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Moderate Baseline Vagal Tone Predicts Greater Prosociality in Children

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Abstract

Vagal tone is widely believed to be an important physiological aspect of emotion regulation and associated positive behaviors. However, there is inconsistent evidence for relations between children's baseline vagal tone and their helpful or prosocial responses to others (Hastings & Miller, 2014). Recent work in adults suggests a quadratic association (inverted U-shape curve) between baseline vagal tone and prosociality (Kogan et al., 2014). The present research examined whether this nonlinear association was evident in children. We found consistent evidence for a quadratic relation between vagal tone and prosociality across 3 samples of children using 6 different measures. Compared to low and high vagal tone, moderate vagal tone in early childhood concurrently predicted greater self-reported prosociality (Study 1), observed empathic concern in response to the distress of others and greater generosity toward less fortunate peers (Study 2), and longitudinally predicted greater self-, mother-, and teacher-reported prosociality 5.5 years later in middle childhood (Study 3). Taken together, our findings suggest that moderate vagal tone at rest represents a physiological preparedness or tendency to engage in different forms of prosociality across different contexts. Early moderate vagal tone may reflect an optimal balance of regulation and arousal that helps prepare children to sympathize, comfort, and share with others.

Keywords

vagal tone; prosocial behavior; empathic concern; empathy; generosity

Prosocial behaviors and emotions emerge early in life (Davidov, Zahn-Waxler, Roth-Hanania, & Knafo, 2013; Warneken, 2015), but children vary widely in their development of these attributes (Eisenberg et al., 1996a; Knafo & Plomin, 2006). These differences in the propensity for kindness are partially rooted in children's biology. Recent research and theory suggests that parasympathetic nervous system functioning, reflected by activity in the myelinated vagus nerve (i.e. vagal tone), is implicated in processes related to prosociality (Hastings, Miller, Kahle, & Zahn-Waxler, 2014; Miller, Kahle, & Hastings, 2015; Porges, 2011; Stellar, Cohen, Oveis, & Keltner, 2015). Vagal tone has been linked to empathy, or sharing in the emotions of others, sympathy or concern for others' well-being, and prosocial behaviors meant to assist others or help alleviate others' suffering. However, the observed associations in the literature have been inconsistent (Hastings & Miller, 2014; Miller & Hastings, 2016).

Vagal tone is often interpreted as a physiological correlate of individual differences in emotion regulation (Beauchaine, 2001; Porges, 2011), but vagal tone likely has more functions, potentially including threshold for arousal (Hastings et al., 2000). Thus, two ways in which vagal tone may contribute to which children are motivated to be prosocial and whether or when they will show that tendency are (a) having moderate to moderately high vagal tone provides a physiological capacity for regulation of arousal that can be put into play when the distress of others evokes arousal, but (b) even prior to the need for regulation, children need to not have such high vagal tone that displays of distress or need by others fail to meet the threshold for evoking some resonant response. We examined three samples of children from whom a variety of prosocial measures were obtained to test for potential nonlinear associations between children's baseline vagal tone and prosocial emotions and behaviors. We predicted that children with moderate rather than high or low baseline vagal tone might be more prone to kindness towards others.

According to polyvagal theory, the myelinated vagus developed over the course of mammalian evolution to more effectively regulate the sympathetic nervous system, which is metabolically costly if left unchecked, but important for activating defensive strategies in response to threat (i.e., fight-or-flight) (Porges, 2007; 2011). Vagal tone during resting states, or at baseline, represents the degree to which the vagus nerve exerts parasympathetic influence on the sinoatrial node of the heart, effectively slowing heart rate. In the absence of challenge or stressful circumstances, increased vagal tone at rest can contribute to a calm, soothed state (Porges, 2007, 2011). Baseline vagal tone is widely thought to reflect the capacity for flexible physiological and attentional self-regulation that underlies effective emotion regulation and social competence (Beauchaine, 2001, 2015; Porges, 2011; Thayer, Ahs, Fredrickson, Sollers, & Wager, 2012). Individuals with lower baseline vagal tone may be more prone to experiencing stress-related increases in arousal and negative emotionality when presented with various environmental stimuli, potentially constraining their responses (Beachaine, 2001; Calkins, 1997; Porges, 1992, 2011; Thayer et al., 2012). In research on adults and children, baseline vagal tone has been positively linked to various emotion regulation processes, including the ability to sustain attention, the use of effective coping strategies, and impulse control (Suess, Porges, & Plude, 1994; Williams et al., 2015). Higher baseline vagal tone has been linked to fewer externalizing and internalizing problems, more positive and less negative emotionality, and greater social connectedness and social competence (Beauchaine, 2015; Calkins, 1997; Kok & Fredrickson, 2010; Oveis et al., 2009). It may seem surprising, therefore, that examinations of children's vagal tone and various indices of their prosocial development have produced quite inconsistent findings (Hastings & Miller, 2014).

Effective emotion regulation has been characterized as an important facet of feeling empathy and concern for others, and for engaging in prosocial behaviors (Eisenberg, 2000; Eisenberg & Eggum, 2009; Goetz, Keltner, & Simon-Thomas, 2010). For example, parental reports of children's ability to handle stress at 18 months of age have been linked to children's empathy 6 months later, which, in turn, predicted teacher-rated prosocial behavior at 72 and 84 months (Taylor, Eisenberg, Spinrad, Eggum, & Sulik, 2013). Experiencing too much vicarious arousal can lead to personal distress – a self-focused response to the distress of others that is typically characterized by aversive feelings like anxiety (Eisenberg, 2000).

From this perspective, to the extent that baseline vagal tone is a physiological aspect of effective emotion regulation, children with higher vagal tone would be expected to be more prosocial, and this pattern has been observed in several studies (Diamond, Fagundes, & Butterworth, 2012; Liew et al., 2011; Taylor, Eisenberg, & Spinrad, 2015). However, other studies have found the opposite relation. Eisenberg and colleagues (1996a) found that baseline vagal tone was negatively correlated with peer reports of girls' prosocial behavior, and Zahn-Waxler and colleagues (1995) found a negative association between baseline vagal tone and children's observed empathic concern toward injured adults. Other studies have failed to find any relation between baseline vagal tone and prosociality (Eisenberg et al., 1996b; Feldman, 2015). In fact, the majority of tested relations between baseline vagal tone and prosociality in the developmental literature have been statistically non-significant (Hastings & Miller, 2014).

One potential explanation for these contradictory findings is that although ineffective emotion regulation can contribute to less prosociality, the opposite could also be true – that there is such a thing as being over-regulated. Indeed, some research suggests that effective emotion regulation skills can be used to avoid empathizing with and helping others under certain conditions (Zaki, 2014). Expressing kindness might not just be a matter of having greater regulatory capacity, but rather a balance between arousal and regulation that supports sensitivity to others' needs and the motivation to approach and help others.

Children's physiological threshold for increasing arousal might be an important facet of emotion regulation (Calkins & Hill, 2007). We have previously suggested that baseline vagal tone may be linked to thresholds for motivating prosocial responses, "If children with high vagal tone have a high threshold for arousal, they may not react to mild or moderate distress in others, and therefore appear to lack sympathy or the willingness to help" (Hastings, Zahn-Waxler, & McShane, 2006, p. 500). Lower baseline vagal tone may index greater vigilance to environmental cues and preparedness to engage threat-related responses, whereas higher baseline vagal tone may reflect a propensity to evaluate safety in the environment and decreased need for active coping (Beauchaine, 2015; Porges, 2011; Thayer et al., 2012). In other words, higher and lower baseline vagal tone may relate to higher and lower thresholds for increasing arousal, respectively (Hastings et al., 2000, 2006). If this extends to thresholds for arousal in response to cues of need or distress in others, then one would expect that prosociality would be supported by experiencing moderate arousal, versus either high arousal (low thresholds, leading to personal distress) or low arousal (high thresholds, leading to disengaged or callous responding). Thus, we would predict a nonlinear association between children's baseline vagal tone and prosociality. Moderate baseline vagal tone may represent an optimal balance of resting physiological regulation that primes children to notice, be affected by, and respond to the needs of others, but without becoming emotionally overwhelmed or threatened by them.

Converging with this proposal, recent research with adults has found evidence for a quadratic relation (inverted U-shape) between vagal tone and prosociality. Kogan and colleagues (2014) found that individuals with moderate vagal tone reported more prosocial relations with others and greater proneness to experiencing compassion and gratitude, and were rated by strangers as appearing more prosocial. Whether a similar association exists in children is, as of yet, untested. Nor has the quadratic vagal tone-prosociality hypothesis been evaluated using observational measures of helping behaviors. Lastly, whether moderate baseline vagal tone predicts future prosociality is an open question that requires longitudinal data.

Present Studies

We aimed to test the quadratic vagal tone-prosociality hypothesis using six measures of prosociality from three different samples of children. In all six analyses, we used baseline respiratory sinus arrhythmia (RSA) as a measure of vagal tone. RSA refers to heart rate variability that corresponds with breathing. Heart rate increases during inhalation and decreases during exhalation. This phenomenon is mainly under the control of the myelinated vagus nerve, suggesting that RSA is a proximal measure of vagal tone (Berntson et al., 1997).

In Study 1, we tested for a quadratic relation between vagal tone and a self-report measure of empathy and prosocial behavior in 4 to 6 year-old children. In Study 2, we sought to replicate and extend these results by examining 4 year-old children's observed prosocial responses toward an adult simulating injury, as well as sharing behavior in a donation task. In Study 3, we tested whether vagal tone in early childhood quadratically predicted future self-, parent-, and teacher-reported prosociality 5.5 years later.

