.02–0.19, $ps > 0.143$. Only significant demographic variables were included as covariates in relevant models. RSA-R and SCL-R during tasks were not significantly associated with children's body mass index (BMI), $|rs|$ 0.00–0.08, $ps > 0.572$. Stimulant medication status was significantly associated with greater RSA-R during the puzzle task, $r = 0.30$, $p = 0.024$, and with marginally greater RSA-R during the social task, $r = 0.26$, $p = 0.060$. No other significant effects between stimulant use or SSRI use and physiological reactivity measures emerged $|rs|$ 0.04–0.15, $ps > 0.268$. The pattern of significant effects was consistent when accounting for stimulant and SSRI use within models. To reduce overlap with symptom domains, medication status was not included in the final model reported.

Manipulation Checks

Children reported on average that the other peers liked them *just a little* ($M = 2.24$, $SD = 0.66$), with 97 % of the sample providing low peer liking ratings of *not at all*, *just a little* or *some*. Children also reported that they were chosen *not very often* ($M = 2.79$, $SD = 0.67$), with 100 % of the sample providing low frequency ratings of *almost never*, *not very often* or *some of the time*. They rated the puzzles as *quite a bit hard* ($M = 4.29$, $SD = 0.67$), with 100 % of the sample providing high difficulty ratings of *very much*, *quite a bit* or *somewhat*. Children also reported that they found *hardly any words* ($M = 1.69$, $SD = 0.57$), with 100 % of the sample providing low frequency ratings of *none*, *hardly any* or *just a few*. During the debriefing, two participants indicated suspicion that the social rejection task was rigged and two different participants indicated suspicion that the impossible puzzle task was rigged; however, these subjects reported that they were unsure if their suspicion was correct while they completed the task. Treating reactivity data for these participants as missing did not change the pattern of results; hence their data was retained in the final analyses. On average, participants demonstrated a

Table 1 Descriptive statistics and correlations of study variables

	Descriptive statistics				Correlations							
	M	*SD*	Range	n	2	3	4	5	6	7	8	9
Symptoms domains												
1. ADHD Symptoms	6.41	6.40	0 − 18	61	0.62***	0.37**	0.64***	–0.36**	0.20	0.11	0.10	–0.06
2. ODD Symptoms	1.52	2.28	0 − 8	61	–	0.38**	0.53***	–0.58***	0.08	0.03	0.06	0.08
3. Internalizing Problems	55.69	11.46	33 − 81	61		–	0.60***	–0.49***	0.17	0.28*	0.02	0.01
Parent-ratings												
4. Negativity/Lability	1.78	0.53	1.00 − 2.93	61			–	–0.57***	0.26+	0.13	0.11	0.03
5. Emotion Regulation	3.41	0.39	2.13–4.00	61				–	–0.20	–0.18	–0.12	0.16
Social Rejection												
6. RSA-R	–0.23	0.83	–2.66–1.13	54					–	–0.06	0.21	–0.11
7. SCL-R	2.42	2.03	–0.22–8.19	59						–	–0.10	–0.07
Impossible Puzzle												
8. RSA-R	–0.41	0.55	–1.45–1.13	55							–	–0.29*
9. SCL-R	2.45	2.63	–2.36–10.96	59								–

Note. ADHD = attention-deficit/hyperactivity disorder; ODD = oppositional defiant disorder; RSA-R = respiratory sinus arrhythmia reactivity; SCL-R = skin conductance level reactivity. Positive negativity/lability scores and lower emotion regulation scores indicate more emotion dysregulation; Positive RSA-R values indicate an increase in PNS activity and positive SCL-R values indicate an increase in SNS activity; $^{+}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

significant decrease in RSA ($p = 0.049$) and increase in SCL ($p < 0.001$) during the social rejection task and during the impossible puzzle task (both $ps < 0.001$), suggesting increases in physiological arousal reflected in PNS withdrawal and SNS activation.

