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Dynamic Measures of RSA Predict Distress and Regulation in Toddlers

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Abstract

In this study, we examined a new method for quantifying individual variability using dynamic measures of Respiratory Sinus Arrhythmia (RSA). This method incorporated temporal variation into the measurement of RSA and provided information beyond that offered by more traditional quantifications such as difference scores. Dynamic and static measures of change in RSA were tested in relation to displays of emotion and affective behaviors during a fear eliciting episode in a sample of 88 typically-developing and high-fear toddlers during a laboratory visit at age 24 months. Dynamic measures of RSA contributed information that was unique from traditionally-employed, static change scores in predicting high-fear toddlers' displays of shyness during a fear-eliciting episode. In contrast, RSA change scores offered information related to boldness in non-high-fear children. In addition, several associations included estimates of nonlinear change in RSA. Implications for the study of individual differences in RSA and relations with emotion and emotion regulation are discussed.

Keywords

RSA; Emotion Regulation; Toddlers

The unfolding of processes of emotion and their regulation is complex, often involving frequent, rapid changes in expressions and experiences of emotion (Cole, Martin, & Dennis, 2004; Ekman, 1994). However, emotion regulation research in young children has not wholly captured these aspects of regulatory processes. Several critiques have suggested that regulatory processes might be more accurately depicted if current measures, often relying on averages across time, were replaced with more temporally-sensitive techniques able to depict dynamic change (Thompson, 1994; Cole et al., 2004; Thompson, Lewis, & Calkins, 2008).

Dynamic models of emotion suggest that emotional expression, experience, and regulation are dependent on contextual and situational demands (Zautra, Reich, Davis, Potter, & Nicolson, 2000). Levels of positive and negative emotions fluctuate as individuals' subjective experiences shift with changing task demands. The dynamical systems approach to studying emotion emphasizes such fluctuations and overall flexibility as important aspects of a complex system of emotional responding (Camras & Witherton, 2005). The nature of this flexibility varies across individuals based not only on unique situational contexts, but also on distinct developmental histories (Fogel et al., 1992). While ideas such as these are frequently discussed in emotion regulation theory, the integration of dynamic methods into assessments of regulation – including behavioral and physiological changes during emotion

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episodes - has been slow. Thus, it is unclear how dynamic measures might compare to traditional quantifications of regulation.

In this way, widely-used indices of regulation represent potentially important bases of comparison for dynamic measures. One such index is respiratory sinus arrhythmia (RSA), a parasympathetic measure of the variation in time between heart cycles as controlled by the 10th cranial nerve, also referred to as the vagus nerve. Vagal activity generally corresponds to increased activity in the parasympathetic nervous system and a slowing of heart rate. Polyvagal theory posits that dynamic shifts in RSA represent adaptive coping efforts (Porges, 1995); RSA augmentation, or an increase in RSA, reflects the maintenance of internal equilibrium and support for engagement while RSA suppression, or a decrease in RSA, signifies a readiness for behavior in response to threat or challenge (Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996; Porges, 2007). Note that these definitions of changes in RSA are consistent with dynamic theories of emotion suggesting that emotion-related behavior is attuned to the demands of the task at hand.

Indeed, beginning early in development, fluctuations in RSA are associated with individual differences in emotion. From infancy, levels of fear (Stifter & Fox, 1990), frustration (Stifter & Jain, 1996), sadness (Buss, Goldsmith, & Davidson, 2005), approach behaviors (Stifter, Fox, & Porges, 1989), risk for behavior problems (Porges et al., 1996), and internalizing disorders (El-Sheikh, 2001) have all been linked to changes in RSA. A review of the developmental psychobiology literature suggests that links between cardiac measures such as RSA and emotion are particularly strong in investigations of fear (Buss & Goldsmith, 2007). Fearful toddlers typically exhibit lower and less variable RSA than toddlers who are not fearful (Stifter & Fox, 1990; Stifter et al., 1989), though these results are not always consistent (Calkins & Fox, 1992; Marshall & Stevenson-Hinde, 1998). Despite inconsistencies, RSA has shown to be a well-validated measure of parasympathetic response and a generally-supported mechanism of self-regulation. Moreover, the relation between RSA and fear in particular make fear tasks an optimal paradigm in which to investigate novel measurement approaches.

Given that both RSA and emotion are active processes, it is surprising that the most common methods of assessing RSA as a mechanism of regulation are static, thus failing to capture its dynamics. In addition to average task values, one common method of quantifying change in RSA is to calculate a difference score between task and baseline RSA values. RSA suppression, reflected as decreases in RSA from a baseline cognitive challenge to an emotion task, has been linked to better self-regulation (Calkins, 1997) and more positive adjustment (Calkins, Graziano, & Keane, 2007; Calkins, Blandon, Williford, & Keane, 2007). Recent work also suggests that RSA augmentation, reflected as increases in RSA during a social challenge relative to baseline, is related to fewer behavioral problems (Hastings, Nuselovici, Utendale, Coutya, McShane, & Sullivan, 2008).

There have been recent efforts to quantify changes in emotion expression and behaviors with greater temporal sensitivity (e.g., Buss & Goldsmith, 1998; Buss & Kiel, 2004; Dennis, Cole, Wiggins, Cohen, & Zalewski, 2009). For example, changes in the intensity of anger and sadness expressions were quantified by Buss and Goldsmith (1998) across epochs ranging from 5 to 10 seconds in length. Comparisons of these epochs with the occurrence of regulatory behaviors were used to make inferences about the effectiveness of behaviors for different types of emotion that continue to inform studies of emotion regulation; this type of information would not have been available had the authors assigned single, global estimates of emotion or regulatory behaviors for each episode.

If, as conjectured by emotion theory, changes in physiology underlie changes in overt emotional behaviors (Larsen, Berntson, Poehlmann, Ito, & Cacioppo, 2008), fluctuations in physiological measures such as RSA should correspond to some degree with moment-to-moment changes in emotional expressions and behavior. Similar to emotion regulation, RSA is believed to be sensitive to changing contextual demands (Hofheimer, Wood, Porges, Pearson, & Lawson, 1995) and has been described as undergoing rapid changes in order to meet environmental demands and support behavior (Porges & Lipsitt, 1993; Porter, Porges, & Marshall, 1988). Some recent work has attempted to account for the dynamic nature of RSA in relation to emotion behaviors, but have done so using relatively static measures of RSA. For example, recognizing possible differences resulting from task demands, a study by Calkins, Blandon, and colleagues (2007) looked at differences in RSA change scores across various tasks intended to elicit different types of emotional responses. Other studies have looked at changes in RSA over time by modeling mean levels of RSA (e.g., Buss et al., 2005; Alkon et al., 2003; Hill-Soderlund et al., 2008) or RSA change scores (e.g., Buss et al., 2005; Alkon et al., 2003) across several different contexts. Though more sensitive to changes in RSA than single-point aggregate or difference measures, these methods still fail to capture within-episode dynamic changes in RSA. As emotion levels and task demands change, regulation as indexed by RSA fluctuates on much smaller time scales. Thus, ideal measures would not rely on aggregation in these ways, but would capture ongoing changes in RSA during a single emotional challenge.