Study 1

Method

Participants—As described in previous publications (Miller et al., 2013; Utendale et al., 2014), this study included 180 children (95 boys, 85 girls), aged 4.0 – 4.9 years (n = 98) or 6.0 – 6.9 years (n = 82) at recruitment. Four younger and eight older children turned 5 or 7 years old prior to testing. The majority of children were Caucasian (78.7%) and came from middle to upper-middle socioeconomic status families as assessed by annual family income (M = $79,700 Canadian Dollars, SD = $43,470, range from less than $10,000 to over $220,000) and mother education (M = 14.79 years, SD = 2.30). Families were recruited using targeted advertisements and screening in order to oversample for children with externalizing problems. Children with parent-reported cognitive or physical challenges were excluded from the study.

Procedure—Children completed all procedures in the laboratory. Approximately one hour into the visit, two adhesive electrodes were attached to the child's chest to record cardiac inter-beat interval data (IBIs). Approximately 5 minutes later, children's baseline physiological data were obtained during three different baseline procedures. Approximately 40 min after the resting baseline procedures, children were administered the "Me-Not Me" interview to assess their self-perceptions of their own feelings, thoughts, and behaviors related to prosociality.

Baseline Vagal Tone: Electrodes attached to an ambulatory cardiac monitor (Minilogger 2000; Mini-Mitter Inc., 1999) were placed on the child's chest. Children's baseline IBI data were recorded while they were seated during three baseline procedures: listening to soothing music (1 min); watching a calming video (3 min); and sitting quietly (1 min). IBI data were edited for artifacts, and respiratory sinus arrhythmia (RSA) was computed for each baseline procedure using Porges' algorithm in Mxedit software (1985; 1988). The RSA frequency band-pass ranged from .24 to 1.04 Hz (Huffman et al., 1998) and sampling rate was set at 250 Hz. RSA was computed for the entire duration of each baseline procedure. These three RSA values showed high reliability across procedures (α = .95; all $r > .85$), and were averaged to form an index of children's overall baseline vagal tone. Due to not providing useable cardiac data or refusal to wear the electrodes, 26 children were missing vagal tone data. Children with and without vagal tone data were not different in terms of their age, family income, or self-reported prosociality (all *ts* < 0.33). More girls were missing vagal tone data than boys ($\chi^2(1) = 4.02$, $p = .045$).

Self-reported Empathy and Prosocial Behavior: Children reported on their own empathy and prosocial behavior using a structured interview task called the "Me-Not Me" interview (Miller et al., 2013). In this task, the experimenter placed a box with the child's name on it in front of the child. The experimenter read the sentences printed on each of two cards, and the child decided which sentence described him or her and put that card in their box. The wording of the sentences was the same except for endorsing or not endorsing the prosocial action or feeling expressed in the sentence (e.g. "I like" versus "I do not like"). Children completed practice trials (e.g. "I do not like to play" "I like to play") prior to the starting the interview task. The interview included 13 sentence pairs, adapted in part from the Index of Empathy for Children and Adolescents (Bryant, 1982), that described the presence versus absence of empathy, sympathy or prosocial behavior (e.g. "I get sad when I see a girl who can't find anyone to play with"[coded 1] "I do not get sad when I see a girl who can't find anyone to play with" [coded 0]; "I share my cookies and snacks if I see a child who doesn't have any" [coded 1] "I do not share my cookies and snacks if I see a child who doesn't have any" [coded 0]). The mean of children's scores across the 13 pairs was used as a measure of prosociality (possible range 0 – 1; α = .61). Hastings (2016) has reported that 4 to 8 year-old children's self-reported prosociality on the Me-Not Me interview is correlated with observations of their concerned and helpful responses to adults in accident simulation tasks, supporting the validity of this measure. Due to experimenter error, 12 children were missing data on this task, and these children were younger than children who completed the task (t = 3.62, $p < .001$). Children with and without Me-Not Me data were not different in terms of their sex ($\chi^2(1) = 2.01$), family income, or baseline vagal tone (both *t*s < 1.20).

Analyses—We used a path analysis approach in Amos version 23 to model the potential linear and quadratic effects of baseline vagal tone on children's self-reported empathic concern and prosocial behavior. Children's age and sex were included in the model as control variables. All predictors were allowed to covary with each other. Baseline RSA values were centered prior to creating the quadratic term to decrease multicollinearity and allow for interpretation of both linear and quadratic coefficients (Cohen, Cohen, West, & Aiken, 2003). Full information maximum likelihood estimation (FIML) was used to account for missing data and estimate all model parameters using the full sample. FIML is recommended when moderate to large amounts of data are missing (Widaman, 2006). One outlier value for RSA was winsorized prior to analyses (Wilcox, 2012).

Results

Descriptive statistics presented in Table 1. Older children [$t(166) = 4.70$, $p < .001$] and girls [$t(166) = 1.94$, $p = .054$] reported being more empathic and prosocial than younger children and boys. Zero-order correlations among the other variables were not statistically significant.

The path analysis model accounted for 17% of the variance in children's self-reported proneness to help and feel concern for others in need. The quadratic term accounted for 2% of this variance. After controlling for RSA, girls (B = .06, $\beta = .15$, $p = .042$) and older children (B = .06, $\beta = .32$, $p < .001$) still self-reprorted greater prosociality. The model estimates for intercept and linear and quadratic RSA terms are presented in Table 2. For vagal tone, the slope of the linear term was not significant (B = .01, $p = .450$) whereas the slope of the quadratic term was significant and negative (B = −.02, $p = .035$).[1] Thus, the association between baseline vagal tone and self-reported prosociality followed an inverted U-shape (see Figure 1). The estimated peak of the inverted U-shape curve was at the RSA value of 7.09. We used the Johnson-Neyman technique to test for regions of significance (Miller, Stromeyer, & Schwieterman, 2013). This technique allows for estimation of the RSA values at which the simple slopes of the quadratic cross the threshold of significance ($p < .05$). When RSA was less than 6.33, there was a significant positive association between RSA and self-reported prosociality. When RSA was greater than 9.44, there was a significant negative association between RSA and self-reported prosociality. The association between RSA and self-reported prosociality was not statistically significant for RSA values between 6.33 and 9.44.

To determine whether a linear RSA effect could be present in the absence of testing the quadratic effect, we tested an alternative model with the path from the quadratic RSA term predicting prosociality dropped out. However, the path from linear RSA remained statistically non-significant ($p = .252$).

Given that our sample was split into two age groups, we tested a third model to determine whether the quadratic RSA effect might be moderated by age. In this model, the main effect of quadratic RSA was still significant (B = −.02, $p = .035$), but the interaction between quadratic RSA and age was also significant (B = .04, $p = .039$). The quadratic RSA effect was present for younger (B = −.04, $p < .001$) but not older children (B = .02, $p = .281$). We also tested for sex differences for the linear and quadratic RSA effects, but these were not significant (ps >.21).

Study 2

Study 1 showed a significant quadratic relation between kindergarten-aged children's baseline vagal tone and their self-reported proneness to empathize with and help others.

[1]All findings were unchanged when including the outlier RSA value in the analyses (linear B = .01, $p = .564$; quadratic B = −.02, $p = .014$).

However, these findings are limited by the lack of a behavioral measure of prosociality. For this reason, we could not rule out the possibility that children with moderate vagal tone perceived themselves to be more prosocial but were not more likely to actually show compassionate or helpful behaviors when given the opportunity to help others. Therefore, in Study 2 we tested whether vagal tone quadratically predicted children's observed empathic concern and prosocial behavior in an accident simulation performed by an examiner, as well as their altruistic giving toward needy children in a donation task.

Method

Participants—This study included a low-risk community sample of 74 preschool-aged children (M = 4.09 years, SD = .12; 40 girls, 34 boys). As reported in a previous publication (Miller at al., 2015), most children were Caucasian (74%), and came from middle to upper-middle socioeconomic status families as indexed by their family income (M = $75,000 – $90,000; range from $15,000 – $30,000 to over $120,000). Mothers reported that all children had typical cognitive and physical development.

Procedure—Families visited the laboratory for testing. Upon arrival, children played with one examiner while another examiner obtained mother's informed consent. The first examiner informed children that they would be earning tokens over the course of the lab visit that they would be able to trade in for a prize at the end. By completing a variety of tasks, all children earned 20 tokens by the end of the visit. Approximately 15 minutes after consent, electrodes attached to an ambulatory cardiac monitor were placed on the child's chest and back to obtain electrocardiograph (ECG) and impedance cardiograph data. Children then sat quietly and watched a soothing video (2.5 min) to assess their baseline physiological activity. Approximately 60 min after the baseline procedure, children were exposed to a scripted accident simulation in which the examiner pretended to injure herself. Children's responses to these accident simulations were recorded for later coding of empathic concern and prosocial behavior. Approximately 20 min later, just before the end of the lab visit, children participated in another task in which they had an opportunity to donate their prize tokens to hospitalized children.

