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RESEARCH ARTICLE

Biological signatures of emotion regulation flexibility in children: Parenting context and links with child adjustment

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Abstract

Emotion regulation (ER) is a key facet of positive adjustment throughout the lifespan. Recent theoretical and empirical innovations suggest that current methods for assessing ER are limited, because they measure discrete strategy use instead of ER flexibility and are insensitive to ecologically valid social contexts that influence ER. This is particularly important for studying the impact of parenting on ER development during childhood. The current study ($N = 93$; 47 females; $M_{age} = 6.98$, $SD = 1.12$) examined child ER flexibility during a directed reappraisal task (DRT) with two parenting contexts: passive parent presence or active scaffolding. Two biological signatures of ER flexibility were measured: respiratory sinus arrhythmia (RSA), an index of physiological flexibility; and the late positive potential (LPP), an index of neurocognitive flexibility. Emotion regulation behavior was observed during a frustrating wait, and parents reported on child ER and adjustment. Greater ER flexibility indexed via the LPP and RSA both predicted observed ER during the frustrating wait, but only RSA predicted parent-reported trait ER and fewer adjustment problems. Emotion regulation flexibility indexed by the LPP was bolstered by parent presence and scaffolding of child ER during the DRT, but RSA measures were not sensitive to parenting context. Taken together, the results provide converging evidence for the conceptualization of ER in terms of physiological and neurocognitive flexibility in childhood. Furthermore, among school-aged children, while physiological flexibility broadly predicted parent-reported child adjustment, neurocognitive flexibility may be context-sensitive and predictive of concurrent observed ER.

Keywords Emotion regulation · Child development · Late positive potential · Respiratory sinus arrhythmia · Social context

Introduction

Emotion regulation (ER) is a key developmental capacity that reflects a range of processes underlying the monitoring and modulation of emotional experience and expression. Emotion regulation evolves across development through a confluence of biological, cognitive, and social factors and contributes profoundly to emotional well-being, coping, and resilience in children and adults. Given the fundamental role of ER in positive adjustment across the lifespan (Berking & Wupperman, 2012, review; Zeman et al., 2006, review), it is crucial to identify biobehavioral signatures of ER in childhood.

Emotion Regulation Development

Emotion regulation capacities show continuity and change across development (Compas et al., 2017; Hankin et al., 2016). For example, patterns of ER in infancy consistently predict individual differences in ER later in childhood (Stifter et al., 1999) and contribute to healthy functioning later in life (Fox & Calkins, 2003). Emotion regulation developmental changes are driven by maturation of frontal-striatal circuitry, in which regions supporting regulatory control (e.g., prefrontal cortex) show protracted development across early childhood and adolescence and exert increasing control over regions underlying emotional reactivity (e.g., amygdala) (Casey et al., 2014, 2019; Tottenham, 2017). This circuit maturation allows emotions to be more flexibly regulated via

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efficient prefrontally mediated control (Casey et al., 2019; McRae et al., 2012; Perlman & Pelphrey, 2010).

During the school-aged period, while extrinsic emotional scaffolding and social regulation of emotion by caregivers remains predominant, children show maturation of intrinsic cognitive capacities supporting ER in social contexts. In particular, this period is characterized by a growing understanding of one's own and others' emotions, as well as detection of situational factors and social cues that determine the appropriateness of emotion expression (Eisenberg et al., 2004; Gullone et al., 2010; Rothbart et al., 1992; Stegge & Terwogt, 2007; Thompson, 1994; Zeman et al., 2006). Thus, both intrinsic and extrinsic processes interact to lay the groundwork for more internalized, independent, and effortless ER strategy use with age (Cole et al., 2018; Cole et al., 2019; Perry & Calkins, 2018).

Conceptualizing ER Adaptiveness

Adaptive ER during childhood promotes adult well-being (Berking & Wupperman, 2012, review; Zeman et al., 2006, review). For example, the ability to downregulate negative emotions minimizes the influence of early life stressors, resulting in fewer symptoms of psychopathology later in life (Beck, 1979; Cicchetti & Rogosch, 2009; Cloitre et al., 2005; Dvir et al., 2014). In contrast, individuals exhibiting symptoms of psychopathologies, including depression and anxiety, display or report the use of relatively maladaptive ER strategies, such as suppression and rumination, and tend to have more difficulties with ER compared with controls (Aldao et al., 2010, review; Dennis, 2007; Eftekhari et al., 2009; Garnefski et al., 2007; Haga et al., 2009; Martin & Dahlen, 2005; Moore et al., 2008).

Despite decades of research substantiating links between discrete ER strategies and adjustment, recent meta-analyses (Aldao et al., 2010; Webb et al., 2012) show that use of reappraisal, as well as other strategies commonly deemed adaptive, only predict adjustment with small- to medium-effect sizes. A unitary focus on discrete strategies, such as reappraisal, which involves thinking about an upcoming unpleasant emotional experience in a more positive light (Campos et al., 1989; Dennis & Hajcak, 2009; Gross, 1998a, 1998b, 2015; Gross & John, 2003; Gross & Levenson, 1993; Gross & Thompson, 2007; Moser et al., 2006; Ochsner & Gross, 2005; Troy et al., 2013; Urry, 2009), may fail to capture broader aspects of ER as well as social and extrinsic influences. In contrast, recent theoretical innovations (Bonanno & Burton, 2013; Myruski et al., 2019, b) argue that ER may be most accurately measured in terms of *flexibility* in the face of situational demands or opportunities (Bonanno & Burton, 2013). One way to conceptualize a facet of ER flexibility is in terms of the breadth of dynamic emotional range (Myruski et al., 2019, b), which can capture not only whether an individual can modulate emotions or not, but to what degree. Furthermore, ER flexibility may be most appropriately measured in the context of ecologically valid social support.

ER flexibility, measured as magnitude of emotional range, is a stable and clinically relevant individual difference. For example, Westphal et al. (2010) showed that the degree to which participants flexibly modulated (increased and decreased) their emotional expressions to unpleasant stimuli was consistent over 3 years. Furthermore, Zhu and Bonanno (2017) measured facial electromyography (EMG) following prompts to increase, decrease, and maintain personal emotional reactions to unpleasant images. Individuals who demonstrated a broader range of emotional facial expressions reported fewer depressive symptoms. Similarly, following the 9/11 terrorist attacks, individuals with a greater range of emotional flexibility, as measured by observed facial expressions in a directed reappraisal task, showed fewer long-term negative consequences of the event years later (Bonanno et al., 2004). Thus, the ability to flexibly increase and decrease emotional experience and expression is longitudinally related to aspects of positive adjustment (Bonanno, 2005; Bonanno et al., 2004; Coifman et al., 2007).

While a growing body of research has examined ER flexibility in adults (Bonanno & Burton, 2013), little is known about ER flexibility in childhood. This in part is due to methodological challenges, including an overreliance on self-report measures that place a burden on children's developing language and introspection capacities. In addition, crucial contextual factors that influence childhood ER, such as the parent-child social context, must be considered. Research assessing biological signatures of ER flexibility, measured in developmentally appropriate parenting contexts, can address these challenges(Cole et al., 2004).

Biological Signatures of ER Flexibility

Respiratory sinus arrhythmia. The interaction of the sympathetic nervous system (SNS) and parasympathetic nervous system (PSNS), which maintains physiological homeostasis during rest and influences emotional arousal, can be indexed by respiratory sinus arrhythmia (RSA) or the change in interbeat intervals of the heart across the respiration cycle (Porges, 1995, 2001, 2007). RSA measured at baseline has been shown to reflect broad ER capacity in both children and adults (Calkins, 1997; Calkins & Dedmon, 2000; Calkins & Keane, 2004; Dennis et al., 2012, review; Eisenberg et al., 1995; Fabes et al., 1993; Porges, 1996, 1997).