In this study, we propose and test a new method for capturing dynamic fluctuations in RSA, compare it to traditional scores of change in RSA, and test its relation to affective and regulatory behaviors. Because this dynamic measure is hypothesized to be linked to the regulation of emotion in ways that are not captured by RSA change scores, we believe that dynamic measures will be related to observations of affective behaviors during a brief emotion episode when RSA change scores are not.

Method

Participants

Participants were 88 toddlers (42 female) drawn from a larger study of toddler temperament and emotional development. The original sample was recruited from birth records published in local newspapers. The majority of families were Caucasian (90.9%) and middle class (*M* = 50.10, *SD* = 11.43 on the Hollingshead index). All families participated in a laboratory visit scheduled after the child's second birthday (*M* age = 24.46 months, *SD*=0.47 months) where behavioral and cardiac data were collected. The current study includes participants from a 24-month laboratory visit with complete data for the baseline and *Stranger Approach* episodes.

Families were screened when children were 18–20 months in age in order to oversample for toddlers who were high in mother-reported fear and wariness. Screening questionnaires included the Infant Toddler Social Emotional Assessment (ITSEA; Briggs-Gowan & Carter, 2001) and a 6-item wariness screening questionnaire asking parents about their child's fearfulness in novel situations that most children find fun (e.g., meeting a team mascot). Children were classified as high in fear if they scored at least 1 SD above the mean (established on the first 100 cases) on the wariness questionnaire *and also* either scored 1 SD above the published mean on the ITSEA internalizing composite or scored 1 SD above the published mean on 2 of the following ITSEA subscales: general anxiety, separation distress, and inhibition to novelty. Correlations between the wariness questionnaire and ITSEA scales ranged from r =.25 to r =.53 (all ps <.01). This approach resulted in half of the participants in the current study (50.0%) being reported as high in fear.

Task Descriptions

Baseline—At the beginning of the visit, toddlers sat quietly for 5 minutes while either reading a book or coloring a picture with the experimenter.

Stranger Approach—As a part of the 24-month laboratory visit, toddlers and their mothers took part in a *Stranger Approach* episode designed to elicit fear (Buss & Goldsmith, 2000). A female experimenter led the mother and child into a room where mothers were asked to sit quietly and remain uninvolved. The child was given a set of age-appropriate toys to play with. After the child had played with the toys for 30 seconds, a male experimenter entered the room. The stranger approached the child slowly and watched him/her play for up to 2 minutes while he asked several questions (e.g., “Are you having fun today?”).

Behavioral Coding—Videotapes of the *Stranger Approach* were used to assign global ratings of negative affect, positive affect, shyness/withdrawal, and boldness/approach during the episode for each child. Coders who were naïve to screening information assigned ratings for each dimension based on a five-point scale ranging from an absence of the behavior (1) to behavior of the highest intensity and duration (5). All coders reached a minimum level of reliability during training with a master coder and a subset of coding was used to calculate reliability (ICCs: Distress =.87, Positive Affect =.93, Shyness =.91, and Boldness =.89). Episodes were double-coded and discrepancies were resolved by the master coder. All resulting values were normally distributed. Because children were ambulatory during cardiovascular recording, vigor of activity was also coded in order to control for movement, which can produce decreases in RSA (Grossman, Wilhelm, & Spoerle, 2004). Activity during the episode was coded on a 5-point interval scale ranging from no attempts to play and no physical movement or activity (1) to high intensity activity such that the child moves from one activity to another and play is intense (5).

Cardiovascular Recording—Measures of cardiac output were collected using the Mindware WiFi ACQ software, Version 1.0 (Mindware Technologies, LTD, Westerville, OH) during the baseline and *Stranger Approach* episodes. RSA analyses were performed offline. To do this, the ECG signal was sampled at a rate of 500 ms and bandpass filtered at 40 Hz and 250 Hz. The Mindware editing program Mindware HRV, Version 2.51 identified IBIs and detected physiologically improbable intervals based on the overall distribution using a validated algorithm (Berntson, Quigley, Jang, & Boysen, 1990). All data were visually inspected for artifact identification and editing. Using the Mindware HRV program, data were detrended using a first-order polynomial to remove the mean and any linear trends, cosine tapered, and submitted to Fast Fourier Transform (FFT). RSA was defined as the natural log integral of the .24 Hz to 1.04 Hz power band and calculated in 30-second epochs. Children who cried during the *Stranger Approach* (n = 2) were not scored in order to protect against artificial changes in RSA due to changes in respiration (Grossman, Van Beek, & Wientjes, 1990). Of those children who were scored, four did not have RSA during the baseline episode: one child was excluded due to excessive artifact, two were excluded due to crying, and data from one child was lost as a result of technical difficulty. Thus, the final data set contained 88 children with complete heart rate data during the *Stranger Approach* episode and 84 children with baseline data.

Mean levels of baseline and task RSA values were calculated by averaging across 30-second epochs. Changes in RSA were quantified in two ways. First, RSA change scores were created by subtracting baseline values from each task value (Llabre, Spitzer, Saab, Ironson, & Schneiderman, 1991). These scores are discussed as static changes in RSA given that they represent mean levels of RSA during the task relative to baseline RSA levels.

Second, to quantify dynamic changes in RSA within individuals, data were first centered at the entrance of the stranger (i.e., the first 30-second epoch) in order to minimize individual differences in the length of recordings prior to the stranger's entry. Then, variables representing linear (time) and quadratic (time^2) change across five 30-second epochs were added to a stacked data set containing individual values of RSA. Growth curve models in which linear and quadratic time predicted RSA values were used to estimate linear and quadratic trends in RSA across all epochs of the *Stranger Approach*. Individual linear and quadratic trend scores representing the degree of linear and quadratic change in RSA were extracted for each child using the SAS PROC REG procedure. This resulted in estimates for each individual based on epoch-to-epoch changes in RSA over the course of the episode that represented the degree to which changes in RSA were linear and quadratic in nature. Note that purely linear positive and negative changes in RSA over time would appear as relatively equal epoch-to epoch increases or decreases in RSA, respectively. In contrast, positive quadratic change in RSA would appear as decreases in RSA followed by increases in RSA (Figure 1a); negative quadratic change in RSA would appear as increases in RSA followed by decreases in RSA (Figure 1b). Overall dynamic change in RSA for any individual would appear as a combination of linear and quadratic fluctuation over time.