Baseline Vagal Tone—Three electrodes were attached to each child's chest to collect ECG signal, and an additional four electrodes were attached to each child's chest and back to collect impedance cardiograph signal. Data were wirelessly transmitted to a computer for later inspection and editing of artifacts using software from Mindware Technologies (Gahanna, Ohio). Spectral analysis of the ECG data was used to compute RSA in 30-s epochs. Young children have faster heart and respiration rates than adults, and this allows for the measurement of more IBIs and more variability in shorter windows of time. Thus, 15- to 30-s epochs are commonly used epoch lengths for computing RSA in developmental studies (Calkins, 1997; Hill-Soderlund et al., 2008; Huffman et al., 1998; Miller et al., 2013). The frequency band-pass parameters for computing RSA were set to range from .24 to 1.04 Hz (Huffman et al., 1998), and sampling rate was set at 500 Hz. The derivative of change in the impedance signal was used as a proximal measure of respiration (Ernst, Litvack, Lozano, Cacioppo, & Berntson, 1999). The average RSA of the 30-s epochs was used as a measure of baseline vagal tone. Due to not providing useable cardiac data or child refusal to wear the electrodes, four children were missing vagal tone data. Children with and without vagal tone data were not different in terms of their family income, observed empathic concern, or behavior in the donation task (all *ts* < 0.84). All four children missing vagal tone data were boys.

Accident Simulation—Children's empathic concern was observed in response to a 90-s accident simulation in which a female examiner feigned injury after dropping several small objects (Miller, Nuselovici, & Hastings, in press; Zahn-Waxler et al., 1995). Examiners followed a script for showing pain and distress during their accident simulation. Each child's overall empathic concern was coded on a 1 to 7 scale based on their observed prosocial behaviors and displays of sympathy (Hastings et al., 2000). A score of 1 reflected no evidence of concern (e.g. ignore, uninterested, angry). A score of 7 reflected strong displays of sympathy with very helpful acts and/or verbalizations of reassurance (e.g., approach, hug, say "You'll be okay," and stay in proximity). Full descriptions of each point on the coding scale can be reviewed in Hastings et al. (2000). Two people coded the data, and they were blind to children's RSA data. Drift inter-coder reliability was $\alpha = .89$. We observed the full range of scores in the data. The average observed empathic concern score was 4.41. The most common score was 4 (20 children), which reflected sustained attention with some expression of concern (facial [e.g., eyebrows raised and drawn together], vocalic [e.g., "Ooooh!" or "Are you okay?"], or physical [e.g., approach or touch] concern); or mild concern combined with a single act of assistance. Nine different female examiners performed the accident simulation. The quality of enactment of the accident simulation was coded on a 1 to 3 scale: a score of 1 reflected a simulation that was not very credible (e.g., victim broke character, laughed); a score of 2 reflected a simulation that appeared believable, passable, and probably would not strike a child as fake; and a score of 3 reflected a simulation that was particularly believable or authentic. The mean score for the quality of enactment during the accident simulations was 2.01. One child was missing empathic concern data due to experimenter error during the accident simulation.

Donation Task—Children's altruistic behavior was measured using a donation task (Grusec & Redler, 1980; Miller et al., 2015). Children earned 20 prize tokens over the course of their visit to the lab and were told that they could trade them in for a prize. At the end of the visit, before receiving their prize, children were presented with an opportunity to donate their tokens to sick children so that they could also get prizes. An examiner informed the children that she also worked at a hospital with sick children who could not come to the lab to earn prizes. The examiner explained to the child that if they wanted to, they could donate some, none, or all of their tokens by moving tokens from their own box to a separate box for the children in the hospital. To check that children understood the task, the examiner asked children to point to their own box and the box for the sick children. Children were then left alone in the room to decide and were given a bell to ring when they were done. Children's decisions to donate or not, and total tokens donated, were used as measures of altruism.

Analyses—We used two different path analysis models to test whether baseline vagal tone quadratically predicted prosociality. In both models, FIML was used to treat missing data and estimate model parameters using the full sample. Our first model was estimated in Amos version 23, and included sex, linear and quadratic terms for RSA, and interactions between sex and linear RSA and sex and quadratic RSA, as predictors of children's observed empathic concern in the accident simulation. All the predictors were allowed to covary with each other, and the RSA values were mean-centered prior to creating the quadratic term.

Our second model included the same predictors as our first model, but replaced observed empathic concern in the accident simulation with the number of tokens donated in the altruism task as the dependent variable. Zero-inflated negative binomial regression was used in MPlus version 6.11 to test for a potential quadratic relation between RSA and tokens donated. This approach can be used to model count dependent variables characterized by over-dispersion and the presence of excessive zeros (Atkins & Gallop, 2007). The model assumes that the processes underlying the prediction of zeros (i.e. give or not) could be different from the processes underlying the prediction of the number of observed counts (i.e. number of tokens donated). Thus, the model has two components – one that is logistic (zero versus not zero) and one that is negative binomial (number of counts). The beta coefficients for the logistic component are log-odds ratios that represent the probability of not giving or giving as a function of the predictor variables. The beta coefficients for the negative binomial component represent the difference in the log of expected tokens given as a function of the predictor variables. Sex, linear RSA, and quadratic RSA were used as the predictors of both model components.

Results

Descriptive statistics for study 2 are presented in Table 1. We also tested zero-order correlations among the variables. Girls tended to donate more tokens than boys (r =.22, p = .064). None of the other correlations reached or approached statistical significance. Just over half of the children chose to donate at least one token (54%; 40 donated versus 34 did not).

Does RSA quadratically predict observed empathic concern?—Our final model of sex, linear RSA, and quadratic RSA accounted for 6.1% of the variance in children's observed empathic concern in response to the accident simulation. The quadratic term accounted for the majority of this variance (5.9%). Girls and boys did not differ in their observed empathic concern (p = .92). The model estimates for the intercept and linear and quadratic RSA terms are presented in Table 2. Consistent with study 1, there was a significant negative quadratic association between children's baseline RSA and their empathic concern (B = −.14, p = .040). Thus, the association between baseline RSA and empathic concern followed an inverted U-shaped curve (see Figure 2). The paths from quality of enactment of the accident simulation, and the interaction terms between sex and linear RSA and sex and quadratic RSA predicting observed empathic concern, were not significant (all p > .135). We removed these paths from the final model. The estimated peak of the inverted U-shape curve was at the RSA value of 5.94. Based on the Neyman-Johnson technique for calculating regions of significance (p < .05), there was a significant positive association between RSA and observed empathic concnern when RSA was less than 4.95, and a significant negative association when RSA was greater than 7.03. The association between RSA and observed empathic concern was not statistically significant for RSA values between 4.95 and 7.03.

To test whether a linear RSA effect might be obscured by the presence of the quadratic RSA term, we tested a second model in which we dropped the path from the quadratic RSA term predicting observed empathic concern. However, the effect of linear RSA on observed empathic concern remained statistically non-significant (p = .816).

Does RSA quadratically predict altruistic giving?—Our zero-inflated negative binomial regression model used the number of tokens given away in the donation task, and giving versus not giving, as the dependent variables. The alpha coefficient representing dispersion in the data was significantly different from zero (α = .24, p = .004). This suggests that the data from the donation task were indeed over-dispersed, and that we were justified in using the zero-inflated negative binomial approach. The parameter estimates for the final model are presented in Table 3. As seen in the prior models, there was a significant negative quadratic association between baseline RSA and the number of tokens donated by children (B = −.10, p = .048) (See Figure 3). We were not able to use the Johnson-Neyman technique to compute the regions of significance because this requires satisfaction of the typical assumptions of linear models. The linear and quadratic terms of RSA did not predict the likelihood to give or not (B = .18, p = .411 and B = −.11, p = .303, respectively), but girls were more likely to give than boys (B = −1.53, p = .003).

The paths from the interaction between sex and quadratic RSA predicting number of tokens donated and giving versus not giving were not significant (both p > .425). The interaction between sex and linear RSA did not significantly predict giving versus not giving (p = .098), but did predict number of tokens given (B = −.41, p = .036). However, further probing of this interaction showed that the linear effect was not present for either boys (B = .15, p = .344) or girls (B = −.18, p =.098). This suggests that the linear effect of RSA on tokens donated was significantly different for boys versus girls, but neither effect was significantly different from zero. Thus, we removed these interaction terms from the final model.

In an alternative model, we dropped the paths from the quadratic RSA term to determine whether linear RSA might emerge as a significant predictor of children's decisions to donate or not (logistic component) or how many tokens to donate (negative binomial component). The effect of linear RSA on both model components continued to be statistically non-significant (both p > .344).

Study 3

In studies 1 and 2, we found that baseline vagal tone was quadratically related to concurrent self-reported and observed prosociality in early childhood. Does moderate vagal tone in early childhood also predict future prosociality? In Study 3, we tested whether early vagal tone prospectively predicted children's self-, mother-, and teacher-reported prosociality 5.5 years later in accordance with the quadratic hypothesis.

Method

Participants

Time 1: As described in previous publications (Hastings, McShane, Parker, & Ladha, 2007; Hastings, Kahle, & Nuselovici, 2014; Hastings et al., 2008b), this study included 133 children (61 boys and 72 girls). Children were 2.0 – 4.9 years of age at T1 (Mean age = 3.50 years, SD = 0.75 years). Families were predominantly Caucasian (74%) and in the middle- to upper-middle socioeconomic range (M = $80,229 Canadian, SD = $47,777). Families were recruited using targeted advertisements and screening in order to oversample for children with internalizing problems. Parents reported that all children lacked cognitive or physicals delays in development.

Time 2: There was a follow-up assessment 5.5 years later that included questionnaires completed by children (n = 101), their mothers (n = 97), and their teachers (n = 77). Children were 7.50 – 11.67 years of age at T2 (Mean age = 9.07 years, SD = 0.81 years) and included 58 girls and 43 boys. Children who provided data at T2 (child-report, mother-report, and teacher-report) were not significantly different from children who dropped out of the study in terms of sex, race or ethnicity (all $\chi^2(1) < 1.87$), age at T1, family income, RSA at T1, or early teacher-reported prosociality (all *ts* < 1.74).