More recently, however, RSA *flexibility* measured via dynamic change in RSA activity from rest to emotional challenge has been linked to ER and adjustment. Specifically, because high resting state RSA, or greater PSNS engagement, indicates adaptive induction of calm during periods of safety, greater *reduction* in RSA during an emotional challenge—or RSA suppression (ΔRSA)—reflects adaptive PSNS disengagement and SNS engagement or preparation to cope with unpleasant emotions (Porges, 2007). In a longitudinal study tracking RSA throughout early childhood, Calkins and Keane (2004) found that ΔRSA corresponded to less emotional negativity, better social skills, and fewer behavioral problems. Furthermore, greater (more negative) ΔRSA also corresponds to greater reported use of ER strategies and less emotion dysregulation in children (Blandon et al., 2008; Calkins & Keane, 2004; Gottman & Katz, 2002; Hessler & Fainsilber Katz, 2007), including more positive engagement with an experimenter during a frustrating waiting task (Calkins, 1997) and less use of dysregulated ER strategies like defiance (Calkins & Dedmon, 2000). Thus, ΔRSA has shown promise as an index of ER flexibility that predicts observed ER. While previous studies have focused on the link between RSA and adaptive social-emotional functioning (Gentzler et al., 2009; Graziano & Derefinko, 2013; Hastings et al., 2008), examination of RSA during complex parent-child social interactions is lacking (Calkins, 2007; Calkins et al., 2007; Calkins & Dedmon, 2000; Hastings & De, 2008; Skowron et al., 2013).

Late positive potential. While RSA is a downstream peripheral measure of cortical control over physiological processes (Lane et al., 2009; Thayer & Lane, 2000), scalp-recorded event-related potentials (ERPs) can more directly index neural activity reflecting emotion and its' modulation. The late positive potential (LPP) is a slow, positive-going waveform that emerges starting around 200 to 300 milliseconds after a visual stimulus is presented and is maximal at posterior recording sites on the scalp, including occipital sites in children (Hajcak & Dennis, 2009; Kujawa et al., 2013). Greater LPP amplitudes reflect increased attention to and selective perceptual processing of motivationally salient emotional material (Cuthbert et al., 2000; Foti & Hajcak, 2008; Hajcak & Nieuwenhuis, 2006; Schupp et al., 2000).

Given these properties, the LPP has been used as a neurocognitive index of ER across the lifespan (Dennis & Hajcak, 2009; Desatnik et al., 2017; Paul et al., 2013). For example, when adults are asked to engage in cognitive reappraisal by preemptively reinterpreting the meaning of an upcoming unpleasant image in a more positive or neutral way, the magnitude of LPP amplitudes are reduced (Foti & Hajcak, 2008; Hajcak & Nieuwenhuis, 2006; MacNamara et al., 2011; Paul et al., 2013; Schupp et al., 2000). Furthermore, LPP amplitudes are associated with subjective experience of emotional arousal (Cuthbert et al., 2000). Thus, this reappraisal-induced LPP reduction has been interpreted as reflecting decreased emotional arousal resulting from interpretation of the stimuli as less motivationally salient and requiring reduced attentional and perceptual processing (Foti & Hajcak, 2008; Hajcak & Nieuwenhuis, 2006; Hajcak et al., 2010; Hajcak & Olvet, 2008; Moser et al., 2006). Children also show enhanced LPPs to unpleasant and pleasant emotional images compared with neutral (Dennis & Hajcak, 2009; Hajcak & Dennis, 2009; Kujawa et al., 2012, b) and show reappraisal-induced reductions in the LPP (DeCicco et al., 2014) that in turn predict lower parent-reported anxiety symptoms (DeCicco et al., 2014; Dennis & Hajcak, 2009).

The degree to which LPP amplitudes are dynamically modulated may reflect ER flexibility (Hajcak & Nieuwenhuis, 2006; Moser et al., 2009; Myruski et al., 2019, b). For example, restricted change in the magnitude of the LPP between conditions in which participants are instructed to increase or decrease emotion predicts ER difficulties and clinical symptoms including panic (Zhang et al., 2016), high trait anxiety (Qi et al., 2016), and suicidal ideation (Kudinova et al., 2016). In a recent study (Myruski et al., 2019, b), adults showing a greater range of LPP change also reported greater overall coping flexibility.

In children, salient individual differences in reappraisal-induced reduction of the LPP during ER conditions may correspond to neurodevelopmental and age differences in childhood (Babkirk et al., 2015; DeCicco et al., 2012). For example, one study (Babkirk et al., 2015) demonstrated that only approximately half of children 5 years of age evidenced decreased magnitude of the LPP during reappraisal relative to a maintain emotion condition but that this adult-like sign of ER predicted observed ER 2 years later. However, this prior study categorically grouped children based on whether they showed significant reappraisal-induced reduction of the LPP, without focusing on the magnitude of this reduction, which more directly reflects ER flexibility (Myruski et al., 2019, b). Importantly, given the crucial role of parents in young children's ER (Baker et al., 2007; Sales & Fivush, 2005), children's ER flexibility may be underestimated in the absence of a supportive social context, which may account for the prior mixed findings regarding the ability of school-aged children to demonstrate ER via the LPP.

Emotion Regulation in the Context of Parenting

ER in childhood has a prominent social component given the degree to which parents support child ER efforts. Through emotion-related socialization (Eisenberg et al., 1998), parents shape their children's emotional functioning by how they react to their child's emotions, active discussion of emotion, and the parent's own expression and regulation of their emotions (Camras & Shuster, 2013, review; Morris et al., 2007; Halberstadt & Eaton, 2002; Halberstadt et al., 1999). Thus, examining child ER in the context of parenting should maximize ecological validity and generalizability of results.

Consistent with this approach, Social Baseline Theory (Beckes & Coan, 2011) suggests that neurocognitive capabilities are most accurately measured when an individual is assessed in a social context, because the human brain evolved to adapt to emotional stress in social environments. Accordingly, a series of studies with adults demonstrated that threat-related neural activity was reduced in the presence of a socially supportive other relative to a stranger (Coan et al., 2005; Coan et al., 2006; Coan & Maresh, 2014). Similar patterns have emerged in studies with children (Gee et al., 2014; Tottenham, 2015). For example, Gee et al. (2014) showed that children who viewed a picture of their mother, compared with those viewing a picture of a stranger, evidenced greater amygdala-prefrontal connectivity, which is associated with mature ER. This study further suggests that ER may be bolstered during an emotional challenge when a parent versus stranger is present. In the current study, we tested the influence of parents' mere presence on neurocognitive and physiological measures of ER flexibility.

In addition to the impact of the mere presence of a parent on child ER, elaborative socioemotional interactions also contribute to children's ER and self-regulation capacity (Eisenberg et al., 1998; Maccoby, 1992). Social scaffolding is a technique through which parents can increase their children's functioning in a given domain at a level exceeding what they could achieve alone (Bibok et al., 2009; Wood et al., 1976). Effective scaffolding practices draw a child into the zone of proximal development, or the range of ability just above the child's individual functioning, but below the full ability of the parent (Vygotsky, 1978; Wood et al., 1976).

Scaffolding of social-emotional processes, such emotion expression and ER also occurs (Dix, 1991; Gottman et al., 1997; Mermelshtine, 2017; Morris et al., 2011). One such form of scaffolding, emotion coaching, involves emphasizing and placing value on a child's emotional experience and proactively helping them learn to manage and express their emotions through direct instruction (Fabes et al., 2001; Lunkenheimer et al., 2007; Morris et al., 2007) and acceptance (Clarke-Stewart & Beck, 1999; Ramsden & Hubbard, 2002).

Current Study

The goal of the current study was twofold: 1) to examine the social-context sensitivity of the LPP and RSA as biological signatures of ER flexibility; and 2) to test the utility of these metrics by examining their associations with observed ER and adjustment. To capture a period of rapid ER-related neurodevelopment, we targeted ages 5-8 years consistent with prior literature (DeCicco et al., 2012; Tottenham, 2015).

This study is the first to our knowledge to concurrently measure ΔLPP and ΔRSA and to conceptualize them both as ER flexibility metrics reflecting recruitment of biological resources during varying emotion regulation and social contexts. Both RSA and the LPP were measured during two distinct social contexts with a parent (mere presence and active scaffolding) while children simultaneously completed a directed reappraisal task (DRT). This task was chosen because reappraisal has been shown to have positive stress-buffering effects in childhood (Beck, 1979; Cicchetti & Rogosch, 2009; Cloitre et al., 2005; Dvir et al., 2014). The current study will target the magnitude of change in biological signatures across conditions (i.e., directed ER vs maintain emotion) to capture individual differences in ER flexibility. Furthermore, to examine associations between ER flexibility and observed child ER, children engaged in an emotional challenge with parents during which both behavioral ER and RSA suppression (ΔRSA) were measured.