A two-level mixed growth curve model (Singer, 1998) was also used with the centered data in order to examine group differences in patterns of RSA across the episode. As described by Singer (1998) and Hox (2002), this type of model, run using the SAS PROC MIXED procedure, appropriately models the error structure associated with repeated observations over time and also accounts for missing data. At the first level, this model treats time as a continuous variable; group membership is added at the second level as a time-invariant covariate. The individual-level models are noted as follows:

$$\text{Level 1:RSA}=\beta_{oij}+\beta_{1ij}\,\text{time linear}+\beta_{2ij}\,\text{time quadratic}+e_{ij}$$
$$\text{Level 2:}\beta_{oij}=\gamma_{00}+\gamma_{01}\,\text{group}+\omega_{oj}$$
$$\beta_{1ij}=\gamma_{10}+\gamma_{11}\,\text{group}$$
$$\beta_{2ij}=\gamma_{20}+\gamma_{21}\,\text{group}$$

The best fitting model (AIC = 779.5, BIC = 784.5) was a random intercepts model that allowed intercepts, but not slope estimates, to deviate from person to person. The inclusion of an error term in the Level 2 equation predicting individual intercepts (βo_{ij}) represents an estimation of the error resulting from intercepts being allowed to vary from person to person within group. However, the exclusion of this error term in the Level 2 equation predicting individual linear (β_{1ij}) and quadratic slopes (β_{2ij}) reflects the constraint of linear and quadratic slopes to be equal (i.e., parallel) from person to person within group. On the whole, the random intercepts only model estimates a group slope, but constrains individual slopes within each group so that they are parallel to the slope of the overall group.

Results

Correlations of RSA Suppression and Trends

Means and standard deviations for study variables are reported in Table 1. There was no evidence of gender differences in any of the RSA or behavioral variables (all $|t|$s<1.25, *p*s>. 10). Thus, gender was not controlled for in subsequent analyses. Partial correlations controlling for vigor of activity showed that linear and quadratic change in RSA were unrelated to RSA change scores (linear: r =.20 and quadratic r = −.17, *p*s >.05), suggesting that suppression and trend score variables contained unique information about parasympathetic response.

Differences between High-fear and Non-high fear Children

High-fear and non-high fear toddlers (identified from the screening) did not differ in levels of distress ($t_{1,\,86}$ = 0.00, p>.10) or positive affect ($t_{1,\,86}$ = 1.27, p>.10) during the 24 month visit. However, high fear toddlers did show marginally more withdrawal ($t_{1,\,86}$ = −1.86, p<.10) and significantly less boldness ($t_{1,\,86}$ = 2.48, p<.05) than did non-high fear toddlers. Thus, approach and withdrawal behaviors during the *Stranger Approach* were aligned with mother-reported fear while affective displays were not.

Group differences in change in RSA from baseline to task (i.e., difference scores) were tested using a repeated measures ANOVA that included level of RSA as a within-subjects factor (baseline RSA and task RSA), 18-month fear status (i.e., high fear vs. non-high-fear) as a between-subjects factor, and vigor of activity as a covariate. There was a significant main effect of fear status ($F_{1,81}$ = 5.09, p<.05) suggesting that, in general, high-fear toddlers had greater levels of RSA than toddlers who were not high in fear. There was also a significant main effect of episode ($F_{1,\,81}$ = 6.04, p<.05); levels of RSA were greater during the baseline episode than during the *Stranger Approach*. The interaction between episode and 18-month fear status was not significant ($F_{1,81}$ = 0.60, p>.10), suggesting that decreases in RSA from the baseline to the episode did not differ between high-fear and non-high-fear children and the difference in RSA between high fear and non-high-fear children did not differ across the episodes.

Group-level RSA trends modeled as multilevel mixed growth curves are depicted in Figure 2. Significant interactions with fear status emerged for both linear ($F_{1,178}$ = 8.77, p<.01) and quadratic change in RSA ($F_{1,178}$ = 9.90, p<.01). As suggested by Figure 2, high-fear toddlers showed greater linear increases (β =.82, *SE* =.26) and more negative quadratic change (β = −.34, *SE* =.10) during the episode than non-high fear toddlers (Linear: β =.07, *SE* =.17; Quadratic: β = −.01, *SE* =.06). As shown in Figure 2, the combination of greater linear change and more negative quadratic change resulted in an effect of rising and leveling RSA in high-fear toddlers followed by a slow decline. In contrast, less linear and quadratic change in non-high-fear toddlers resulted in a relatively constant level of RSA over time.

Using Dynamic Change in RSA to Predict Emotion Behaviors

Individual estimates of linear and quadratic change were highly correlated (r = −.94) and so were not entered together into a regression analysis (Cohen & Cohen, 1983). Instead, hierarchical regressions were used to test whether variables representing the dynamic measure of RSA contributed to the prediction of emotion outcomes beyond what was contributed by traditional scores of RSA change. In the first step, vigor of activity was entered as a covariate along with a grouping variable representing status as a high-fear or non-high fear child at 18 months. In the second step, RSA change scores (static change in RSA) were added to the model. Individual linear or quadratic trend scores (dynamic change in RSA) were added in the third step[1]. In the fourth and final step, the interactions between 18-month fear and change in RSA and 18-month fear and linear or quadratic trend scores were entered. Nonsignificant interaction terms were trimmed to produce the final models.

Distress—Only vigor of activity was significantly related to distress during the episode in both the model that included the linear trend (β = −.30, t = −2.42, p<.05) and also the model that included the quadratic trend (β = −.31, t = −2.59, p<.05). In both cases, more activity

[1]Given the meaningful nature of the zero values of the change and trend score estimates, these continuous variables were not centered prior to being entered into the regression model. However, in recognition of the recommendations that have been made with regard to centering continuous variables for use in regression models, separate analyses were run using centered terms. Patterns of results were identical to those presented here and are available from the first author upon request.

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was related to less observer-rated distress. Distress and indices of change in RSA were unrelated.