Independent Associations with Symptom Domains

Analyses first examined the independent association of ADHD symptoms with measures of emotion dysregulation, without considering overlapping variance with other symptom domains. Results are displayed in Tables 2 and 3. Greater ADHD symptoms were significantly associated with higher parent ratings of negativity/lability and lower ratings of emotion regulation. In addition, ADHD symptoms were significantly associated with less RSA withdrawal during the social rejection task; though this effect was not supported at the bivariate level (see Table 1). ADHD symptoms were unrelated to the other physiological measures. Follow-up analyses examined whether a similar pattern was found when considering ODD symptoms or internalizing problems as independent predictors. ODD symptoms were also significantly associated with higher parent ratings of negativity/lability and lower ratings of emotion regulation, but were unrelated to physiological reactivity measures. Internalizing problems were significantly associated with higher negativity/lability, lower emotion regulation, and increases in SCL activity during the social rejection task; internalizing symptoms were not independently associated with the other physiological measures.

Unique Associations with Symptom Domains

When ADHD, ODD, and internalizing symptom domains were included in the same model (see Table 2 and 3), ADHD symptoms remained significantly associated with negativity/lability and with increases in RSA during the social rejection task; however, ADHD symptoms were no longer a significant predictor of emotion regulation. In contrast, ODD symptoms and internalizing problems were significantly associated with lower parent-ratings of emotion regulation. Internalizing symptoms also were uniquely associated with greater parent-rated negativity/lability and marginally associated with increases in SCL during social rejection.

Follow-up Associations Between Parent-Ratings and Physiological Measures

In order to ascertain whether physiological reactivity was associated with ratings of emotion dysregulation in daily life, follow-up analyses also examined whether physiological reactivity predicted parent-ratings of negativity/lability and emotion regulation within the full sample. Baseline physiological reactivity was included as a covariate. Parent-rated negativity/lability was significantly associated with increases in RSA during the social rejection task, $\beta = 0.26$, 95 % CI [0.07, 0.46]. Negativity/ lability was not significantly associated with social rejection SCL-R, $\beta = 0.16$, 95 % CI [-0.09, 0.40], impossible puzzle RSA-R, $\beta = 0.08$, 95 % CI [-0.15 − 0.32], or impossible puzzle

Table 2 Independent and unique associations between symptom domains and parent-rated measures of emotion regulation

	Negativity/ Lability			Emotion Regulation		
	β	[95 % CI]	ΔR^2	β	[95 % CI]	ΔR^2
Independent associations:						
ADHD Symptoms	0.62***	[0.46, 0.79]	0.39	–0.36**	[–0.57,–0.15]	0.13
(income)	–0.18**	[–0.30,–0.07]				
ODD Symptoms	0.50***	[0.32, 0.67]	0.24	–0.58***	[–0.77,–0.40]	0.34
(income)	–0.15*	[–0.27,–0.04]				
Internalizing Problems	0.60***	[0.44, 0.76]	0.30	–0.49***	[–0.63,–0.35]	0.24
(income)	–0.01	[–0.23, 0.20]				
Unique Associations:			0.52			0.43
ADHD Symptoms	0.43***	[0.24, 0.62]		.07	[–0.17, 0.31]	
ODD Symptoms	0.10	[–0.07, 0.27]		–0.50***	[–0.76,–0.25]	
Internalizing Problems	0.40***	[0.22, 0.57]		–0.33**	[–0.51,–0.14]	
(income)	–0.03	[–0.18, 0.12]				

Note. ADHD = attention-deficit/hyperactivity disorder; ODD = oppositional defiant disorder. Positive negativity/lability scores and lower emotion regulation scores indicate more emotion dysregulation. Independent associations examined symptom domains in separate models and unique associations included all symptom domains within the same model; log transformed income was included as a covariate when predicting negativity/lability; ΔR^2 reports variance explained above and beyond the effect of covariates; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

SCL-R, β = 0.03, 95 % CI [-0.24, 0.30]. Parent-rated emotion regulation was not significantly associated with social rejection RSA-R, β = -0.16, 95 % CI [-0.35, 0.03] or SCL-R, β = -0.20, 95 % CI [-0.44, 0.05], or impossible puzzle RSA-R, β = -0.04, 95 % CI [-0.40, 0.29], or SCL-R, β = 0.17, 95 % CI [-0.05, 0.38].