The first hypothesis was that children who complete the Directed Reappraisal Task (DRT) while parents provide scaffolding, versus alone, will show greater ER flexibility measured via reappraisal-induced ΔRSA and ΔLPP. Children who complete the task with parents merely present will show intermediate levels of ER flexibility indexed by the LPP and RSA.

The second hypothesis was that greater ER flexibility measured during the DRT will predict observed ER during an emotional challenge and greater parent-reported child emotional adjustment. Given the possibility that the LPP and RSA may be differentially sensitive to context, we posited that these biological signatures would be likely to predict outcomes regardless of social context manipulations. Exploratory analyses examined whether flexibility measured via ΔRSA versus ΔLPP differed in their association with ER and adjustment.

Method

Participants

Ninety-seven 5- to 9-year-old children [49 (50.5%) females; M_{age} = 6.96, *SD* = 1.15] were recruited to participate along with the primary caregiver of each child.[1] Seven children were excluded from the EEG analyses due to technical error ($n = 1$), unusable recording ($n = 4$)[2], or EEG refusal ($n = 2$). Twelve

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[1] Subset of the current sample was included in a cross-cultural comparison (Myruski et al., 2019a), which only included children aged 5-7 years and did not include ECG or observed ER data.

[2] In two cases, technical errors caused the EEG data to not be recorded, and in two cases an insufficient number of trials remained following artifact rejection (see EEG processing and LPP quantification).

children were excluded from the ECG analyses due to unusable recordings ($n = 11$)[3] or ECG refusal ($n = 1$).[4] Thus, 90 [45 (50.0%) female; $M_{\text{age}} = 7.07$, $SD = 1.12$] children were included in all EEG analyses, and 85 [46 (54.1%) female; $M_{\text{age}} = 7.02$, $SD = 1.15$] were included in all ECG analyses.

Participants were recruited from the New York City community via multiple sources (e.g., Facebook advertisement, parenting blogs, family-oriented community events, Craigslist) to maximize the sample diversity. The ethnicities of included children were as follows: 38 (40.9%) white; 19 (20.4%) black/African American; 8 (8.6%) Hispanic/Latino; 9 (9.7%) Asian; 3 (3.2%) black and another category; 1 (1.1%) Hispanic and another category; 2 (2.2%) reported other; and 13 (14.0%) opted not to answer. Parents included consisted of 88 (94.6%) mothers and 5 (5.4%) fathers. Parent education ranged from high school (9th grade) to doctorate level (*median* = bachelor's degree), and annual household income ranged from less than \$10,000 to \$150,000 and up (*median* = \$70,000 to \$90,000).

Phone screens were conducted with parents before appointment scheduling to exclude participants with previous and/or current psychological disorders, such as autism or attention deficit hyperactivity disorder and language or learning delays. Parents were compensated \$50, and children received a sticker page, astronaut ice cream, and a small gift (e.g., slinky).

Materials and Procedure

The study lasted approximately 3 hours with breaks included and proceeded as follows: (a) informed consent and assent (10 min)[5]; (b) parent questionnaires (20 min); (c) ECG and EEG application (30 min); (d) baseline task (10 min); (e) directed reappraisal task (45 min); (f) clean-up (15 min); (g) break (10 min); (h) waiting task (10 min)[6]; (i) debriefing (10 min).

Questionnaires

Emotion Regulation Checklist. Parents completed the emotion regulation checklist (ERCL) (Shields & Cicchetti, 1997), a 24-item measure of child ER (e.g., "my child is easily frustrated") using a response scale of (1) rarely/never to (4) almost/always. This measure yields subscales [positive regulation ($\alpha = 0.83$) and emotional lability/negativity ($\alpha = 0.96$)]. Because these scales have been shown to be significantly intercorrelated ($r = -0.50$, $p < 0.001$; Shields & Cicchetti, 1997; $r = -0.40$, $p < 0.001$; current study), a single overall ER score was generated by averaging the positive regulation and emotional lability/negative scale (reversed). This total ER scale has been shown to have acceptable internal consistency ($\alpha = 0.89$), which was confirmed in the current sample ($\alpha = 0.79$).

Screen for Child Anxiety Related Emotional Disorders (SCARED - Parent Version). The SCARED (Birmaher et al., 1997) is a 41-item measure of child anxiety symptoms (e.g., "My child is nervous.") reported by the parent on a scale from (0) not true or hardly ever true to (2) very true or often true. The current study targeted the total anxiety scale, an aggregate score, including symptoms of general anxiety disorder, panic disorder, separation anxiety disorder, school anxiety, and social anxiety. Each subscale and the total anxiety scale demonstrated internal consistency ($\alpha = 0.74$-0.93; Birmaher et al., 1997), which was confirmed for the total anxiety scale in the current sample ($\alpha = 0.87$).

Child Behavioral Checklist (CBCL). Parents also completed the CBCL (Achenbach & Rescorla, 2001). Five-year-olds were assessed using the CBCL for ages 1½ to 5 (100 items), and 6-, 7-, and 8-year-olds were assessed using the CBCL for ages 6 and up (113 items). For both versions, parents reported on their child's emotional and behavioral problems (e.g., "cries a lot") on a scale from (0) not true to (2) very true or often true. The total problems scale is an aggregate score, including internalizing, externalizing, and other problems, and was the target of the current study. This total problems scale has been shown to be internally consistent ($\alpha = 0.80$; Achenbach & Rescorla, 2001). Reliability for the current sample was also established ($\alpha = 0.95$).

Electrocardiography (ECG) and Electroencephalography (EEG) Application Following completion of questionnaires, a Biopac MP150 wireless system (Biopac Systems, CA, USA) was applied. Sticker-based electrodes were placed on each clavicle, and one on the left rib, and were connected via three leads to a small box attached to a Velcro strap attached around the child's waist. ECG data were wirelessly transmitted to a computer to allow for ambulatory recording with Acqknowledge v4.4 software. ECG was recorded continuously during baseline tasks, the DR task, and two behavioral tasks; manual event-markers indicated the beginning and ending of each task. Following ECG application, children were fitted with an elasticized nylon EEG cap, and electrodes were applied according to the international 10/20 system while he/she watched cartoons on the computer outside the EEG booth. EEG was recorded during the DR task using Biosemi 64 Ag/AgCl active scalp electrodes sampled at 512 Hz. Eye movements were measured by electro-oculogram (EOG) signals from electrodes placed around each eye. To monitor vertical eye movements, electrodes were positioned 1 cm above

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[3] ECG recordings were unusable due to either disruption in wireless signal transmission or leads becoming detached during recording.

[4] Pattern of results pertaining to EEG did not differ when conducted without those participants missing ECG data.

[5] Written, informed consent and verbal informed assent was obtained prior to any data collection and in accordance with the Hunter College, CUNY IRB.

[6] The order of (e., f.) the DRT and (g.) behavioral tasks block was counterbalanced across participants in the original study protocol. However, due to significant movement artifacts and child distress during the DRT when it was completed at the end of the 3-hour visit, all subsequent children completed the DRT before behavioral tasks.

and below the left eye and to monitor horizontal eye movements electrodes were positioned 1 cm from the outer edge of each eye. Preamplification of the EEG signal was applied at each electrode during recording to improve the signal-to-noise ratio. The voltage from each electrode was referenced online with respect to the common mode sense active electrode, which produces a monopolar (nondifferential) channel.

Baseline Task To compare biological indicators of ER flexibility in behavioral challenges with an emotionally neutral baseline, children completed a computerized baseline task lasting approximately 5 minutes. Children were instructed to follow audio directions to either open or close their eyes for periods of 20 seconds. During eyes-open trials, children were instructed to look at a cartoon rocket ship that will appear on the screen. During eyes-closed trials, children were instructed to relax and keep their eyes closed until they hear the next instruction. A total of 14 trials (7 eyes-open, 7 eyes-closed) were presented randomly. ECG was recorded continuously throughout the baseline task.