Positive Affect—Vigor of activity was related to positive affect in the model including linear trend (β =.52, t = 4.82, p<.01) such that greater activity was associated with more positive affect during the episode.

Vigor of activity was also related to positive affect in the model including the quadratic trend (β =.52, t = 5.13, p<.01). Again, greater vigor of activity was associated with more positive affect during the episode. A significant interaction also emerged between target status and quadratic change in RSA (β = −.25, t = −2.08, p<.05). As suggested by Aiken & West (1991), this interaction was probed by recoding the grouping variable so that the high-fear and non-high-fear toddlers each served as the reference group for the interpretation of the main effect of quadratic change in RSA. Probing the interaction in this manner revealed that quadratic change in RSA was unrelated to positive affect for non-high-fear children (β =.13, t = 1.09, p>.10), but was negatively related to positive affect for high-fear children (β = −.29, t = −1.11, p<.10). This relationship, shown in Figure 3, suggests that greater positive affect was related to increases followed by decreases in RSA for high-fear children.

Shyness—Only more activity was related to less shyness during the episode in the models including the linear (β = −.40, t = −3.71, p<.01) and quadratic trends (β = −.39, t = −3.58, p<.01). In both cases, greater activity was associated with less shyness in the presence of the stranger.

Boldness—Vigor of activity was related to boldness in the models including linear (β =.53, t = 5.57, p<.01) and quadratic change in RSA (β =.52, t = 5.50, p<.01). Target status was also marginally related to boldness in the model including the quadratic trend (β = −.16, t = −1.87, p<.10). Consistent with previous analyses, more activity and status as a non-high-fear child was related to greater boldness during the episode. In addition, RSA change scores were marginally associated with boldness in both models (Linear: β = −.17, t = −1.73, p<.10; Quadratic: β = −.18, t = −1.86, p<.10). In both cases, greater decreases in RSA from baseline to task (i.e., suppression) was associated with more boldness during the episode.

Post-hoc analyses—A post-hoc analysis was conducted to examine whether the patterns of results obtained here may have resulted from baseline differences in RSA between high-fear and non-high-fear children. An ANCOVA controlling for vigor of activity showed that non-high fear toddlers had significantly lower levels of RSA than high-fear children during the *Stranger Approach* ($F_{1,85}$ = 7.18, p<.01). However, a t-test (as children were stationary for baseline) showed that RSA for the two groups did not differ at baseline ($t_{1,82}$ = −1.67, p>.10). Given that RSA change scores did not differ between high-fear and non-high fear children, this pattern suggests that differences in levels of RSA seen during the episode in this sample were not due to arbitrarily high levels of RSA in high-fear toddlers.

Discussion

Hypotheses of the current study were largely confirmed. Dynamic change in RSA differed between high-fear and non-high-fear toddlers and was related to toddlers' emotion behaviors in ways that were different from traditionally-used static measures of change in RSA. Neither dynamic nor static change in RSA were related to toddlers' displays of distress or shyness during a fear-eliciting task. However, patterns of dynamic and static change in RSA did offer unique information about children's displays of positive affect and bold behaviors. Moreover, several findings emerged that suggested the importance of nonlinear change in RSA in relation to emotion behaviors during a fear-eliciting task.

Dynamic Measures of RSA Depict Differences between High-Fear and Non-high-fear Toddlers

Group-level differences were seen between high-fear and non-high-fear children for patterns of linear and quadratic change in RSA. High-fear children showed greater degrees of positive linear and negative quadratic change in RSA over the course of the episode. Note that as overall change would be reflected as combined linear and quadratic change (Figure 2), this suggests that high-fear children showed decreases in RSA later in the episode – and possibly later suppression - than non-high fear children. Conversely, one may interpret these findings as illustrating the ability of non-high-fear children to suppress RSA, resulting in levels of RSA that were lower than those of high-fear children throughout the episode. While this idea is supported by the plot of means in Figure 2, it raises an important question relative to the extant literature on RSA. As discussed earlier, although results are not always consistent, non-high-fear children typically exhibit *higher* levels of RSA than children who are high in fear (Stifter & Fox, 1990;Stifter et al., 1989). Yet, this idea is largely based on RSA measured at rest (i.e., baseline) or during a cognitive challenge rather than during an emotion task. Some work has examined static measures of RSA during emotion-eliciting episodes, including one study by Marshall and Stevenson-Hinde (1998) that found no differences in RSA between high fear children and their less fearful peers.

In addition, recall that high RSA at baseline is considered adaptive in that it represents a readiness for RSA suppression upon the encounter of threat. That is, when suppression is adaptive, children with higher baseline RSA may have more opportunity for decreases in RSA than those with lower baseline levels, as suggested by the law of initial values. However, adaptive responses may also be reflected either as greater suppression during situations of perceived threat (Porges, 2007) or as greater augmentation during a social encounter (Hastings et al., 2008). Thus, questions remain regarding suppression and augmentation in the presence of a moderately threatening male stranger; it is unclear whether non-high-fear children showed RSA suppression or whether fearful children in the current study showed RSA augmentation in response to the episode.

Unfortunately, while centering time at the entrance of the stranger created greater temporal consistency across individuals during the episode, it prohibited discussion of changes in RSA relative to levels prior to the stranger's entry. Though post-hoc analyses suggested that differences in baseline levels of RSA were not responsible for different links between changes in RSA and emotion behaviors in high-fear and non-high-fear children, the replication of these findings in an episode including an *in situ* baseline measure of RSA would certainly be of interest. Furthermore, given recent evidence that baseline RSA and change in RSA during periods of challenge interact to longitudinally predict children's internalizing and externalizing symptoms (Hinnant & El-Sheikh, 2009), subsequent work should also consider possible interactions between baseline RSA and changes in RSA during emotion episodes.

Dynamic Changes in RSA Offer Unique Information about Toddlers' Positive Affect

Dynamic scores of change in RSA contributed information about boldness that was unique from static RSA change scores. More negative quadratic change, suggesting increases followed by decreases in RSA (Figure 1b), were related to more positive affect in high-fear toddlers during the episode. Viewed from the perspective of Polyvagal theory, this suggests that high-fear toddlers who were able to either engage in social interaction with the stranger (supported by increases in RSA) or suppress heightening levels of RSA (depicted as rising, then falling RSA) were more positive. In addition, these results suggest that even late suppression of RSA is adaptive, as high-fear toddlers whose dynamic patterns showed decreases in RSA late in the episode received higher observer ratings of positive affect. This type of change may be lost in aggregates of RSA levels across whole episodes. Indeed, static measures of RSA did not contribute to toddlers' displays of positive affect. Moreover, the ability to combine linear and quadratic trend scores in the prediction of emotion behaviors would help to delineate the importance of the timing of change. For example, although both may show RSA suppression as an estimate of average change, toddlers who show both negative linear changes in RSA and negative quadratic changes in RSA (Figure 4a) would show patterns of decreases in RSA with a later onset than toddlers with negative linear and positive quadratic change (Figure 4b). The ability to compare these two profiles of toddlers will be important for fully capturing the importance of dynamic change in RSA for emotion outcomes.