Table 3 Independent and unique associations between symptom domains and physiological reactivity to failure

	RSA-R social rejection			SCL-R social rejection			SCL-R impossible puzzle			SCL-R impossible puzzle		
	β	[95 % CI]	ΔR^2	β	[95 % CI]	ΔR^2	β	[95 % CI]	ΔR^2	β	[95 % CI]	ΔR^2
Independent associations:												
ADHD Symptoms	0.25*	[0.04, 0.45]	0.06	0.05	[–0.21, 0.31]	0.00	0.11	[–0.16, 0.39]	0.03	–0.06	[–0.32, 0.20]	0.00
Baseline physiology	–0.55 ***	[–0.78,–32]		0.12	[–0.19, 0.42]		–0.42**	[–0.70,–0.14]		–0.01	[–0.28, 0.26]	
(Child age)				–0.34**	[–0.57,–0.12]							
ODD Symptoms	0.11	[–0.08, 0.29]	0.01	0.04	[–0.19, 0.27]	0.00	0.02	[–0.25, 0.29]	0.02	0.08	[–0.25, 0.42]	0.02
Baseline physiology	–0.54***	[–0.76,–0.31]		0.11	[–0.21, 0.43]		–0.41**	[–0.70,–0.12]		0.00	[–0.28, 0.28]	
(Child age)				–0.35**	[–0.56,–0.15]							
Internalizing Problems	0.14	[–0.06, 0.35]	0.02	0.23*	[0.01, 0.45]	0.05	–0.02	[–0.28, 0.24]	0.02	0.01	[–0.27, 0.29]	
Baseline physiology	–0.53***	[–0.74,–0.31]		0.10	[–0.18, 0.39]		–0.41**	[–0.70,–0.13]		–0.01	[–0.29, 0.27]	0.00
(Child age)				–0.32**	[–0.53,–0.11]							
Unique Associations:			0.06			0.05			0.04			0.03
ADHD Symptoms	0.28*	[0.04, 0.51]		0.00	[–0.30, 0.30]		0.18	[–0.18, 0.53]		–0.17	[–0.44, 0.11]	
ODD Symptoms	–0.10	[–0.30, 0.11]		–0.06	[–0.35, 0.24]		–0.06	[–0.38, 0.26]		0.19	[–0.20, 0.58]	
Internalizing Problems	0.06	[–0.18, 0.30]		0.25+	[–0.01, 0.51]		–0.06	[–0.35, 0.22]		0.01	[–0.30, 0.31]	
Baseline Physiology	–0.55***	[–0.77,–0.32]		0.11	[–0.19, 0.40]		–0.43**	[–0.71,–0.15]		0.00	[–0.26, 0.26]	
(Child age)				–0.31**	[–0.55,–0.08]							

Note. ADHD = attention-deficit/hyperactivity disorder; ODD = oppositional defiant disorder; RSA-R = respiratory sinus arrhythmia reactivity; SCL-R = skin conductance level reactivity. Positive RSA-R values indicate an increase in PNS activity and positive SCL-R values indicate an increase in SNS activity. Independent associations examined symptom domains in separate models, unique associations included symptom domains within the same model; child age is a covariate when predicting SCL-R to social rejection; ΔR^2 reports variance explained above and beyond the effect of baseline physiology and demographic variables; $^{+}p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Discussion

The present study sought to extend our understanding of the emotion dysregulation profile of children with elevated ADHD symptoms. To our knowledge this is the first study to examine both parent ratings *and* physiological indicators of emotional reactivity and emotion regulation in a sample with elevated ADHD symptoms. Results suggest that ADHD symptoms are uniquely associated with emotion dysregulation, reflected in higher parent ratings of emotional negativity and lability, as well as blunted RSA withdrawal in response to an experience of social rejection. These effects were not accounted for by co-occurring ODD symptoms or internalizing problems, suggesting that there may be a pattern of emotion dysregulation that is specific to ADHD symptomatology.