Directed Reappraisal Task Children completed one of three versions of a computerized Directed Reappraisal Task [DRT; adapted from DeCicco et al., 2012], during which ECG and EEG were simultaneously recorded. Child and parent (when applicable) behavior also was video recorded for subsequent coding of child engagement. In each version of the DRT, children viewed a total of 30 unpleasant and 15 neutral images from the International Affective Picture System (IAPS). The stimuli were presented in three conditions (negative, reappraisal, neutral), counterbalanced across participants, each condition lasting approximately 10 minutes with breaks offered between conditions. Based on random assignment, one third of the sample was placed in the Parent-Absent Group and completed the DRT without parent assistance. In this version of the task, picture stimuli were preceded by auditory stories that are played twice in a row to ensure comprehension. Children were instructed to think about each picture so that it matched the preceding story. Unpleasant pictures (e.g., snake) were paired with either a preceding negative ("This poisonous snake is very dangerous.") or reappraising story ("This snake is harmless; it doesn't have teeth."), which framed how the children should interpret the subsequent picture. Neutral pictures were preceded by neutral stories. Each story was followed by a 500-millisecond delay before picture stimulus onset. Pictures were then presented for 2,000 millisecond with a 1,500 millisecond intertrial interval between each picture and the next story.

Another third of the sample were assigned to the Parent-Present Group. This version of the task is identical to the other nonscaffolding version, except that the parent was present in the recording booth but did not interact with the child or participate during the DRT. Parents were instructed to sit comfortably on a stool behind the child and complete a questionnaire while their child completed the computer task. Parents were asked to refrain from interacting with their child, except to redirect their attention back to the computer should the child attempt to talk to them. The purpose of including this condition in the experimental design was to examine the impact of the mere presence of the parent on children's neurocognitive responses to the DRT.

Finally, the remaining third of the sample were placed in the Parent-Scaffolding Group and completed a DRT during which parents scaffolded child reappraisal. The parameters of this DRT were the same as the one used for the other groups, except that parents sat in the recording booth with their child *and* participated actively in the task. During each trial, parents read aloud a scaffolding script that appeared on the computer screen (e.g., Mom reads: "Next we will see a picture of a snake. Most snakes are harmless, and they don't come close to people."), followed by the same audio story used in the nonscaffolding versions of the DRT (e.g., "This is a snake that is completely harmless; it doesn't even have teeth."), followed by the picture stimulus. To allow for differences in reading speed, the parent clicked the mouse to manually advance to the next part of the trial after they read each scaffolding script. Parents received instructions for how to complete the task earlier during the EEG application period, so that they had time to prepare. Parents were instructed to read the scaffolding scripts in a neutral but natural tone and to refrain from elaborating on the story in any way except what is prompted on the screen.

Following the DRT, the EEG cap and ECG leads were removed. Participants cleaned up briefly and then took a 5–10-minute break.

Waiting Task Following the break, ECG leads were reapplied before children and parents completed the waiting task (WT) (Cole et al., 2003) in which children are asked to wait to open an attractively wrapped gift until their parent completes paperwork in the same room. Before the start of the task, the researcher gave the parent a questionnaire to complete, placed a gift on the table, and gave the child a small, boring toy (a plastic fish). Parents were instructed to read the following prompt to their children: "This is a surprise for you, but you must wait until I finish my work to open it." The goal of this task was for children to inhibit themselves from opening the present. Parents were free to interact with their children as they wished, allowing for variability in the tendency to scaffold their children's attempts at ER. This task lasted 10 minutes and was video recorded for subsequent coding.

Debriefing Parents and children were first debriefed separately during which researchers explained the main goals of the study. The parent and child were then brought together to discuss their experiences and ask any remaining questions. If the child reported any moderate to severe emotional distress or endorsed any questionnaire items of concern (e.g., suicidality, bullying), this was discussed during debriefing. All participants were given contact information for family and child-oriented mental health resources.

ECG processing and RSA quantification The ECG was segmented during recording based on the onset and offset of the baseline task and behavioral tasks. Also, ECG was segmented based on the onset and offset of each DR task condition (reappraisal, negative, neutral) to compare RSA differences between conditions. Mindware 3.14 Software was later used to process data, reject artifacts, and compute scores. Interbeat intervals (IBI) were defined as the temporal distance between R-spikes, which represent the contraction of the ventricles of the heart. ECG recordings were segmented into 30-second sections, which were each manually inspected for missing or incorrectly labeled R-spikes. Segments with greater than 10% artifacts were not included in computed scores, consistent with criteria used in previous studies (Blandon et al., 2008). A frequency band-pass filter was applied ranging from 0.24 to 1.04 Hz, which represents the range of spontaneous respiration, consistent with previous studies examining RSA in children (Hastings et al., 2008; Skowron et al., 2013). The Porges (1985) method was used to calculate RSA by applying an algorithm to the heart period data via Mindware software, which results in natural log transformed variance in heart rate period while accounting for respiration in units of $\ln(\mathrm{ms})^2$.

As a manipulation check, we first examined whether RSA differed across the target within-subject conditions (reappraisal, negative) during the DRT by conducting a paired-samples *t*-test. For the sample as a whole, there was no significant difference in RSA in the reappraisal versus negative condition [$t\ (84) = -0.289$, $p = 0.773$].

RSA suppression (ΔRSA) was quantified using residual scores, which have been used in prior studies comparing biological responses to emotional stimuli (Myruski et al., 2017), and which offer an advantage over subtraction scores such that residuals are less vulnerable to bias induced by intercorrelation with the baseline (Weinberg et al., 2014, 2015). ΔRSA scores in the DRT were computed to reflect reappraisal-induced ΔRSA by generating residuals with baseline RSA as the predictor, RSA in the negative condition as a covariate, and RSA in the reappraisal condition as the outcome. ΔRSA scores in the WT were also computed by generating residuals with baseline RSA as the predictor, and RSA in the WT as the outcome. In both cases, more negative ΔRSA scores indicated greater ability to flexibly engage regulatory processes to reduce emotional arousal, the targeted physiological indicator of ER flexibility.

EEG processing and LPP quantification Brain Vision Analyzer (Version 2.2, GmbH, Munich, DE) was used to prepare the EEG data. All data were re-referenced offline to the mastoids and filtered with a low cutoff frequency of 0.1 Hz and a high cutoff frequency of 30 Hz. Stimulus-locked data were segmented into epochs for each trial ranging from 400 ms before picture onset to 2,000 ms after (length of stimulus presentation), with a 400-ms baseline correction. Ocular correction was performed to identify and correct blinks and horizontal eye movements (Gratton, Coles, & Donchin, 1983). Artifacts were identified using the following criteria and removed from analyses: data with voltage steps greater than 75 μV, changes within a given segment greater than 200 μV, amplitude differences greater than 120 μV in a segment, and activity lower than 0.2 μV per 100 milliseconds. In addition to this semiautomatic identification of artifacts, trials were visually inspected for further artifacts, which were removed on a trial-by-trial basis.[7] All EEG parameters used were consistent with other studies with children in this age range (Babkirk et al., 2015; DeCicco et al., 2012).

Electrode sites and time window of the LPP were delineated based on prior research using the LPP to examine emotional processes in the target age group (Babkirk et al., 2015; Kujawa, Hajcak, et al., 2012). The early window was specifically targeted for analyses, because previous studies (Babkirk et al., 2015) have shown that this segment of the LPP predicts ER strategy use in children. Furthermore, because there is some variability in the electrodes and time windows across these prior studies, we finalized our selections by selecting the maximal region from the grand average waveform collapsed across all conditions, as recommended by Luck and Gaspelin (2017). Thus, the LPP was quantified as the mean amplitude from 250 to 800 ms post-stimulus onset at electrode sites PO3, PO4, PO7, PO8, POz, O1, Oz, O2, and Iz for each stimulus type (negative, reappraisal, neutral) within the DRT (Fig. 1).

As a manipulation check, we examined whether the LPP differed across the target within-subject Conditions (reappraisal, negative) during the DRT by conducting a paired-samples *t*-test. We confirmed that, as previous studies (Hajcak & Nieuwenhuis, 2006) have shown, LPP amplitudes were significantly lower in the reappraisal ($M = 27.60$, $SD = 11.14$) versus negative ($M = 30.87$, $SD = 13.62$) condition, $t\ (89) = 3.33$, $p = 0.001$.