That dynamic change in RSA should be related to observations of positive affect and boldness but not distress or shyness is difficult to explain. Past work suggests that discrete negative emotions such as fear and sadness are more sensitive measures than global ratings of negative affect or distress (Buss & Goldsmith, 2007). However, little is known about the ways that positive emotion might be uniquely related to measures of cardiac function such as RSA in young children. One of the few studies that examined positive emotions in toddlers found less suppression of RSA during the elicitation of positive emotion than in tasks that elicited fear or frustration (Calkins & Dedmon, 2000). In the adult literature, physiological response patterns have been tied to behaviors associated with characteristic emotion responses rather than to discrete emotional displays (Davidson, 1994; Stemmler, 1994, Rainville, Bechara, Naqvi, & Damasio, 2006), though conclusions are limited in that not all of this work has used episodes that elicit the targeted emotions (e.g., Rainville et al., 2006). This is of additional interest in the current study given that the behaviors that were associated with physiological change – positive affect and boldness – are both approach-oriented in nature. Moreover, these approach behaviors were displayed by some toddlers in a context where most children exhibited some level of wariness. A distinction between approach and withdrawal-related behaviors has been important in integrating knowledge about positive affect into the emotion literature using other physiological measures (e.g., Davidson, 1998; Harmon-Jones & Allen, 1998). Thus, follow-up work should consider patterns of physiological response along with behaviors and eliciting context.

The current results thus contribute to the literature in two important ways. First, they provide evidence that nonlinear change in RSA is both related to emotion outcomes and also differentially representative of patterns of RSA in high-fear and non-high-fear toddlers. Second, it suggests that it may be important to consider the timing of changes in RSA as opposed to overall levels of change. It is not clear from the current data whether the patterns of change in RSA seen for non-high-fear toddlers are not adaptive for those who were high in fear or whether high-fear toddlers simply do not show these patterns of change. Replicating the current results in larger samples will be important for addressing these types of issues.

In addition, subsequent research should consider whether dynamic measures of change in RSA are linked with more dynamic measures of change in emotion behaviors. In the current study, moment-to-moment fluctuations in processes of physiological regulation were linked with static ratings of emotion over the course of a fear-eliciting episode. As previously discussed, emotion theorists have suggested that dynamic changes in regulation occur at multiple levels of emotion behavior (e.g., Cole et al., 2004; Larsen et al., 2008; Thompson et al., 2008). Thus, there may be additional information to be gained by including dynamic measures of emotion expression. That is, the dynamic measurement of fear regulation may offer insight into individual differences in associations between emotional and physiological regulation that was not available within the current approach

Traditional Change Scores Predict Boldness/Approach for Non-high-fear Toddlers

Change scores of RSA were most informative about boldness in non-high-fear toddlers. Greater suppression of RSA during the episode was related to more boldness for toddlers who were not high in fear, as was low fearfulness itself. Low levels of fear have been linked with low and high intensity approach behaviors (Putnam & Stifter, 2005; Gray, 1987), suggesting a propensity for low-fear individuals to engage more readily in these types of behaviors. To the extent that RSA suppression supports selective engagement with one's environment (Porges et al., 1996), global decreases in RSA over the duration of a stranger interaction may have supported engagement in play or conversation with the stranger, and these behaviors may have been particularly salient in non-high fear toddlers.

Based on past research, one might expect that boldness in toddlers would be linked with RSA augmentation rather than RSA suppression, as augmentation is believed to provide support for interaction during periods of social challenge (Hastings et al., 2008). However, it is important to note that this study differs methodologically from past work on RSA augmentation in two important ways. First, the social challenge in the current study was an adult male. Hastings and colleagues employed a socially-challenging paradigm where children interacted with same-aged, same-sex unfamiliar peers. Without speculating as to differences in degree of threat between the two protocols, one might argue that there are important distinctions to be made between a child interacting with his/her peers and interacting with an adult. Past work supports the idea that children's behaviors with peers differ from interactions with adults (Hartup, 1979) and that peer interactions in childhood are unique from interactions with adults (Asher & Coie, 1990). Second, Hastings and colleagues used residualized change scores, calculations that are more static in nature, to represent change in RSA from baseline to task.

RSA suppression is also commonly interpreted as biological efforts to regulate negative arousal (e.g., Buss et al., 2005; Calkins & Keane, 2004). As indicated above, an alternative explanation for the current findings may be that non-high-fear toddlers were able to regulate negative arousal associated with the entry of the stranger in a way that was not observed in high fear toddlers. This is aligned with a number of studies linking inhibited behaviors in childhood, including fearfulness and withdrawal, with a failure to suppress RSA in novel and challenging contexts (Calkins et al., 2007; Buss & Goldsmith, 2007). Furthermore, it may be that the consistency with which non-high-fear toddlers are able to suppress RSA makes the temporal dynamics of RSA suppression less important for these types of children. As illustrated in Figure 2, non-high-fear children were characterized by stably low levels of RSA and showed almost no dynamic changes (see also Table 1). Given that neither baseline levels of RSA nor RSA change scores differed between high-fear and non-high-fear children, this pattern may again reflect the importance of temporal differences in RSA suppression that are lost in aggregate measures.

Limitations

Some limitations of the current study included a small sample size resulting in limited power. Replication of these results in a larger sample of children would help to clarify marginal findings and allow additional tests of independence to be used, particularly if extreme groups were included. In addition, the models for regression analyses that produced individualized estimates of linear and quadratic change in RSA did not contain enough degrees of freedom to test the significance of each individual estimate. Therefore the extent to which observed patterns were significant for any individual may have differed. Though a larger sample and longer emotion-elicitation episodes may help to resolve this issue, there remains a question regarding the meaningfulness of units of change in the time domain as dynamic methods become more refined.