Procedure—Children were tested in their homes at both time points. At T1, electrodes were attached to children to measure their cardiac activity while watching a calming video with their parents or while having their parents read a children's book. Children's RSA was computed from these data. At T2, children self-reported on their prosociality, and mothers and teachers reported on children's prosociality at home and at school, respectively, by completing reporter-specific versions of the Social Skills Rating System (SSRS; Gresham & Elliott, 1990).[2]

Baseline Vagal Tone at T1: In order to keep children seated and stationary during a baseline period, children either watched a calming video with their parents ($n = 41$) or had their parents read them a children's book ($n = 87$). Parents chose the activity that they thought would be most effective for keeping their children still. Examiners provided the video and book. IBI data collected during the baseline procedure were inspected and edited for artifacts and outliers. RSA was computed using Porges' algorithm in Mxedit software (Porges, 1985). Sampling rate was set at 250 Hz and the high frequency band for computing RSA was set to range from .24 – 1.04 Hz (Huffman et al., 1998). RSA was computed in 20 s epochs (Calkins, 1997; Hill-Soderlund et al., 2008; Huffman et al., 1998; Miller et al., 2013). The average RSA across all epochs was used as a measure of children's vagal tone. Vagal tone did not differ between children depending on whether the video or book was used ($t < 1.0$). Children exposed to the video or book procedure also did not differ on measures of prosociality (all $t < 1.94$). RSA data could not be computed for 9 children due to not

[2]The standard scoring of the SSRS includes subscales for cooperative behavior (all 3) and empathy (child only). However, the items assigned to these scales do not all share construct validity with prosociality as it is usually defined; in particular, several items reflect compliance (e.g., "uses free time at home in an acceptable way", "easily makes transitions from one classroom to another"). Therefore, we selected those items that most closely adhered to our construct definition of prosociality. It is important to note, though, that quadratic effects were significant with the standard scoring of the SSRS scales.

providing useable cardiac data or refusal to wear the electrodes. Children with and without vagal tone data were not different in terms of their sex ($\chi^2(1) = 0.01$), T1 age, family income, early teacher-reported prosociality, or T2 child-, mother-, and teacher-reported prosociality (all *ts* < 1.51). Children who were missing vagal tone data were younger at T2 compared to children who had vagal tone data ($t = 2.60$, $p = .011$).

Early Teacher-Reported Prosociality at Preschool: One year after the initial assessment, teachers reported on children's prosocial behaviors with peers using the Social Competence and Behavior Evaluation: Preschool Edition (SCBE; La Freniere & Dumas, 1995). Ten items were averaged (1, 3, 35, 39, 45, 50, 52, 53, 60, 63) to form an index of children's cooperation with others, helpfulness, sympathy, comforting, and perspective taking (e.g., "Sensitive to another's problems," "comforts or assists another child in difficulty"), $\alpha = .83$. Teachers rated items on a 6-point scale ranging from 1 (never) to 6 (always). Due to some teachers not completing or returning the questionnaire measures, SCBE data were missing for 43 children. Children with and without SCBE data were not different in terms of sex ($\chi^2(1) = 2.53$), T1 or T2 age, family income, T1 baseline vagal tone, or T2 child-, mother-, and teacher-reported prosociality (all *t*s < 1.74).

Child-Reported Prosociality at T2: Children reported on their own prosociality at T2 using the SSRS. Ten items were averaged (2, 3, 5, 14, 15, 17, 20, 24, 26, 29) to form an index of children's self-reported empathy and prosocial behavior toward friends and adults (e.g., "I try to understand how my friends feel when they are angry, sad, or upset", "I listen to my friends when they talk about problems they are having"), $\alpha = .89$. Children rated items on a scale ranging from 0 (*never*) to 2 (*very often*).

Mother-Reported Prosociality at T2: Mothers' reports of their children's prosociality within the family were obtained from averaging eight items (11, 15, 16, 19, 27, 29, 34, 36) from the SSRS (e.g., "volunteers to help family members with tasks", "congratulates family members on accomplishments"), $\alpha = .73$. Mothers rated items on a scale ranging from 0 (*never*) to 2 (*very often*).

Teacher-Reported Prosociality at T2: Teachers' reports of children's prosociality at school were obtained from averaging nine items (7, 19, 20, 21, 22, 23, 24, 28, 30) from the SSRS (e.g., "gives compliments to peers", "volunteers to help peers with classroom tasks"), $\alpha = .84$. Teachers rated items on a scale ranging from 0 (*never*) to 2 (*very often*).

Analyses—We used path analysis in Amos version 23 to model the hypothesized relations between children's vagal tone and future prosociality. We tested three separate models using child-reported, mother-reported, or teacher-reported prosociality as the dependent variable of interest. The predictor variables for all models were children's age at T1 and T2, sex, linear and quadratic terms for RSA at T1, and interactions between sex and linear RSA and sex and quadratic RSA. All predictor variables were allowed to covary with each other in all models. FIML was used to treat missing data and estimate model parameters using the full sample.

Results

Descriptive statistics for study 3 are presented in Table 1. We tested for zero-order correlations among the variables. Older children at T1 had higher baseline RSA ($r = .25$, $p = .006$) and were rated as more prosocial by teachers at T2 ($r = .31$, $p = .001$). Children who were rated as more prosocial by teachers at preschool-age were also rated as more prosocial by teachers at T2 ($r = .35$, $p = .009$). Children, mother, and teacher-reported prosociality at T2 were not correlated with each other, RSA, T1 prosocial measures, age, or sex.

Does baseline RSA in early childhood quadratically predict child-reported prosociality 5.5 years later?—Our path analysis model of sex, T1 age, T2 age, T1 linear RSA, and T1 quadratic RSA accounted for 12% of the variance in T2 child-reported prosociality toward peers and adults. The quadratic term accounted for 9% of this variance. Sex and age did not significantly predict child-reported prosociality (all $p > .70$). The model estimates for the intercept and linear and quadratic RSA terms are presented in Table 2. We found a negative quadratic association between children's T1 RSA and their reported prosociality ($B = -.03$, $p = .003$) (See Figure 4). Children with moderate baseline RSA in early childhood reported being more empathic and prosocial 5.5 years later than preschoolers with low or high baseline RSA. The estimated peak of the inverted U-shape curve was at the RSA value of 4.87. Based on the Neyman-Johnson technique for calculating regions of significance ($p < .05$), there was a significant positive association between T1 RSA and T2 child-reported prosociality when RSA was less than 3.63, and a significant negative association when T1 RSA was greater than 5.58. The association between T1 RSA and T2 child-reported prosociality was not statistically significant for RSA values between 3.63 and 5.58.

The paths from the interaction terms between sex and T1 linear RSA and sex and T1 quadratic RSA predicting T2 child-reported prosociality were not significant (both $p > .467$). These interaction terms were removed from the final model.

Does baseline RSA in early childhood quadratically predict mother-reported prosociality in the family context 5.5 years later?—Our path analysis model of sex, T1 age, T2 age, T1 linear RSA, T1 quadratic RSA, and the interactions between sex and T1 linear RSA and sex and T1 quadratic RSA accounted for 30% of the variance in mother-reported prosociality in the home at T2. The quadratic term accounted for 25% of this variance. Sex and age did not significantly predict child-reported prosociality (all $p > .28$). The model estimates for the intercept and linear and quadratic RSA terms are presented in Table 2. We found a negative quadratic association between children's baseline RSA at T1 and their mother-reported prosociality at T2 ($B = -.06$, $p < .001$) (See Figure 5). Children with moderate baseline RSA in early childhood were reported by their mothers to be more prosocial within the family environment 5.5 years later than preschoolers with low or high baseline RSA. The estimated peak of the inverted U-shape curve was at the RSA value of 5.06. Based on the Neyman-Johnson technique for calculating regions of significance ($p < .05$), there was a significant positive association between T1 RSA and T2 child-reported prosociality when RSA was less than 4.50, and a significant negative association when T1

RSA was greater than 5.52. The association between T1 RSA and T2 child-reported prosociality was not statistically significant for RSA values between 4.50 and 5.52.

The path from the interaction between sex and T1 quadratic RSA was not significant in predicting future mother-reported prosociality (B = .04, $p = .119$). Conversely, the path from the interaction between sex and T1 linear RSA was significant in predicting future mother-reported prosociality (B = −.11, $p = .026$). T1 linear RSA negatively predicted future mother-reported prosociality for girls (B = −.07, $p = .045$), but not for boys (B = .04, $p = .249$). Both interaction terms were retained in the final model.

Does baseline RSA in early childhood quadratically predict teacher-reported prosociality in the school context 5.5 years later?—Our path analysis model of sex, T1 age, T2 age, T1 linear RSA, and T1 quadratic RSA accounted for 13% of the variance in teacher-reported prosociality in school at T2. The quadratic term accounted for 6% of this variance. Child age at T1 negatively predicted T2 teacher-reported prosoociality (B = −.15, $\alpha = -.30$, $p = .039$). Sex and T2 age did not significantly predict child-reported prosociality (all $p > .10$). The model estimates for the intercept and linear and quadratic RSA terms are presented in Table 7. Children's baseline RSA at T1 quadratically marginally predicted T2 teacher-reported prosociality at school (B = −.03, $p = .069$). Thus, children with moderate baseline RSA in early childhood tended to be reported by their teachers to be more prosocial in the school environment 5.5 years later than preschoolers with low or high baseline RSA (see Figure 6). The estimated peak of the inverted U-shape curve was at the RSA value of 4.82. Based on the Neyman-Johnson technique for calculating regions of significance ($p < .05$), there was a significant negative association between T1 RSA and T2 teacher-reported prosociality when RSA was greater than 6.40. The association between T1 RSA and T2 child-reported prosociality was not statistically significant for RSA values less than 6.40.