One of the most important contributions of the present study was the examination of PNS and SNS reactivity in children with ADHD using two standardized failure tasks. In the broader child literature, blunted RSA withdrawal (or RSA activation), particularly in response to negative and threatening situations, is generally found to be maladaptive (see Graziano and Derefinko 2013). The present results were consistent with this general effect, suggesting that children with elevated ADHD symptoms fail to demonstrate RSA withdrawal in response to social rejection. In addition, parent ratings of emotional negativity and lability also were associated with both high levels of ADHD symptoms and less RSA withdrawal during social rejection. Though the cross-sectional nature of the data precludes casual conclusions, it may be that in youth with elevated ADHD symptoms high rates of negative and labile emotional reactions result, in part, from a failure to exhibit adaptive RSA withdrawal in response to social challenges. This interpretation is in line with polyvagal theory (Porges 2001, 2003), which proposes that RSA withdrawal during challenging situations enables individuals to effectively regulate emotions, focus attention, and respond adaptively. Given that a similar effect was not found in response to the puzzle task, it also may be that children with high levels of ADHD symptoms show the greatest problems regulating emotions in social contexts (Bunford et al. 2015b). Indeed, the social interaction style of children with ADHD is frequently described as intense and dysregulated (McQuade and Hoza 2014). It is possible that poor RSA regulation during social exchanges contributes to this pattern of impairment. One important direction for future research will be to examine the longitudinal implications of blunted RSA withdrawal in response to social rejection and whether this pattern of reactivity directly contributes to problematic social behaviors.

Interpretation of results also must be couched within the context of other research examining PNS and SNS reactivity in youth with ADHD. For instance, researchers have found that greater ADHD symptoms are associated with exaggerated RSA withdrawal when performing poorly on a measure of short-term memory (Ward et al. 2015) and in response to a challenging block building task (Beauchaine et al. 2013). In addition, others have failed to find ADHD and control group differences in RSA reactivity in response to reward and punishment (Beauchaine et al. 2001; Crowell et al. 2006). Taken together, this literature suggests that children with ADHD demonstrate a different pattern of RSA reactivity depending on the task demands. One critical factor may be the ability of children with ADHD to perform a given task. If children with ADHD find a task more cognitively taxing or more difficult to complete than their non-ADHD counterparts, they may perceive the task as more threatening and therefore evidence greater RSA withdrawal. To disentangle the potential effects of task performance, the present study examined RSA and SCL reactivity during performance standardized social and cognitive failure experiences. In this context, ADHD symptoms were associated with blunted RSA withdrawal during social rejection but were unrelated to RSA reactivity when solving impossible puzzles. Similar task-specific differences in the association between RSA reactivity and adjustment have been found by other researchers when comparing reactivity to social and cognitive tasks (e.g., Obradović et al. 2011), suggesting that the nature of task demands may be a critical factor. Future investigations should therefore consider how contextual factors influence patterns of physiological responding in youth with ADHD. Studies that compare physiological reactivity profiles across multiple tasks may be particularly useful in advancing research.