Conclusions

In line with past recommendations in the emotion regulation literature, we found evidence that dynamic changes in the measure of RSA contribute information about emotion processes that is unique from traditionally-employed static measures. This study presents one possible method for creating and testing a temporally-sensitive measure of changes in RSA across a single emotion-eliciting episode. This technique could easily map onto continuous coding currently being used to capture the dynamic regulation of emotions and it offers a unique opportunity for comparisons of individual regulation within and across tasks.

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References

Aiken, LS.; West, SG. Multiple regression: Testing and interpreting interactions. Thousand Oaks, CA: Sage Publications; 1991.

Alkon A, Goldstein LH, Smider N, Essex MJ, Kupfer DJ, Boyce WT. The MacArthur Assessment Battery Working Group. Developmental and contextual influences on autonomic reactivity in young children. Developmental Psychobiology 2003;42:64–78. [PubMed: 12471637]

Asher, SR.; Coie, JD. Peer rejection in childhood. New York: Cambridge University Press; 1990.

Berntson GG, Quigley KS, Jang JF, Boysen ST. An approach to artifact identification: Application to heart period data. Psychophysiology 1990;27:586–598. [PubMed: 2274622]

Briggs-Gowan, MJ.; Carter, AS. Infant Toddler Social and Emotional Assessment (ITSEA) Manual (Technical report). New Haven, CT: Author; 2001 Jun.

Buss KA, Goldsmith HH. Fear and anger regulation in infancy: Effects on the temporal dynamics of affective expression. Child Development 1998;69:359–374. [PubMed: 9586212]

Buss, KA.; Goldsmith, HH. Manual and normative data for the Laboratory Temperament Assessment Battery—Toddler Version (Tech. Rep.). University of Wisconsin—Madison, Department of Psychology; 2000.

Buss, KA.; Goldsmith, HH. Biobehavioral approaches to early socioemotional development. In: Brownell, CA.; Kopp, CB., editors. Socioemotional development in the toddler years. New York: Guilford Press; 2007. p. 370-395.

Buss KA, Goldsmith HH, Davidson RJ. Cardiac reactivity is associated with changes in negative emotion in 24-month-olds. Developmental Psychobiology 2005;46:118–132. [PubMed: 15732055]

Buss KA, Kiel EJ. Comparison of sadness, anger, and fear facial expressions when toddlers look at their mothers. Child Development 2004;75:1761–1773. [PubMed: 15566378]

Carter AS, Briggs-Gowan MJ, Jones SM, Little TD. The infant-toddler social and emotional assessment (ITSEA): Factor structure, reliability, and validity. Journal of Abnormal Psychology 2003;31:495–514.

Calkins SD. Cardiac vagal tone indices of temperamental reactivity and behavioral regulation in young children. Developmental Psychobiology 1997;31:125–135. [PubMed: 9298638]

Calkins SD, Blandon AY, Williford AP, Keane SP. Biological, behavioral, and relational levels of resilience in the context of risk for early childhood behavior problems. Development and Psychopathology 2007;19:675–700. [PubMed: 17705898]

Calkins SD, Dedmon SE. Physiological and behavioral regulation in two-year-old children with aggressive/destructive behavior problems. Journal of Abnormal Child Psychology 2000;28:103–118. [PubMed: 10834764]

Calkins SD, Fox NA. The relations among infant temperament, security of attachment, and behavioral inhibition at twenty-four months. Child Development 1992;63:1456–1472. [PubMed: 1446562]

Calkins SD, Graziano PA, Keane SP. Cardiac vagal regulation differentiates among children at risk for behavior problems. Biological Psychology 2007;74:144–153. [PubMed: 17055141]

Calkins SD, Keane SP. Cardiac vagal regulation across the preschool period: Stability, continuity, and implications for childhood adjustment. Developmental Psychobiology 2004;45:101–112. [PubMed: 15505799]

Camras LA, Witherington DC. Dynamical systems approaches to emotional development. Developmental Review 2005;25:328–350.

Cohen, J.; Cohen, P. Applied multiple regression/correlation analysis for the behavioral sciences. 2. Hillsdale, N.J: Lawrence Earlbaum Associates; 1983.

Cole PM, Martin SE, Dennis TA. Emotion regulation as a scientific construct: Methodological challenges and directions for child development research. Child Development 2004;75:317–333. [PubMed: 15056186]

Davidson RJ. Asymmetric brain function, affective style and psychopathology: The role of early experience and plasticity. Development and Psychopathology 1994;6:741–758.

Davidson RJ. Affective style and affective disorders: Perspectives from affective neuroscience. Cognition and Emotion 1998;12:307–320.

Dennis TA, Cole PM, Wiggins CN, Cohen LH, Zalewski M. The functional organization of preschool-age children's emotion expressions and actions in challenging situations. Emotion 2009;9:520–530. [PubMed: 19653775]

Ekman, P. Moods, emotions, and traits. In: Ekman, P.; Davidson, RJ., editors. The nature of emotion : fundamental questions. New York: Oxford University Press; 1994. p. 56-58.

El-Sheikh M. Parental drinking problems and children's adjustment: Vagal regulation and emotional reactivity as pathways and moderators of risk. Journal of Abnormal Psychology 2001;110:499–515. [PubMed: 11727940]

Fogel A, Nwokah E, Dedo JY, Messinger D, Dickson KL, Matusov E, Holt SA. Social process theory of emotion: A dynamic systems approach. Social Development 1992;1(2):122–142.

Gray JA. Perspectives on anxiety and impulsivity. Journal of Research in Personality 1987;21:493–509.

Grossman P, Van Beek J, Wientjes C. A comparison of three quantification methods for estimation of respiratory sinus arrhythmia. Psychophysiology 1990;27:702–714. [PubMed: 2100356]

Grossman P, Wilhelm FH, Spoerle M. Respiratory sinus arrhythmia, cardiac vagal control, and daily activity. American Journal of Physiology - Heart and Circulatory Physiology 2004;287:728–734.

Harmon-Jones E, Allen JB. Anger and frontal brain activity: EEG asymmetry consistent with approach motivation despite negative affective valence. Journal of Personality and Social Psychology 1998;74:1310–1316. [PubMed: 9599445]

Hartup, WW. Peer relations and the growth of social competence. In: Kent, MW.; Rolf, JE., editors. Primary Prevention of Psychopathology. Vol. 3. Hanover, New Hampshire: University Press of New England; 1979. p. 150-170.