The paths from the interaction terms between sex and T1 linear RSA and sex and T1 quadratic RSA predicting T2 teacher-reported prosociality were not significant (both $p > .137$). We removed these terms from the final model.

Was there evidence for linear RSA effects on future prosociality?—To determine whether the presence of linear RSA effects might be obscured by the quadratic RSA terms, we tried excluding the paths from the quadratic RSA terms in all three models. The linear RSA terms continued to be non-significant predictors across all three models (all $p > .282$).

Was there evidence for quadratic RSA effects on future prosociality over and above early prosociality?—To determine whether the quadratic RSA effects were present after partially controlling for early prosociality, we tried including teacher-reported prosociality at preschool-age as an additional variable that was dependent on sex, T1 age, T1 linear RSA, and T1 quadratic RSA, and as a predictor of T2 prosociality (T2 child-, mother-, and teacher-reported prosociality) in three separate models. The quadratic RSA term still predicted T2 teacher-reported prosociality (B = −.04, $p = .020$) after controlling for earlier teacher-reported prosociality (B = .18, $p < .001$). The quadratic RSA terms also continued to predict T2 child- and mother-reported prosociality (B = −.03, $p = .004$ and B = −.07, $p < .001$, respectively) after controlling for early prosociality, which did not significantly predict

T2 child- or mother-reported prosociality (both $p > .78$). RSA was not linearly or quadratically associated with early prosociality (all $p > .50$).

General Discussion

Baseline vagal tone is often viewed as a physiological correlate of healthy functioning because it has been related to better adjustment and regulation of emotion and arousal (Beauchaine, 2001, 2015; Thayer & Lane, 2000). Emotion regulation can contribute to prosociality (Eisenberg, 2000; Eisenberg & Eggum, 2009; Goetz et al., 2010). According to these perspectives, several researchers have proposed that baseline vagal tone should be positively associated with prosocial development, but the evidence for this has been mixed (Hastings & Miller, 2014). It has previously been suggested that higher vagal tone might interfere with other-oriented engagement with the needs of others (Hastings et al., 2000, 2006), and recent work with adults identified curvilinear associations between baseline vagal tone and multiple measures of prosociality (Kogan et al., 2014). Moderate baseline vagal tone may represent an optimal level of parasympathetic functioning for supporting prosocial tendencies in children as well as adults. Across six different measures of prosociality in three different samples of children, we found consistent evidence for a quadratic association between vagal tone and the tendency to comfort, share, and help others. Young children with moderate rather than low or high baseline vagal tone reported being more empathic and prosocial (Study 1), were observed to show more empathic concern toward an injured adult (Study 2), shared more of their earned resources to help sick children (Study 2), and viewed themselves, and were viewed by others, as being more prosocial 5.5 years later (Study 3). Thus, the quadratic relation between baseline vagal tone and prosociality is present at multiple points in development, including as early as 4 years.

Our findings add to a growing literature that emphasizes the importance of testing for quadratic relations between parasympathetic regulation and psychological functioning (Kogan et al., 2013, 2014; Marcovitch et al., 2010; Spangler, Bell, & Deater-Deckard, 2015). For example, Marcovitch and colleagues (2010) found that moderate vagal withdrawal (i.e., RSA suppression) during an executive functioning task was related to better task performance compared to low or high RSA suppression. Their interpretation of their finding was that children who showed too little RSA suppression perhaps did not sufficiently orient attention to the task and that this negatively impacted their performance. Conversely, children who showed too much RSA suppression potentially experienced too much physiological arousal that interfered with their ability to focus on performing the task. One interpretation of our findings uses a line of reasoning that is similar to that of Marcovitch and colleagues (2010), but applied to baseline vagal tone rather than vagal reactivity. Consistent with polyvagal theory and the neurovisceral integration model (Porges, 2007; Thayer & Lane, 2000) low baseline vagal tone is often viewed as reflecting less healthy autonomic functioning and increased arousal that underlie a tendency towards hypervigilance of stressors and risk for maladjustment. Being primed to experience physiological over-arousal in response to environmental stressors, including the distress of others, may undermine children's ability to effectively attend to the needs of others, and this may explain why children with lower baseline vagal tone were less prosocial compared to children with moderate baseline vagal tone. In contrast, high baseline vagal tone is often viewed as reflecting better autonomic functioning that supports one's ability to maintain homeostasis and is related to better attentional control and emotion regulation. Perhaps the distress of others may not be evocative enough to elicit arousal and other-oriented focus in children with very high baseline vagal tone. These children may also use attentional control to inhibit experiencing arousal and negative affect in response to the distress of others. Appraising the needs of others as salient and experiencing some degree of arousal in response to those needs are important, basic aspects of empathy and prosocial responding (de Waal, 2008; Miller et al., in press), and these might be hindered in children with particularly high baseline vagal tone. Conversely, moderate baseline vagal tone may reflect an optimal balance of physiological arousal (e.g., vigilance at rest) and regulation that primes children for prosocial responding. This preparedness may reflect children's tendency to notice and respond to the needs of others, but not become personally distressed and overwhelmed by them. It will be important for future research to test measures of attention and emotion regulation as possible mediators of the relation between different levels of vagal tone and prosociality. However, given that baseline vagal tone has been linked to a variety of psychological and behavioral constructs, we believe there are likely multiple processes that could explain the quadratic association.

In Study 1 and Study 3 we found quadratic relations between vagal tone and child-reported prosociality, both concurrently and over time. In Study 2, we replicated and extended these findings using behavioral measures of empathic concern and altruistic giving. Our studies provide the first evidence for the quadratic vagal tone-prosociality hypothesis using observed behavioral measures of helping, and the first evidence that this relation appears to be stable over development. The longitudinal findings from Study 3 suggest that early vagal tone is associated with the expression of prosociality across contexts (home and school based on mother- and teacher-report, respectively). Moderate resting vagal tone may relate to the ability to successfully practice noticing and responding to the needs of others when prosocial opportunities arise. This may set children on a path toward expressing more prosocial behaviors in the future, but greater support for this interpretation requires longitudinal research that uses repeated measures of baseline vagal tone and prosociality over time. We attempted to control for earlier prosociality, but observed stability across time only within teacher-reported measures, potentially due to reporter differences or the use of different measures of prosociality at preschool and T2. Thus, whether the longitudinal quadratic link between vagal tone and prosociality is independent of the stability of prosocial behavior is still unclear.

There is some debate as to whether the links between parasympathetic functioning and social-emotional adjustment change or are constant over development (Beauchaine et al., 2007; Graziano & Derefinko, 2013). The overwhelming majority of studies in the literature, however, have not reported testing for quadratic associations. Our findings in conjunction with recent work by Kogan and colleagues (2014) suggest that there could be continuity across childhood and into adulthood in the quadratic associations between baseline vagal tone and prosociality. Moderate levels of baseline vagal tone may reflect ideal regulatory capacities for supporting prosocial tendencies in children and adults, but early moderate vagal tone may also contribute to the development of greater prosociality in the future.

Investigating the environmental and biological processes that might lead to early moderate baseline vagal tone is an interesting avenue for future research.

Moderate vagal tone seems to represent a tendency for general prosociality, across forms and situations. We measured prosociality using multiple methods. Interestingly, the quadratic pattern of findings was present for both helping tasks in Study 2, even though they measured prosociality in very different ways: expressing concern, comforting and helping an adult in pain; and donating earned prize tokens to sick children. The quadratic pattern of findings was also present across reporters in Study 3, even though they reported on prosociality in different contexts and to different targets (peers and adults in the home and school environments). Different kinds of prosocial behaviors may have different underlying mechanisms and motivations (Fortuna & Knafo, 2014; Paulus, 2014), but they might also share a core feature of requiring that the prosocial actor be affected to some degree, but not become overwhelmed, by the needs of others. The multiple quadratic relations observed in these studies suggest that moderate vagal tone may support children's general propensity for different forms of kindness across different contexts, consistent with the proposal that there may be a "prosocial disposition" (Knafo-Noam, Uzefovsky, Israel, Davidov, & Zahn-Waxler, 2015).

What are the specific values of RSA that reflect moderate vagal tone? By testing for regions of significance, we were able to calculate the specific baseline vagal tone values that marked where the positive and negative associations with prosociality transitioned from statistically significant to nonsignificant. For example, the relation between vagal tone and observed empathic concern in Study 2 was positive and significant for baseline vagal tone values less than 4.95. Conversely, when vagal tone was greater than 7.03, the relation with empathic concern was negative and significant. The interval of data between the regions of significance, where the association between vagal tone and prosociality was nonsignificant, indicates the range of vagal tone values that reflect moderate vagal tone. Thus, for the sample and measure of prosociality in Study 2, when baseline vagal tone ranged from 4.95 to 7.03, children demonstrated the most empathic concern, and increases and decreases in vagal tone were not expected to have a significant effect on empathic concern. We believe this is a powerful approach for identifying specific ranges of vagal tone that underlie adjustment and problems.