As with the ΔRSA metric, ER flexibility via the LPP (ΔLPP) was assessed by computing residual scores, with LPPs in the negative condition as the predictor, and LPPs in the reappraisal condition as the outcome. Greater negative residual scores indicate a greater reappraisal-induced

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[7] Participants with fewer than eight artifact-free trials for one or more condition were removed from analysis, consistent with Moran, Jendrusina & Moser (2013) who showed that the LPP becomes reliable at that benchmark. Average trial counts out of a total possible 30 trials for each condition are as follows: Negative ($M = 27.13$; $SD = 4.48$); Reappraisal ($M = 27.38$; $SD = 4.15$); Neutral ($M = 26.87$; $SD = 3.31$).

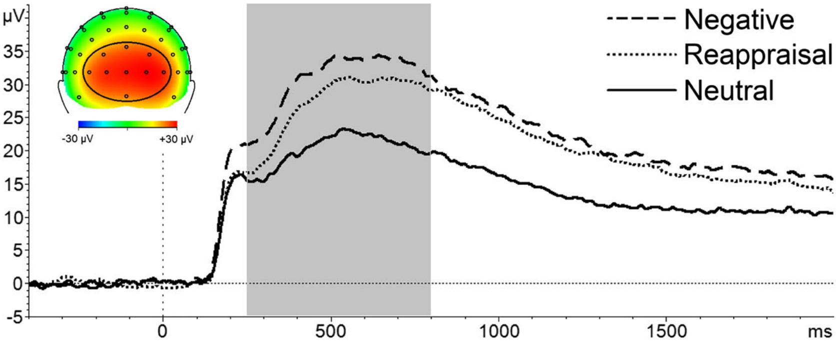

Fig. 1 LPP was segmented between 250 and 800 ms following stimulus onset. The waveform represents grand average amplitudes averaged across social context groups, separately for each condition during the Directed Reappraisal Task. Topographic map represents grand average mean activity during the target time window. The manipulation check showed the expected differentiation of the LPP across conditions, with reduced amplitudes in the reappraisal versus negative condition

reduction of the LPP, the targeted neurocognitive indicator of ER flexibility.

Behavioral Coding.

Directed Reappraisal Task: Child Engagement The DR task was coded using a scheme developed by the researchers to examine child attention to and engagement with the task. For each trial, audio story and picture presentation portions were coded separately for behaviors indicating inattention or disengagement from the task, including talking and looking away from the screen. Videos were coded by four independent coders ($M_{\kappa} = 0.81$, $SE = 0.12$), and inattention was quantified for each child as the sum score, separately for each DR task condition (neutral, negative reappraisal). Child engagement in the DR task was used to rule out that the influence of parent context simply prompted children to be more attentive to the task, rather than directly bolstering ER.

Waiting Task: Child Emotion Regulation Strategy Use The WT was coded for ER strategy use and flexibility using a coding scheme developed by Babkirk et al. (2015; Appendix). Three active behaviors typically considered adaptive during an ER challenge (comforting, object engagement, and alternative activity use) and three passive or inappropriate behaviors (attentional avoidance, prohibited social engagement, and prohibited object engagement) were coded. Frequency was coded in 30-second epochs by four independent coders ($M_{\kappa} = 0.76$, $SE = 0.01$). To account for individual differences in overall activity, ratio scores were computed for each child by dividing the frequency of use for each strategy by the total frequency across all behaviors. Ratio scores were log-transformed to correct for positive skew, a common approach for behavioral coding data. A greater ER strategy ratio score indicates greater proportional use of that strategy throughout the task.

Results

Descriptive Statistics

Of the total 93 child participants, 30 (33.3%) were in the parent-scaffolding (PS) group, 32 (34.4%) were in the parent-present (PP) group, and 31 (33.3%) were in the parent-absent (PA) group.[8] Gender differences were examined for biological, behavioral, and parent-report measures using independent samples *t*-tests. There were no significant gender differences for the LPP, RSA, behaviors exhibited during the WT, or parent-reported ER or adjustment (p's > 0.05). Pearson correlations were conducted to examine relationships between child age and the biological, behavioral, and parent-report measures. LPP amplitudes in the negative condition were significantly negatively correlated with age, with younger children showing greater magnitude LPP ($r = -0.261$, $p = 0.013$). However, age was not significantly correlated with LPP residual scores ($p > 0.05$). In the WT, younger children tended to use significantly less attentional avoidance ($r = 0.242$, $p = 0.022$), and significantly more prohibited object engagement ($r = -0.256$, $p = 0.015$). Because age was significantly correlated with biological and observed measures of ER, age in months was entered as a covariate in regression analyses below.

Pearson correlations were conducted to examine associations between residual scores for ER flexibility metrics. No significant correlations emerged between ΔLPP and ΔRSA during the DRT ($r = -0.076$, $p = 0.498$), nor between ΔLPP and ΔRSA during the WT ($r = 0.116$, $p = 0.300$), indicating

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[8] For LPP analyses ($n = 90$), 30 (33.3%) were in the parent-scaffolding (PS) group, 31 (34.4%) were in the parent-present (PP) group, and 29 (32.2%) were in the parent-absent (PA) group. For RSA analyses ($n = 85$), 26 (30.6%) were in the parent-scaffolding (PS) group, 31 (36.5%) were in the parent-present (PP) group, and 28 (32.9%) were in the parent-absent (PA) group. Age and gender distributions did not significantly differ across LPP, RSA samples, nor the entire sample, p's > 0.10.

that these measures may represent independent biological signatures of child ER.

Inattention during the Directed Reappraisal Task Child inattention during the DRT was investigated as a potential confound of neurocognitive and physiological responses to emotional stimuli. Pearson correlations were conducted between frequency of child inattention in each condition (negative, reappraisal, neutral) and each biological signature (ΔLPP and ΔRSA) during the DRT. For all conditions, inattention was not significantly related to ΔRSA [negative: $r = -0.044$, $p = 0.696$; reappraisal: $r = 0.074$, $p = 0.515$; neutral: $r = 0.046$, $p = 0.689$] or ΔLPP [negative: $r = 0.023$, $p = 0.838$; reappraisal: $r = -0.044$, $p = 0.703$; neutral: $r = 0.030$, $p = 0.796$].[9] Furthermore, a 3 (Condition: negative, reappraisal, neutral) x 3 (Social Context: parent-scaffolding, parent-present, parent-absent) repeated-measures ANOVA was conducted with inattention frequency as the dependent variable. No significant main effect of Condition [F (2, 160) = 0.633, $p = 0.532$] or Condition x Social Context interaction [F (4, 160) = 0.830, $p = 0.508$] emerged. Thus, child inattention during the DRT did not significantly differ across conditions nor social context groups.

Effects of Social Context on the Emotional Arousal To rule out the possibility that parent-child context specifically impacted emotional arousal to negative interpretations of unpleasant stimuli, as opposed to bolstering ER flexibility captured by the comparison of reappraisal and negative interpretations, we tested for group differences in LPP and RSA in the negative condition. Univariate ANOVAs with DR Group (PS, PP, PA) as the between-subjects variable and the LPP and RSA in the negative condition as the outcome variables did not reach significance [F (1, 87) = 0.32, $p = 0.726$; F (1, 85) = 0.05, $p = 0.948$].

Analytic Plan

The first hypothesis was that children who complete the DRT while parents provide scaffolding, versus alone, will show greater ER flexibility measured via reappraisal-induced ΔRSA and ΔLPP, whereas those who complete the task with parents merely present will show intermediate levels of ER flexibility. To test the first hypothesis, we conducted two univariate ANOVAs with Social Context (parent-scaffolding, parent-present, parent-absent) as the between-subjects variable, and ER flexibility metrics ΔLPP and ΔRSA as the dependent variables. Greater reappraisal-induced reduction of the LPP and RSA, or more negative ΔLPP and ΔRSA residual scores, indicated greater ER flexibility.

The second hypothesis was that greater ER flexibility measured during the DRT will predict observed active ER strategies typically considered adaptive during an emotional challenge and greater parent-report of adaptive ER and child adjustment. Because a goal of the study was to provide evidence for these biological signatures as predictors of child ER and adjustment, we focused analyses on testing whether they predicted outcomes above and beyond the social context manipulation. We explored whether flexibility measured via ΔRSA versus ΔLPP differed in their association with these outcomes. The ΔLPP (during the DRT) and ΔRSA (during the DRT) metrics of ER flexibility were each separately examined as predictors of parent-report of ER and adjustment (e.g., anxiety, internalizing and externalizing problems), as well as child observed ER during emotional challenges (e.g., attentional avoidance, alternative activities).