Hastings PD, Nuselovici JN, Utendale WT, Coutya J, McShane KE, Sullivan C. Applying the polyvagal theory to children's emotion regulation: Social context, socialization, and adjustment. Biological Psychology 2008;79:299–306. [PubMed: 18722499]

Hill-Soderlund AL, Mills-Koonce WR, Propper C, Calkins SD, Granger DA, Moore GA, Gariepy J, Cox MJ. Parasympathetic and sympathetic responses to the strange situation in infants and mothers from avoidant and securely attached dyads. Developmental Psychobiology 2008;50:361–376. [PubMed: 18393278]

Hinnant JB, El-Sheikh M. Children's externalizing and internalizing symptoms over time: The role of individual differences in patterns of RSA responding. Journal of Abnormal Child Psychology 2009;37:1049–1061. [PubMed: 19711181]

Hofheimer JA, Wood BR, Porges SW, Pearson E, Lawson EE. Respiratory sinus arrhythmia and social interaction patterns in preterm newborns. Infant Behavior and Development 1995;18:233–245.

Hox, J. Multilevel analysis techniques and applications. Mahwah, New Jersey: Lawrence Erlbaum Assiciates; 2002.

Larsen, JT.; Berntson, GG.; Poehlmann, KM.; Ito, TA.; Cacioppo, JT. The psychophysiology of emotion. In: Lewis, M.; Haviland-Jones, JM.; Feldman Barrett, L., editors. Handbook of Emotions. 3. New York: Guilford Press; 2008. p. 180-195.

Llabre MM, Spitzer SB, Saab PG, Ironson GH, Schneiderman N. The reliability and specificity of delta versus residualized change as measures of cardiovascular reactivity to behavioral challenges. Psychophsiology 1991;28:701–711.

Marshall PJ, Stevenson-Hinde J. Behavioral inhibition, heart period, and respiratory sinus arrhythmia in young children. Developmental Psychobiology 1998;33:283–292. [PubMed: 9810478]

Porges SW. Orienting in a defensive world: Mammalian modifications of our evolutionary heritage. A polyvagal theory. Psychophysiology 1995;32:301–318. [PubMed: 7652107]

Porges SW. The polyvagal perspective. Biological Psychology 2007;74:116–143. [PubMed: 17049418]

Porges SW, Doussard-Roosevelt JA, Portales AL, Greenspan SI. Infant regulation of the vagal “brake” predicts child behavior problems: A psychobiological model of social behavior. Developmental Psychobiology 1996;29:697–712. [PubMed: 8958482]

Porges SW, Lipsitt LP. Neonatal responsivity to gustatory stimulation: The gustatory-vagal hypothesis. Infant Behavior and Development 1993;16:487–494.

Porter FL, Porges SW, Marshall RE. Newborn pain cries and vagal tone: Parallel changes in response to circumcision. Child Development 1988;59:495–505. [PubMed: 3359867]

Putnam SP, Stifter CA. Behavioral approach-inhibition in toddlers: Prediction from infancy, positive and negative affect components, and relations with behavior problems. Child Development 2005;76:212–226. [PubMed: 15693768]

Rainville P, Bechara A, Naqvi N, Damasio AR. Basic emotions are associated with distinct patterns of cardiorespiratory activity. International Journal of Psychophysiology 2006;61:5–18. [PubMed: 16439033]

Singer JD. Using SAS PROC MIXED to fit multilevel models, hierarchical models, and individual growth models. Journal of Educational and Behavioral Statistics 1998;24:322–354.

Stemmler, G. Physiological processes during emotion. In: Philippot, P.; Feldman, RS., editors. The regulation of emotion. Mahwah, New Jersey: Lawrence Erlbaum Associates; 1994. p. 33-70.

Stifter CA, Jain A. Psychological correlates of infant temperament: Stability of behavior and autonomic patterning from 5 to 18 months. Developmental Psychobiology 1996;29:379–391. [PubMed: 8732809]

Stifter CA, Fox NA. Infant reactivity: Physiological correlates of newborn and 5-month temperament. Developmental Psychobiology 1990;26:582–588.

Stifter CA, Fox NA, Porges SW. Facial expressivity and vagal tone in five- and ten-month-old infants. Infant Behavior and Development 1989;12:127–137.

Thompson, RA. Monographs for the Society for Research in Child Development. Vol. 59. 1994. Emotion regulation: A theme in search of a definition; p. 25-52.

Thompson RA, Lewis MD, Calkins SD. Reassessing emotion regulation. Child Development Perspectives 2008;2:124–131.

Zautra AJ, Reich JW, Davis MC, Potter PT, Nicolson NA. The role of stressful events in the relationship between positive and negative affects: Evidence from field and experimental studies. Journal of Personality 2000;68:927–951. [PubMed: 11001154]

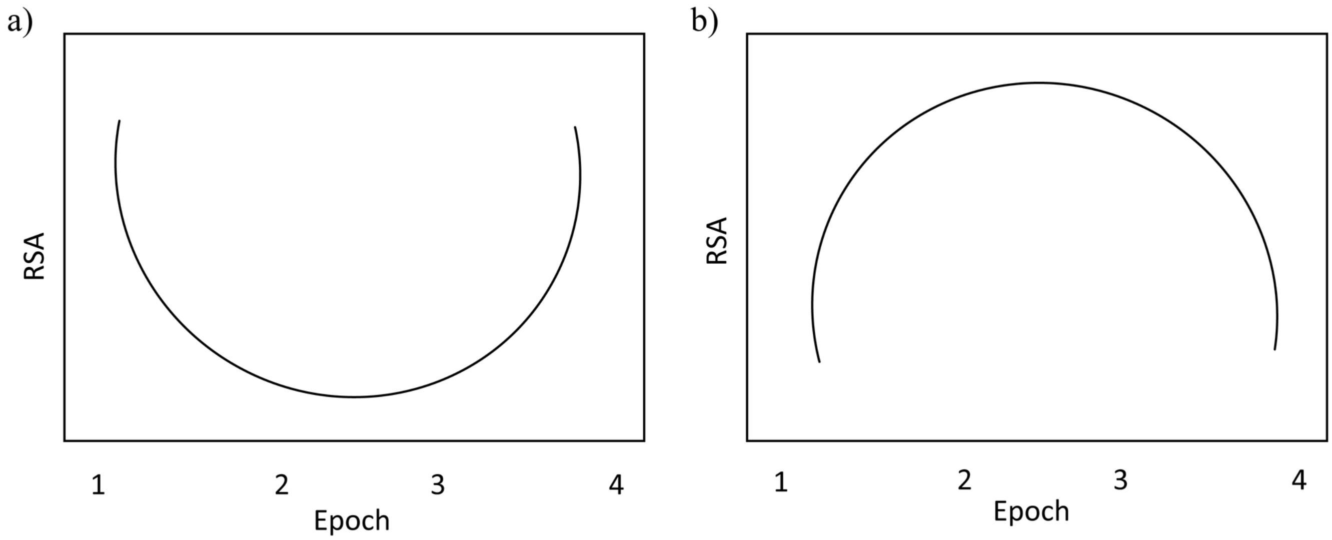

Figure 1.
Hypothetical data depicting quadratic change in RSA over time.