Results also have important implications for examining the role that comorbid ODD symptoms and internalizing problems play in the emotion dysregulation profile of children with ADHD. Although children high in ADHD symptoms were also rated by parents as more impaired in their ability to understand and respond appropriately to emotions, this association was fully accounted for by ODD symptoms and internalizing problems. In addition, we found that children with more internalizing problems demonstrated greater SCL reactivity in response to social rejection, suggesting a stronger SNS response. This finding fits well with arguments that SCL activation is involved with avoidant and inhibited responding and may reflect an exaggerated reaction of fear and anxiety (Beauchaine 2001). Thus some aspects of emotion dysregulation may not be specific to children with elevated ADHD symptoms, highlighting the importance of examining multiple aspects of emotion dysregulation and comorbid symptomatology.

It also is noteworthy that few correlations between physiological measures and parent-rated measures emerged. For instance, even though children high in internalizing symptoms were also rated by parents as high in emotional negativity and lability and low in emotion regulation, these parent ratings were not associated with SCL reactivity during the social task.

Non-significant associations like these are fairly common in the literature (e.g., El-Sheikh 2005; Hubbard et al. 2002; Quas et al. 2000) and may suggest that behavioral and physiological measures supply distinct information about individuals' experiences of emotions and regulatory processes. Interestingly, in the present study, greater specificity of findings was found when examining the relation between symptom domains and physiological indicators than with parent ratings; it may be that physiological measures provide a more fine-grained assessment of differences in emotionality and regulatory capacities than parent ratings, which may be more subjective and global in nature.

Although results provide important insights regarding emotion dysregulation in children with ADHD, there are several limitations that must be noted. As mentioned previously, the data is cross-sectional; thus, causal conclusions cannot be made. There also may be limitations to the tasks we used to evoke physiological reactivity. In order to standardize performance, tasks were relatively simple in nature and therefore may not fully reflect the complex social and cognitive challenges that youth face in daily life. The chat-room task also may be less socially salient for younger children, who may have more limited experience with social media. In addition, subjects in the present study were withdrawn from stimulant medication only on the day of the assessment. Though stimulant medication status did not account for the significant associations found, stimulant use may have influenced effects. It also is important for researchers to consider alternative approaches to characterizing children's disruptive behavior. For instance, temperamental profiles have shown promise in differentiating children with emotion regulation challenges and may have more specificity than symptom ratings (e.g., Karalunas et al. 2014).

Additional limitations relate to the nature of the sample. To begin, the sample size was small, which limited our ability to detect small magnitude effect sizes and to examine more complex analyses. For instance, moderated mediational effects between ADHD, co-morbidity, and emotion dysregulation (Bunford et al. 2015b) as well as curvilinear associations between RSA and adaptive functioning (Marcovitch et al. 2010) have been found by other researchers; these more complex models should be explored in future research. In addition, because the sample was not specifically recruited for clinical elevations in ODD and internalizing problems, interpretation of findings regarding these symptom domains should be considered preliminary and may be specific to samples with elevated ADHD symptoms. Finally, the sample was primarily Caucasian, with a relatively high socio-economic status level. Thus, results should not be assumed to generalize to all children.

Despite these caveats, the present study adds to a growing body of literature indicating that ADHD is characterized by emotion dysregulation. Results have important implications for treatment and suggest that behavioral and physiological manifestations of emotion dysregulation should be targeted in youth with elevated ADHD symptoms. Mindfulness-based strategies and biofeedback have shown preliminary promise in improving RSA regulation in other clinical populations (Kim et al. 2015; Price and Crowell 2016); though researchers have not considered their efficacy for ADHD samples, it is possible these approaches may be useful adjuncts to current ADHD treatments. Emotion regulation skills also may be promoted in children with ADHD through parent coaching (e.g., Havinghurst et al. 2010). Preliminary evidence suggests that preschoolers with ADHD display improved emotion knowledge and functioning when participating in a behavioral intervention that also coaches parents to respond to children's emotions in ways that promote emotion regulation (termed emotion socialization; Herbert et al. 2013). In light of the present findings, future research in this area should consider whether physiological reactivity influences children's response to these intervention approaches and predicts the clinical course of ADHD.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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