To test the second hypothesis, linear regressions were conducted with age and gender entered as the first step. DRT social context group was entered as the second step to examine the contribution of ER flexibility above and beyond social context, particularly given the possibility that ΔLPP or ΔRSA were differentially sensitive to social context. ΔLPP or ΔRSA were entered in the third step.[10] The outcome measures were parent-reported ER and adjustment measures, and child ER during the WT ratio scores, separately for each scale/behavior, for a total of nine regressions for each ER flexibility metric.

The ΔRSA measure of physiological flexibility during the WT also was examined in relation to child ER strategy use during the WT through a series of linear regressions, conducted as follows: 1st step: age and gender; 2nd step: DRT social context group; 3rd step: ΔRSA (RSA at baseline vs. WT); outcome measures: child ER strategy ratio scores, separately for each behavior, for a total of six regressions.

Due to the number of regressions conducted, multiple comparisons were corrected using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995). This technique involves ranking p values and accounts for the number of tests conducted but is not as stringent as the Bonferroni's correction. Because all tests with original p-values < 0.05 remained significant after applying the Benjamini-Hochberg procedure, original p-values are reported in the results below. Regression tables are presented in the Supplement.

Hypothesis 1: Social Context Sensitivity of the LPP and RSA

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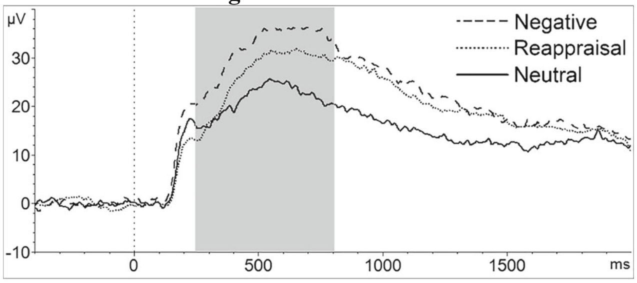
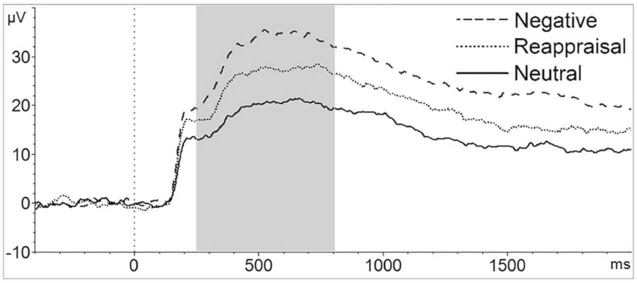
[9] These correlations were also non-significant when conducted separately for each Social Context (see Supplement).

[10] We also conducted regressions with interactions between the LPP X Social Context and RSA X Social Context in the model to test whether biological signatures of ER flexibility predicted outcomes differentially based on parenting context manipulations. The interactions did not significantly predict outcome variables. Because H2 focused on predicting outcomes with biological signatures regardless of social context while controlling for DRT group, the interactions were not included in final analyses.

a. Parent-Scaffolding



b. Parent-Present



c. Parent-Absent

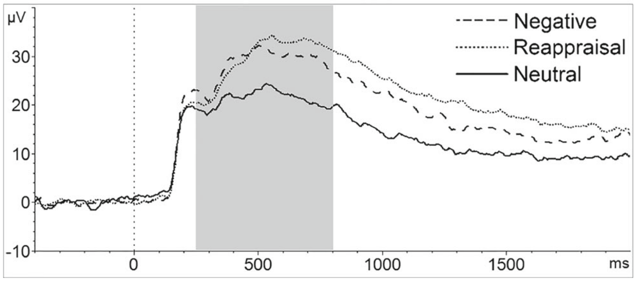


Fig. 2 The waveforms depict LPP amplitudes in the target window (250 to 800 ms), separately by social context (**a** parent-scaffolding, **b** parent-present, **c** parent-absent) and condition (negative, reappraisal, neutral)

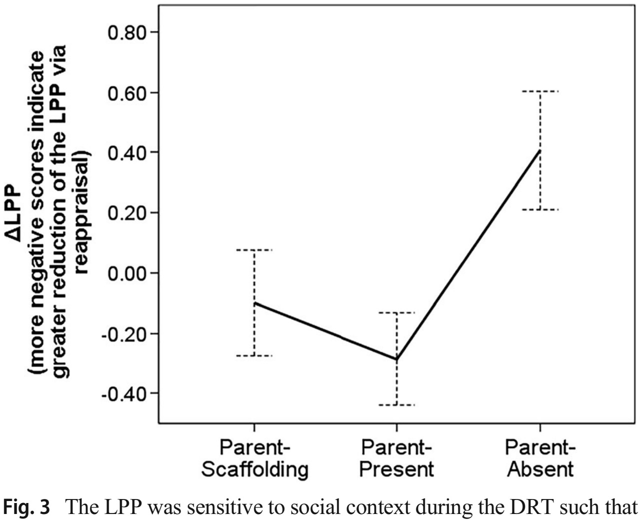


Fig. 3 The LPP was sensitive to social context during the DRT such that ΔLPP was significantly greater for the parent-scaffolding and parent-present group compared to the parent-absent control. Error bars represent ±1 SEM

The hypothesis was that children who complete the DRT while parents provide scaffolding, versus alone, will show greater ER flexibility measured via reappraisal-induced ΔRSA and ΔLPP, whereas those who complete the task with parents merely present will show intermediate levels of ER flexibility.

Social context-sensitivity of the LPP during the DRT As predicted, there was a significant main effect of Social Context on ΔLPP [$F(2, 87) = 4.12$, $p = 0.020$, $\eta_p^2 = 0.09$], such that children in the parent-present group ($M = -0.29$, $SE = 0.17$, $p = 0.007$) and parent-scaffolding group ($M = -0.10$, $SE = 0.18$, $p = 0.047$) showed significantly greater reappraisal-induced reduction of the LPP, reflected by more negative residual scores, compared with children who completed the DRT alone ($M = 0.41$, $SE = 0.18$; Figs. 2 and 3). Counter to predictions, the parent-present and scaffolding groups did not significantly differ from one another.

Social context-sensitivity of RSA during the DRT Contrary to predictions, there was no significant main effect of Social Context on ΔRSA, $F(2, 82) = 0.21$, $p = 0.812$, $\eta_p^2 = 0.005$.

Summary: Social-context sensitivity of the LPP and RSA As predicted, ΔLPP was sensitive to the between-subject manipulation of Social Context. The reappraisal-induced reduction of the LPP was significantly greater when parents were present or actively scaffolding child ER versus when children attempted ER while alone. However, contrary to predictions, parent-scaffolding and parent-present contexts did not significantly differ. Also contrary to our hypothesis, ΔRSA was not sensitive to social context during the DRT.

Hypothesis 2: ER Flexibility Metrics Predicting ER and Adjustment

The hypothesis was that greater ER flexibility measured during the DRT will predict more use of observed ER during an emotional challenge and greater parent-report of adaptive ER and child adjustment, above and beyond the effects of social context. We explored whether flexibility measured via ΔRSA versus ΔLPP differed in their association with these outcomes.

Parent-report of child ER and adjustment Neurocognitive flexibility measured via ΔLPP did not significantly predict parent-reported child ER or child adjustment (p's > 0.10).

Greater physiological flexibility during the DRT, measured via ΔRSA, predicted greater parent-reported child emotion regulation [$\beta = -0.190$; $\Delta R^2 = 0.07$; $\Delta F(1, 80) = 4.908$, $p = 0.030$; Fig. 4, top] and fewer symptoms of anxiety [$\beta = 0.227$; $\Delta R^2 = 0.05$; $\Delta F(1, 80) = 4.394$, $p = 0.039$; Fig. 4, bottom]. DRT Social Context group did not significantly predict parent-reported child ER or adjustment (p's > 0.10).

Observed ER Greater neurocognitive flexibility measured via ΔLPP was related to greater use of active alternative activities during the WT [$\beta = -0.261$; $\Delta R^2 = 0.07$; ΔF (1, 85) = 5.731, $p = 0.019$; Fig. 5, left]. DRT Social Context group did not significantly predict child behavior during the WT (p's > 0.10).