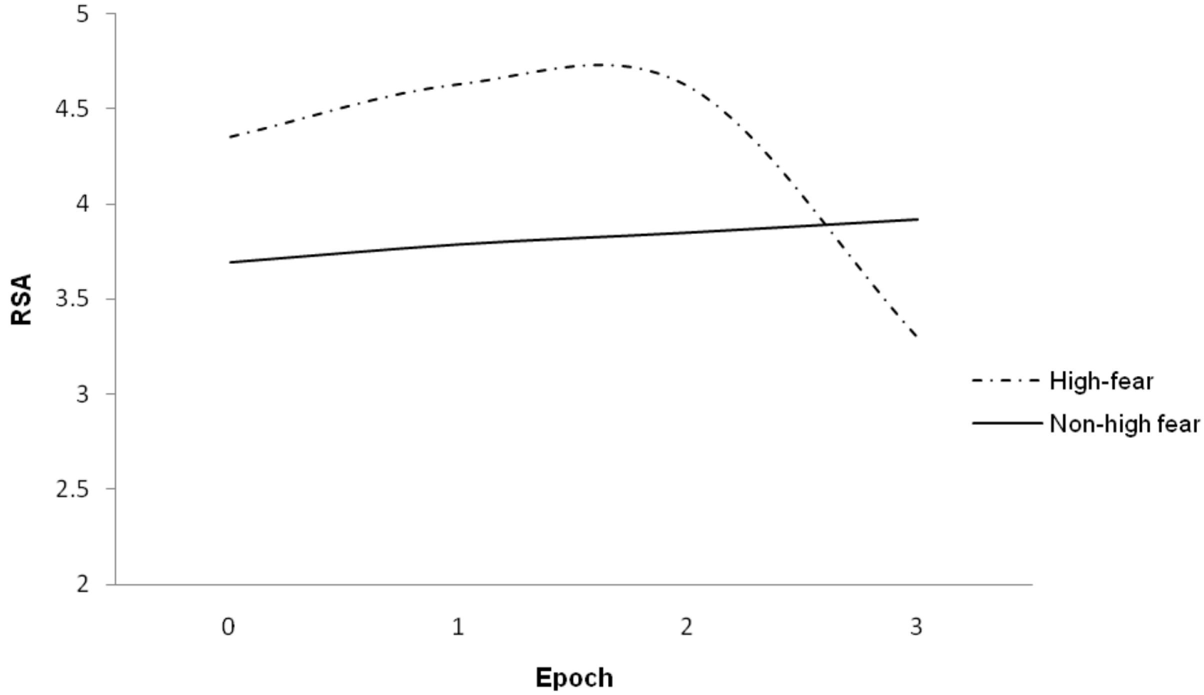

Figure 2.
Trends in RSA during the *Stranger Approach* episode for high fear and non-high fear toddlers.

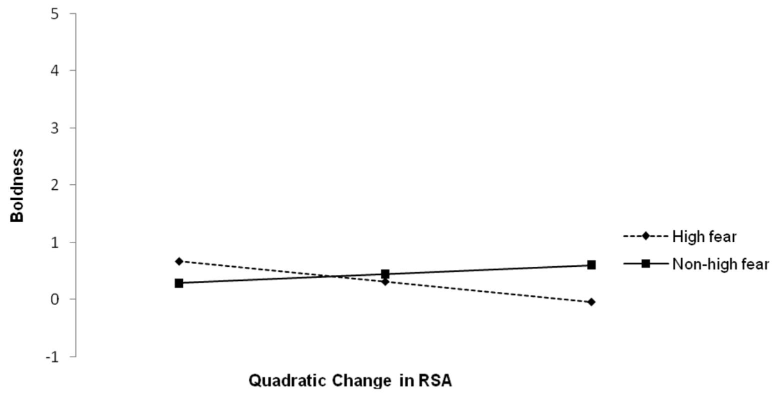

Figure 3.
Interaction between 18-month fear status and quadratic change in RSA predicting positive affect during the *Stranger Approach*.

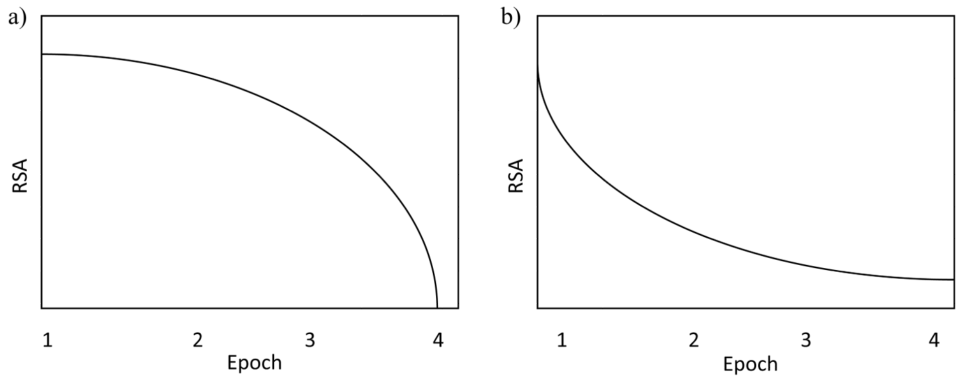

Figure 4.
Hypothetical data depicting negative linear change paired with negative (a) and positive (b) quadratic change.

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Table 1

Means and Standard Deviations for Study Variables (N = 88)

Variable	High-Fear	Non-High Fear
Change in RSA	−0.27 (0.94)	−0.51 (0.96)
Linear trend	0.29 (1.33)	0.12 (1.69)
Quadratic trend	−0.07 (0.52)	−0.02 (0.74)
Boldness/Approach	2.02 (0.90)	2.57 (1.15)
Shyness/Withdrawal	2.66 (0.83)	2.32 (0.88)
Negative affect	1.39 (0.62)	1.39 (0.87)
Positive affect	1.41 (0.76)	1.61 (0.75)
Vigor of activity	2.32 (0.83)	2.57 (0.90)

Note: Numbers outside of parenthesis are means. Numbers in parenthesis are standard deviations.