Although we found a similar pattern of quadratic associations across our studies, there were some notable differences across samples in the threshold values for marking the regions of significance. In Study 1, baseline vagal tone values had to be particularly high (greater than 9.44) for the concurrent association with self-reported prosociality to be negative and significant. Conversely, in Study 3, T1 baseline vagal tone values had to be particularly low (less than 3.63) for the association with T2 child-reported prosociality to be positive and significant. In addition to sample differences in the regions of significance, the baseline vagal tone values that represented the estimated peaks of the inverted U-shape curves, where vagal tone maximizes prosociality, varied across samples. Comparing the curves across samples, the Study 1 quadratic curve was estimated to have the highest baseline vagal tone value for maximizing prosociality (7.09), whereas the quadratic curve for teacher-reported prosociality in Study 3 was estimated to have the lowest vagal tone value for maximing prosociality (4.82). Some of these differences across studies could potentially be due to differences in the types of samples (at-risk versus community). For example, Study 1 used targeted recruitment and screening to oversample for children with externalizing problems, and children from at-risk samples have been shown to have lower levels of baseline vagal tone and less vagal suppression in response to challenge (Graziano & Derefinko, 2013). In Study 1, the wider interval of data between the regions of significance (baseline vagal tone values between 6.33 and 9.44) might suggest that for children with increased externalizing problems there is a higher upper limit for what could be considered ideal baseline vagal tone for supporting prosociality. Externalizing problems are often negatively associated with measures of prosociality (Hastings et al., 2000). Thus, children with externalizing problems may require greater physiological regulatory capacity to maintain and maximize other-oriented focus in order to help others. The degree to which vagal tone is related to threshold for arousal may also be different for children with externalizing problems compared to more typically-developing children. However, there are a number of other plausible explanations for some of the observed differences across samples, including differences in sample age, the measures of prosociality used, and the methods of RSA computation. Further research is necessary to systematically untangle how the nature of quadratic relations between parasympathetic regulation and prosociality might vary as a function of sample type or age.

Previous inconsistencies regarding whether the linear relation between vagal tone and prosocial development is positive, negative, or not present, may be in part due to the portion of the distribution of vagal tone sampled in each study (Kogan et al., 2013, 2014). Samples of vagal tone in the low range would be expected to produce a positive linear relation with prosociality, whereas samples in the high range would be expected to find a negative association. Conversely, samples containing the full range of vagal tone would fail to find a significant linear effect. It is worth noting that we did not find much evidence for linear effects of RSA on children’s prosociality. This mirrors most of the developmental literature, in which the majority of tested linear relations between RSA and prosociality have been statistically non-significant (Hastings & Miller, 2014).

In our analyses, the lone evidence for a linear effect was in a sex by linear RSA interaction prospectively predicting mother-reported prosociality 5.5 years later (Study 3). Mothers described their school-age daughters as less prosocial when the girls had higher baseline vagal tone as preschoolers. This is in line with a previous study finding that vagal tone negatively predicted peer reported prosocial behavior for girls (Eisenberg et al., 1996a). Eisenberg and colleagues speculated that girls with higher vagal tone might be more uninhibited and assertive, and that this might negatively affect others’ perceptions of their prosocial behavior due to gender stereotypes about appropriate behavior for girls (1996a). This remains a possible explanation for our finding. However, the overwhelming majority of relations tested across our studies consistently pointed to the presence of a quadratic rather than linear association between vagal tone and prosocial development.

Similarly, there was only one indication of possible age differences in the quadratic association between baseline vagal tone and prosociality, as the concurrent relation was present for younger but not older children in Study 1. Older children endorsed more items reflecting prosociality in the “Me-Not Me” interview which, although developmentally appropriate, may have conferred different properties to the measure for preschoolers versus school-age children. It is possible that the measure was more susceptible to social desirability bias in our group of older children, or that the simple forced-choice procedure was more appropriate for eliciting self-report responses from the younger children. Further research is necessary to replicate and potentially clarify the meaning of this interaction effect.

It should be noted that in addition to baseline vagal tone, another important way to study parasympathetic functioning is via vagal reactivity during emotionally evocative tasks. This can be measured using change scores between mean RSA at rest and mean RSA during a task (vagal suppression and vagal augmentation) (Calkins, 1997; Graziano & Derefinko, 2013; Scrimgeour, Davis, & Buss, 2016). Vagal suppression typically supports adaptive orienting and coping in response to potentially challenging, threatening or difficult events (Porges, 2007, 2011). In accordance with the perspective that high baseline vagal tone reflects greater capacity for regulation of arousal and emotion, higher baseline vagal tone has been related to a greater capacity to show vagal suppression (Graziano & Derefinko, 2013; Marcovitch et al., 2010). Based on this perspective, and assuming that the link between baseline vagal tone and vagal suppression is linear, one might expect that moderate vagal suppression in response to the suffering of others could mediate the link between moderate vagal tone and increased prosociality. However, higher baseline vagal tone has not always been associated with more vagal suppression (Calkins, 1997; Muhtadie, Koslov, Akinola, & Mendes, 2015), and it is unclear whether vagal suppression is appropriate or healthy in contexts that call for calm, prosocial engagement (Hastings et al., 2008a; Miller & Hastings, 2016; Miller et al., 2015). Adding further complexity, a number of recent studies have moved towards using longitudinal data methods to model physiological change as a dynamic process that unfolds over the course of an event (Brooker & Buss, 2010; Kahle, Miller, Lopez, & Hastings, 2016; Miller et al., 2013, 2015). For example, Miller and colleagues (2016) used a latent growth curve approach to model children’s dynamic, nonlinear RSA change in response to an empathy induction. Greater vagal flexibility in the form of showing both vagal suppression and vagal augmentation/recovery, but at specific points in time during an empathic event, was associated with increased subjective empathic feelings and the development of prosocial behavior (Miller et al., in press). This is a marked departure from traditional techniques for computing vagal suppression and augmentation as reactivity scores, and it is unclear whether baseline vagal tone is related to these kinds of dynamic measures of RSA. In addition, whether there is such a thing as too much or too little vagal augmentation, suppression, or flexibility in response to situations that may evoke empathic and prosocial responses is an open question.

The present study had a number of additional limitations that should be considered. The samples in our studies were limited in terms of racial/ethnic and socioeconomic diversity, potentially limiting the generalizability of the findings. Respiration data were only collected and controlled for in the computation of RSA in Study 2, although there is some debate as to whether controlling for respiration is necessary in studies of cardiac vagal tone (Denver, Reed, & Porges, 2007; Ritz, 2009). Other aspects of RSA computation also varied across the three studies, including the statistical metric of RSA (Porges method for Studies 1 and 3 versus spectral analysis of high frequency heart rate variability for Study 2), the software used (Mxedit for Studies 1 and 3 versus MindWare Technologies for Study 2), and epoch length for computing RSA (60 and 180-s for Study 1, 30-s for Study 2, and 20-s for Study 3). Conversely, these differences may reflect a strength of the research, as the quadratic effect was robust across these procedural variations. Our data do not speak to whether moderate baseline vagal tone predicts other positive aspects of children's development besides prosociality. However, this seems plausible given that researchers have found quadratic relations between vagal tone and adult well-being (Kogan, Gruber, Shallcross, Ford, & Mauss, 2013) and vagal tone has been linked to a variety of child outcomes. The measures in our study confounded emotional and behavioral aspects of prosociality, like empathy and prosocial behavior. However, it is also important to recognize that these aspects often appear as a global construct (Hastings et al., 2000; Knafo-Noam et al., 2015), and there is theoretical and empirical value in studying and understanding patterns of prosociality that include both emotions and actions (Padilla-Walker & Carlo, 2014). Lastly, we focused exclusively on baseline parasympathetic functioning as measured during brief, resting procedures, but prosociality is a complex construct that is rooted in multiple neurobiological processes. This is one likely reason for the modest effect size of the observed quadratic relations. We do not contend that prosociality is specific to baseline vagal tone, or that baseline vagal tone is the only neurobiological measure that is functionally linked to prosociality.

Conclusions

This study contributes to a growing body of research on the neurobiological bases of kindness and compassion. Looking beyond simple linear associations might be one helpful method for making sense of the complex relations between neurobiology and prosociality. Although research focusing on vagal tone and prosocial development has produced conflicting findings, the present investigation found consistent evidence for the quadratic vagal tone hypothesis across multiple measures of prosociality in three different samples of children. The collective findings across our three studies suggest that children's moderate vagal tone predicts greater proneness to prosociality in general. Comforting others who are in pain, sharing with others who are less fortunate, and getting along with family members, peers, and teachers, may share a core requirement – to be moved or affected, but not overwhelmed, by the needs of others. To the extent that vagal tone is associated with general capacity for emotion regulation and threshold for arousal based on perception of environmental safety, our findings suggest early moderate vagal tone may reflect an optimal balance of regulation and arousal that helps prepare children to sympathize, comfort, and share with others.