Greater concurrent physiological flexibility during the WT measured via ΔRSA was related to less use of passive attentional avoidance [$\beta = 0.258$; $\Delta R^2 = 0.06$; ΔF (1, 80) = 5.948, $p = 0.017$; Fig. 5, right]. DRT Social Context group did not significantly predict child behavior during the WT (p's > 0.10).

Summary: ER flexibility and adjustment Consistent with hypotheses, greater neurocognitive flexibility, measured as greater reappraisal-induced reductions in the LPP, significantly predicted greater use of active alternative activities during the frustrating WT but did not significantly predict parent-report of child ER or adjustment.

Also as predicted, greater physiological flexibility, measured as greater reappraisal-induced ΔRSA during the DRT, significantly predicted adaptive parent-reported child ER and fewer parent-reported symptoms of anxiety. In addition, ΔRSA during the WT significantly predicted lower concurrent use of passive attentional avoidance during the WT.

Discussion

The current study used a bio-behavioral, multimethod approach to examine the context-sensitivity and predictive utility of complementary biological signatures of child ER flexibility, the LPP, and RSA. Results showed that while both the LPP

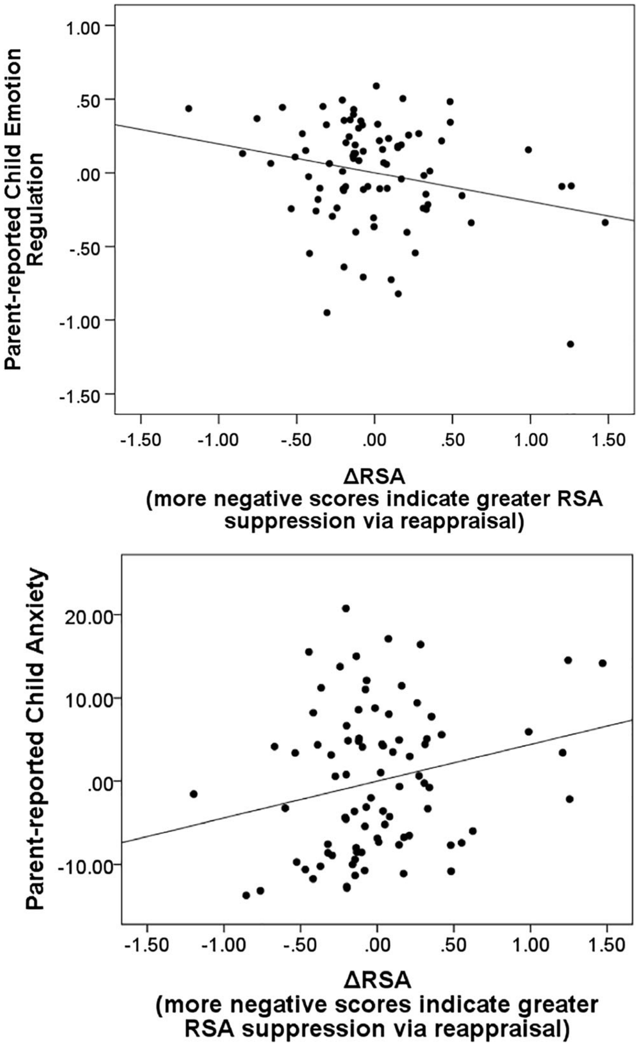


Fig. 4 Greater reappraisal-induced ΔRSA was related to greater parent-reported child emotion regulation (top) and fewer symptoms of anxiety (bottom)

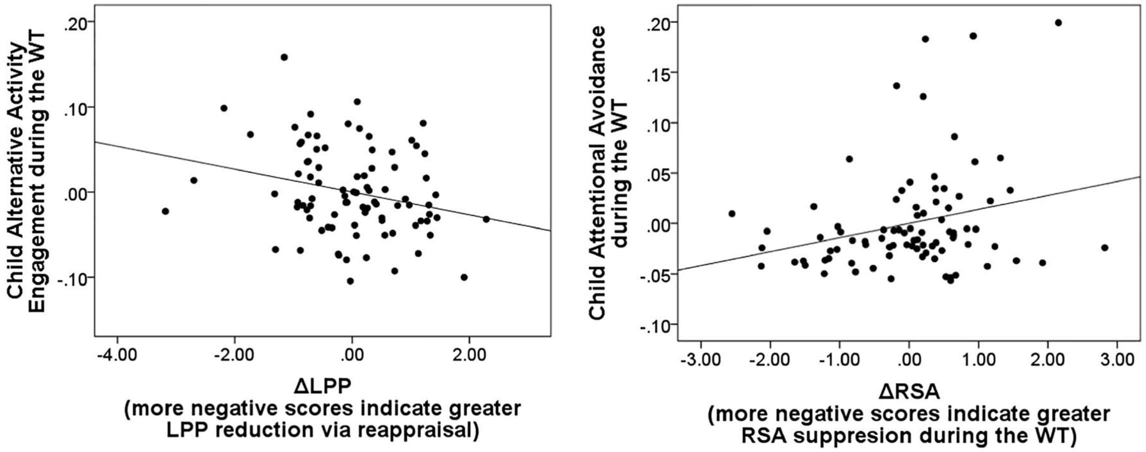


Fig. 5 Left: Greater reappraisal-induced reduction of the LPP, indicating greater magnitude neurocognitive ER flexibility, significantly predicted greater use of alternative activity engagement strategies during the frustrating WT. Right: Greater concurrent ΔRSA in the WT versus Baseline was related to less frequent use of passive avoidance strategies to cope with the frustration of waiting

and RSA metrics of flexibility predicted observed child ER, they also diverged in several important ways. Broadly, while only the LPP showed sensitivity to parenting social context during the DRT, RSA was a better predictor of parent-reported child ER and adjustment, suggesting that these biological signatures capture distinct aspects of child ER flexibility.

As predicted and consistent with previous studies examining child ER (Babkirk et al., 2015; Calkins, 1997; Diener & Mangelsdorf, 1999) both the LPP and RSA were related to observed child ER during the emotionally frustrating WT, providing support for the use of these metrics to target regulatory processes that occur in ecologically valid emotional challenges. Yet, the LPP and RSA diverged in terms of the specific outcomes each metric predicted. Greater ΔRSA during the WT versus baseline predicted less use of attentional avoidance strategies like passive distraction or gaze aversion. This suggests that children with greater physiological flexibility indexed by engaging the SNS to cope with frustration are less likely to use more passive strategies, consistent with studies documenting that greater ΔRSA is linked to active coping (Calkins & Keane, 2004; Hastings et al., 2008). In contrast, greater reappraisal-induced reduction of the LPP uniquely predicted more use of active alternative activities to cope with the frustration of waiting. Because these strategies require more effortful and active cognitive and behavioral capacities, it follows that they would be related to neurocognitive flexibility. This distinction between the LPP and RSA suggests that while the RSA may represent an index of ER flexibility that corresponds to broad ER competence, the LPP metric may be a more targeted measure of cognitively demanding components of ER flexibility.

Consistent with this, the LPP and RSA metrics also diverged in relation to predicting parent-reported ER and adjustment. First, they were not significantly related to each other, suggesting that they index distinct aspects of ER flexibility. Furthermore, although the LPP was significantly reduced in the reappraisal versus negative condition in the sample as a whole, the same pattern was not detected for RSA. While unexpected, this may be due to high interindividual variation in the degree of reappraisal-induced ΔRSA. Sources of variation could include adjustment, consistent with the significant association documented in this study between adjustment and ER flexibility measured via RSA. For example, as predicted, greater ΔRSA in response to the reappraisal versus negative interpretations of unpleasant pictures in the DRT was related to a range of positive adjustment factors, including greater parent-reported ER and fewer symptoms of anxiety. In contrast, the LPP did not significantly predict parent-reported ER or adjustment. This difference may again indicate that a main feature of the RSA metric of ER is to capture broad, nonspecific aspects of ER that be accurately captured by self-report, whereas the LPP may index more specific components of current ER flexibility during a specific cognitive task.