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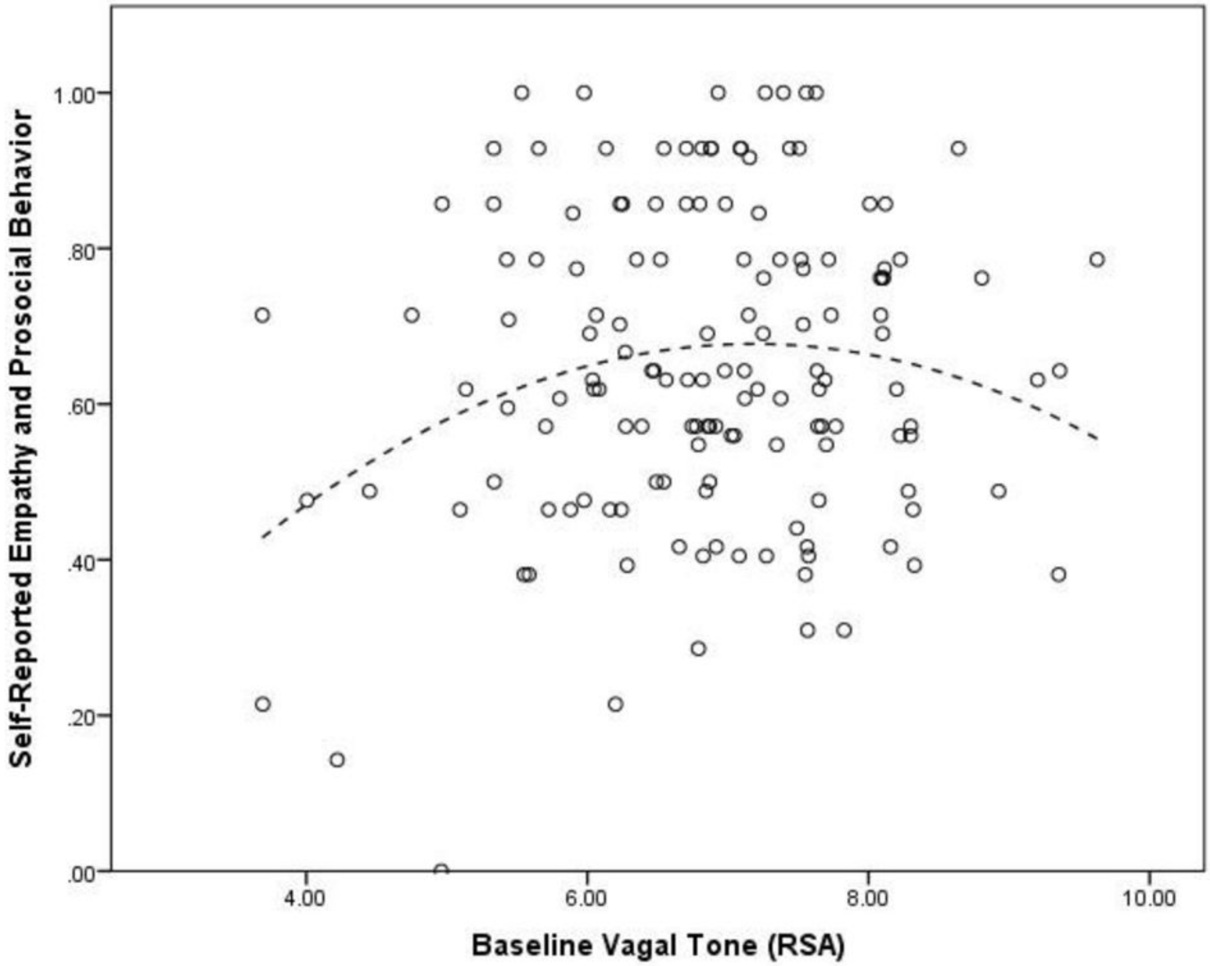

Figure 1.
Quadratic line fit to data to represent relation between baseline RSA and children's self-reported prosociality in Study 1.

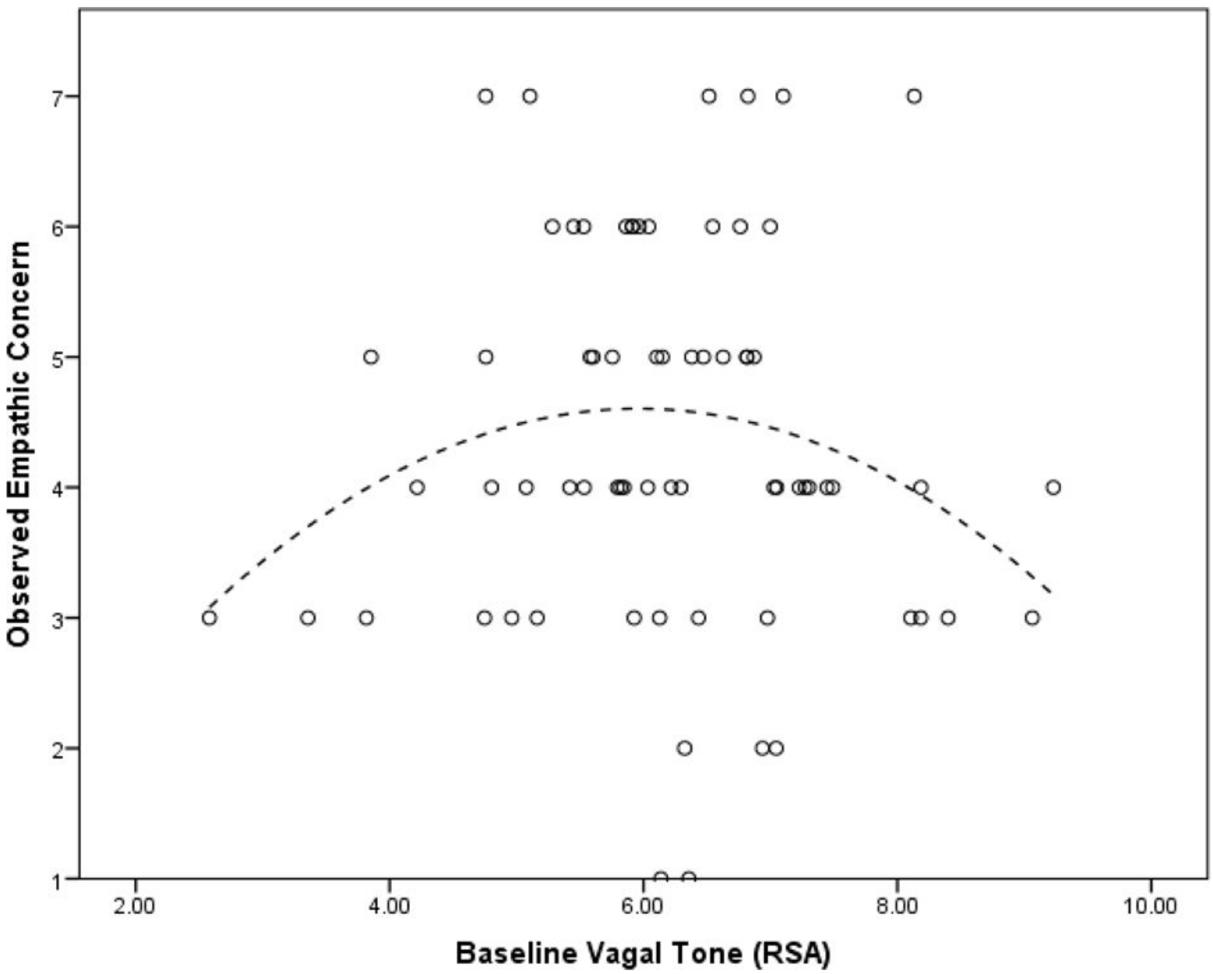

Figure 2.

Quadratic line fit to data to represent relation between baseline RSA and children's observed empathic concern in Study 2.