As predicted, the LPP was sensitive to social context during the DRT. The reappraisal-induced reduction of the LPP, or ΔLPP, was significantly greater when parents were either merely present or when they actively scaffolding child ER during the task compared with when children completed the DRT alone. Importantly, there was no significant difference across social context groups for the LPP in the negative condition alone. This provides evidence that parental presence and scaffolding did not simply reduce emotional reactivity to unpleasant pictures and bolsters the interpretation that parenting context specifically impacted ER flexibility across reappraisal *compared with* negative conditions. Taken together, these results suggest that children's neurocognitive ER flexibility is bolstered by their parent and further may be measured most accurately when children are in such ecologically valid social contexts.

Unexpectedly, the magnitude of reappraisal-induced reduction of the LPP did not significantly differ between contexts where parents actively scaffolded versus when they were merely present. We ruled out the possibility that parent presence, whether active or passive, has the primary effect of maintaining the child's focus on the task, as observed levels of inattention did not differ between groups. Another explanation is that parental presence may be sufficient to enhance neurocognitive functioning, consistent with Social Baseline Theory (Beckes & Coan, 2011), and that this effect maximized the social bolstering of ER such that active scaffolding afforded no additional advantage. That is, the parents' presence may have acted as a cue to engage regulatory circuitry that they would typically use when co-regulating in daily life, consistent with the findings of Gee et al. (2014). Future research should examine how individual differences in parental sensitivity or emotional scaffolding in habitual interactions influence the extent to which this mere-presence context bolsters ER.

Contrary to predictions, the RSA metric of ER flexibility was not sensitive to social context. These findings, along with the result that RSA and the LPP were not significantly intercorrelated, may be due to difference in the developmental maturation of the biological underpinnings of the LPP and RSA in the sample age range. Specifically, middle- to late-childhood is characterized by increasing development of and reliance on cognitively-based ER as prefrontal-subcortical connections mature (Beauregard et al., 2004; Calkins & Keane, 2004; Desatnik et al., 2017; Fox, 1989, 1994; Ochsner & Gross, 2004; Paul et al., 2013). Although physiological underpinnings of RSA are also subject to developmental change, if neural circuitry underlying the LPP shows relatively heightened plasticity during this period, the LPP might accordingly be more influenced by social-environmental factors (consistent with Tottenham, 2015) compared with the relatively stable PSNS processes underlying RSA. Another possibility is that, with cognitive development, older children show increasing reliance on and preference for more cognitively based strategies, such as reappraisal, making the cognitively tuned LPP a more sensitive measure for the reappraisal task used in this study. Future research should tease apart the impact of neurocognitive development and strategy preferences across multiple ER strategy types to better evaluate this possibility.

While findings provide support for the use of the LPP and RSA as biological signatures of child ER, several limitations must be addressed. First, biological signatures were not measured in conjunction with child self-reported emotional arousal in the current study, due to limitations in children's ability to subjectively report their affective state or ER success accurately. However, LPP and RSA have been shown to vary with self-ratings in older children and adults (Cuthbert et al., 2000; Hajcak & Nieuwenhuis, 2006; Schupp et al., 2000), thus increasing confidence that modulation of these signatures does indeed reflect regulation. Next, as is the case with many developmental neuroscience studies, there was data loss due to movement artifacts or child refusal of or discomfort with the physiological equipment. The length of the procedure (up to 3 hours) may have been fatiguing for some, although this duration is consistent with prior studies in this age group (DeCicco et al., 2012) and necessary given the goal to assess multiple biological and behavioral indices of ER. Nevertheless, the current sample is smaller than the projected sample, and some statistical tests may be underpowered, precluding the detection of certain effects, or explaining a small portion of variance. This limitation is compounded by the study's three group between-subjects design. Furthermore, the sample consisted of children between 5 and 8 years old, and although this age group was intentionally targeted due to the potential for social bolstering of neurocognitive processes (Tottenham, 2015), the breadth of this range is relatively wide in terms of developmental stages, particularly because ER has been shown to become more effortless with age (Cole et al., 2018). There may have been age effects within each social context grouping, but the sample size of the current study did not allow for the detection of any age-related differences in sensitivity to the effect of parenting context. For instance, scaffolding may have a larger effect on the LPP for younger children versus older children who may have internalized more of the ER learned through socialization. Despite this shortcoming, significant predicted patterns did emerge, although effect sizes may be exaggerated due to the limited sample size.

Because social context had a significant impact on the LPP, social context was included as a covariate in regressions predicting psychological adjustment and observed ER. We also tested for interactions between biological signatures and social context groups in these models (see footnote), none of which were significant. Again, this may be due to subsample sizes being too small to detect significant links between the LPP and outcomes within each group separately. Alternatively, individual differences in ER flexibility captured by the LPP may predict observed ER and adjustment beyond the impact of social context during reappraisal. Future research should probe these questions with larger sample sizes.

In addition, RSA was recorded continuously throughout the WT (10 minutes), and scores were computed as an average for each child. However, children likely differed in the trajectory of their ANS responding throughout these tasks, and this variation was not captured in the current study. For instance, some children may have shown high degrees of ΔRSA during the first minute of the WT when excitement about the gift was at its peak, whereas others could have perceived the gift as increasingly salient as the task progressed, necessitating a greater degree of regulation towards the end of the task. Also, as some researchers point out (Beauchaine, 2001; Erblich et al., 2011), RSA at least partially reflects arousal and task engagement, not purely ER processes per se. Although the current findings did show that ΔRSA concurrently predicted observed ER across the duration of the entire WT, we did not directly code arousal or task engagement independently from target behaviors. Future research should build on these results by tracking individual differences in RSA trajectories minute to minute and directly compare these fluctuations to changing ER strategy use throughout the task.

Another caveat is that the LPP and RSA are inherently measured on grossly different timescales, with the LPP capturing neurocognitive processes occurring in less than 2,000 milliseconds, and RSA indexing physiological processes averaged across approximately 10-minute time periods during the DRT. This limitation, while also representing a strength in assessing complementary ER flexibility metrics on complementary timescales, prevents direct comparison on a stimulus-by-stimulus basis.

Future research can build on the current findings by investigating how more finely grained individual differences may influence the LPP and RSA metrics of ER flexibility. First, these measures of ER flexibility may be impacted by variation in overall emotional reactivity across individuals. Specifically, some children may have shown a low degree of flexibility due to blunted emotional reactivity across both the negative and reappraisal conditions. In addition, dyad-level differences in relationship quality, such as attachment, were not assessed in the current study. Because parent-child social context was shown to have a positive influence on child ER, as measured by the LPP in particular, a logical next step will be to establish whether this benefit is a function relationship quality. For example, greater bolstering of reappraisal-induced reduction of the LPP may be expected for more securely attached dyads, whereas social context may confer a detriment to ER flexibility via the LPP for insecurely attached dyads.

Finally, because this study was designed to examine biological signatures of child ER in a typically developing sample, clinically relevant symptoms were relatively low. This may explain why the LPP was not related to any parent-report measures of emotional adjustment. Several previous studies have shown that ΔRSA is related to behavioral problems and mental health in children (Calkins & Keane, 2004), an effect we have replicated in the current study. Furthermore, although greater ΔRSA was conceptualized as adaptive in the context of the current, relatively low-risk sample, recent research (Shakiba et al., 2020) suggests that moderate levels of ΔRSA may be optimal among higher risk samples, such as those experiencing early childhood adversity. That is, the association between ΔRSA and adaptive regulation could be described as an inverted-U curve such that under- *or* over-regulation predicts poor psychological adjustment. The results of the current study are consistent with this view and add to the body of literature that, at least among typically developing children, greater ΔRSA suppression indicates adaptive regulation. Subsequent research should examine the LPP in relation to symptomology in clinical samples, while taking social context into account. For instance, social support could differentially influence neural processes related to ER flexibility in high anxious versus nonanxious samples. This future research has potential to inform diagnostic practices and allow clinicians to track treatment outcomes.

Taken together, the findings of the current study document that LPP metrics of ER flexibility are sensitive to social context and provide support for the use of the LPP and RSA as complementary biological signatures of child ER flexibility among 5- to- 8-year-olds. While both metrics predicted observed child ER, RSA predicted child adjustment and trait measures of ER, whereas the LPP more specifically targeted active, effortful, and cognitively elaborated ER. Findings have implications for how biological correlates of ER should be measured and highlight the importance of multimethod approaches that account for social context and multiple biological underpinnings of ER flexibility.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13415-021-00888-8.

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Data availability None of the data or materials for the experiments reported here is available, and none of the experiments were preregistered.

Declaration

Conflicts of interest None

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