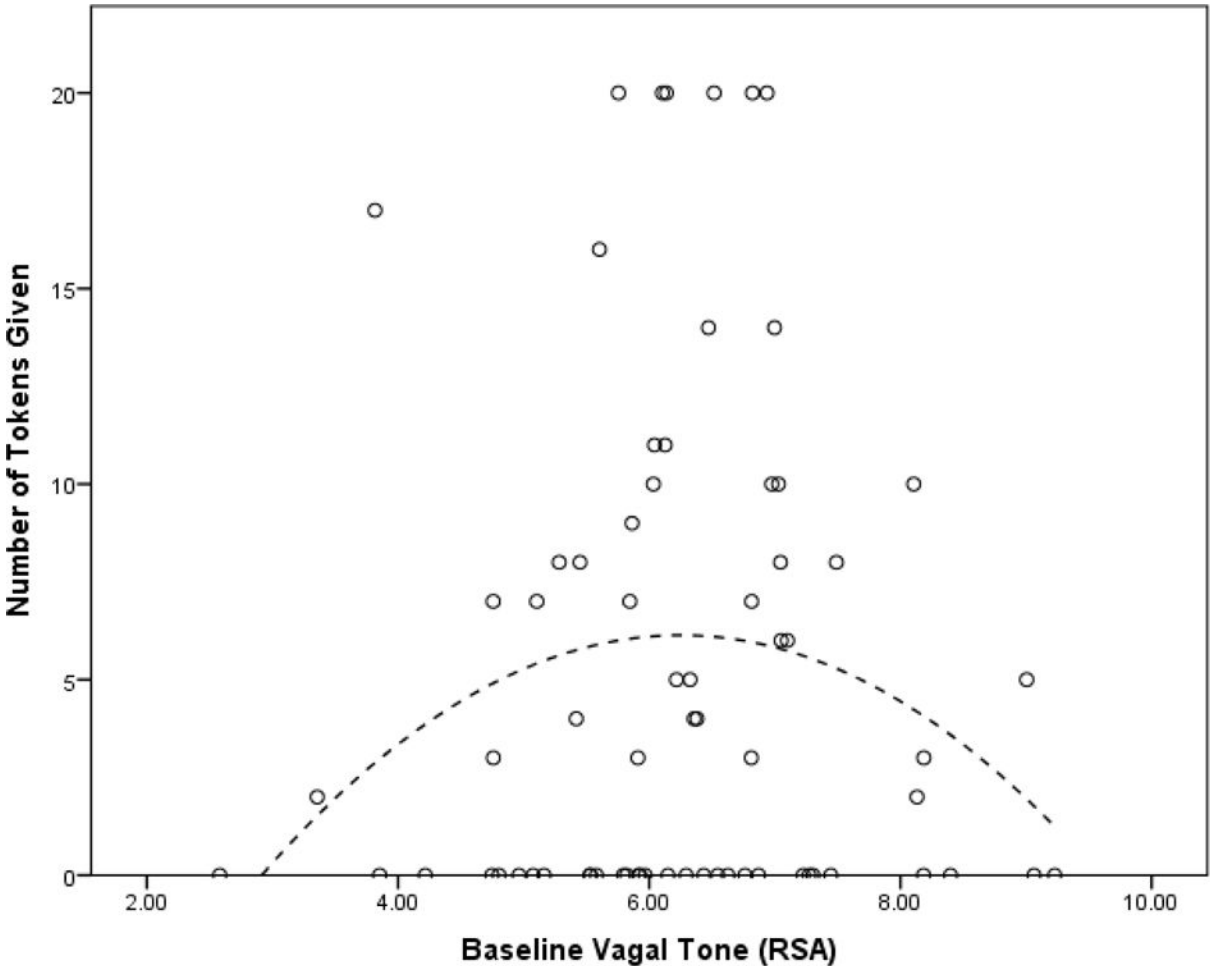

Figure 3.

Quadratic line fit to data to represent relation between baseline RSA and the number of tokens children donated to sick children in Study 2.

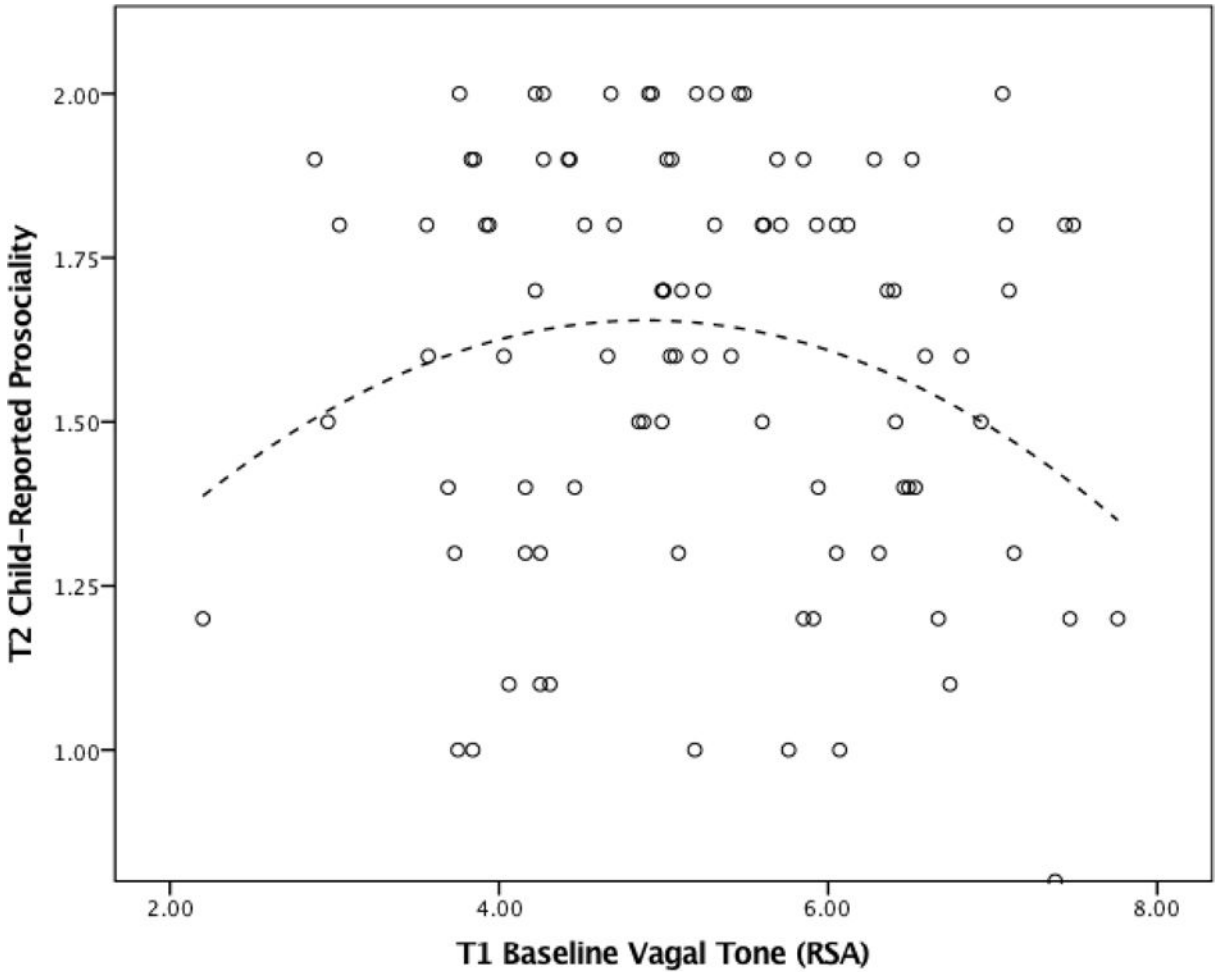

Figure 4.

Quadratic line fit to data to represent relation between baseline RSA at preschool age and children's self-reported prosociality 5.5 years later in Study 3.

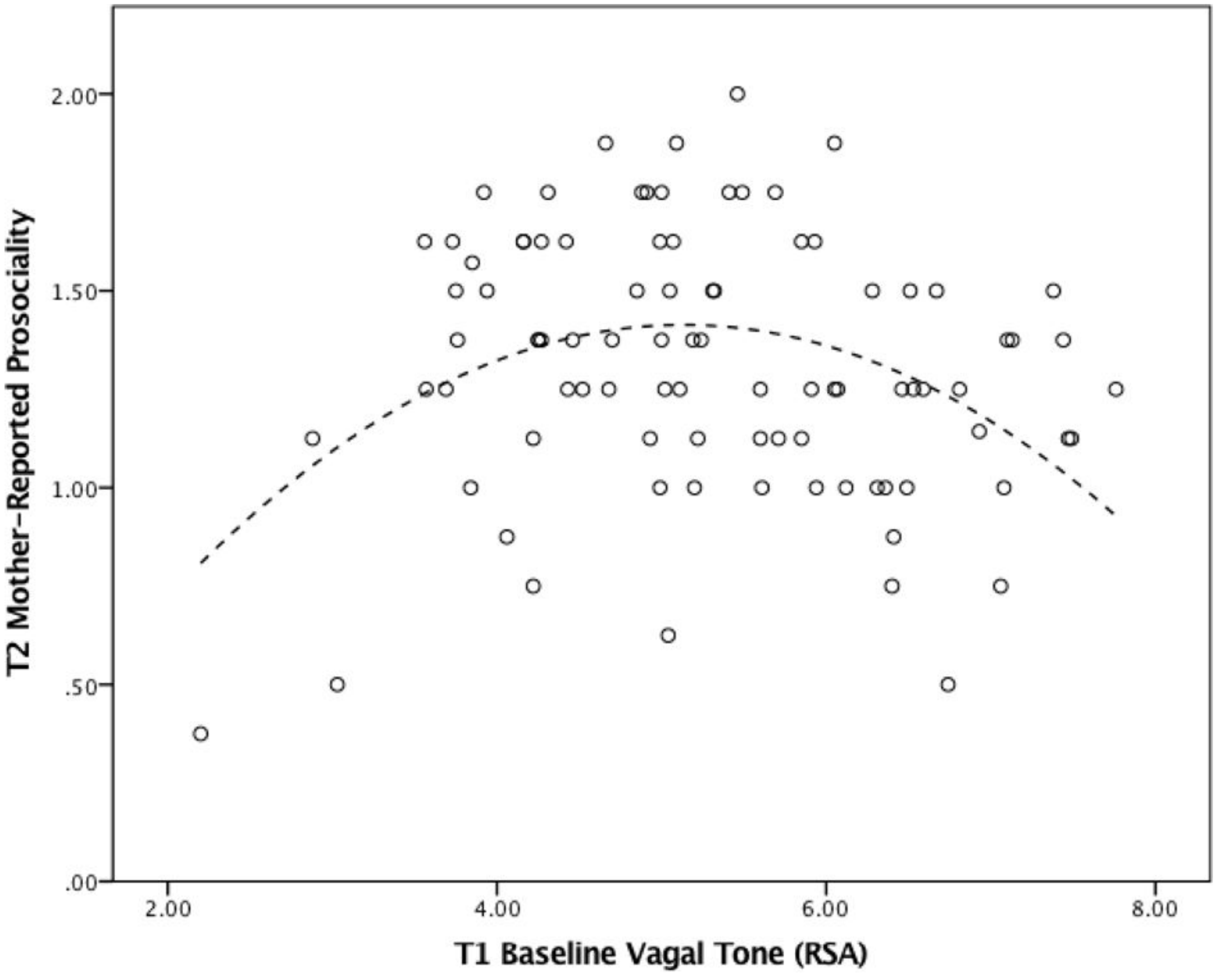

Figure 5.

Quadratic line fit to data to represent relation between baseline RSA at preschool age and children's mother-reported prosociality 5.5 years later in Study 3.

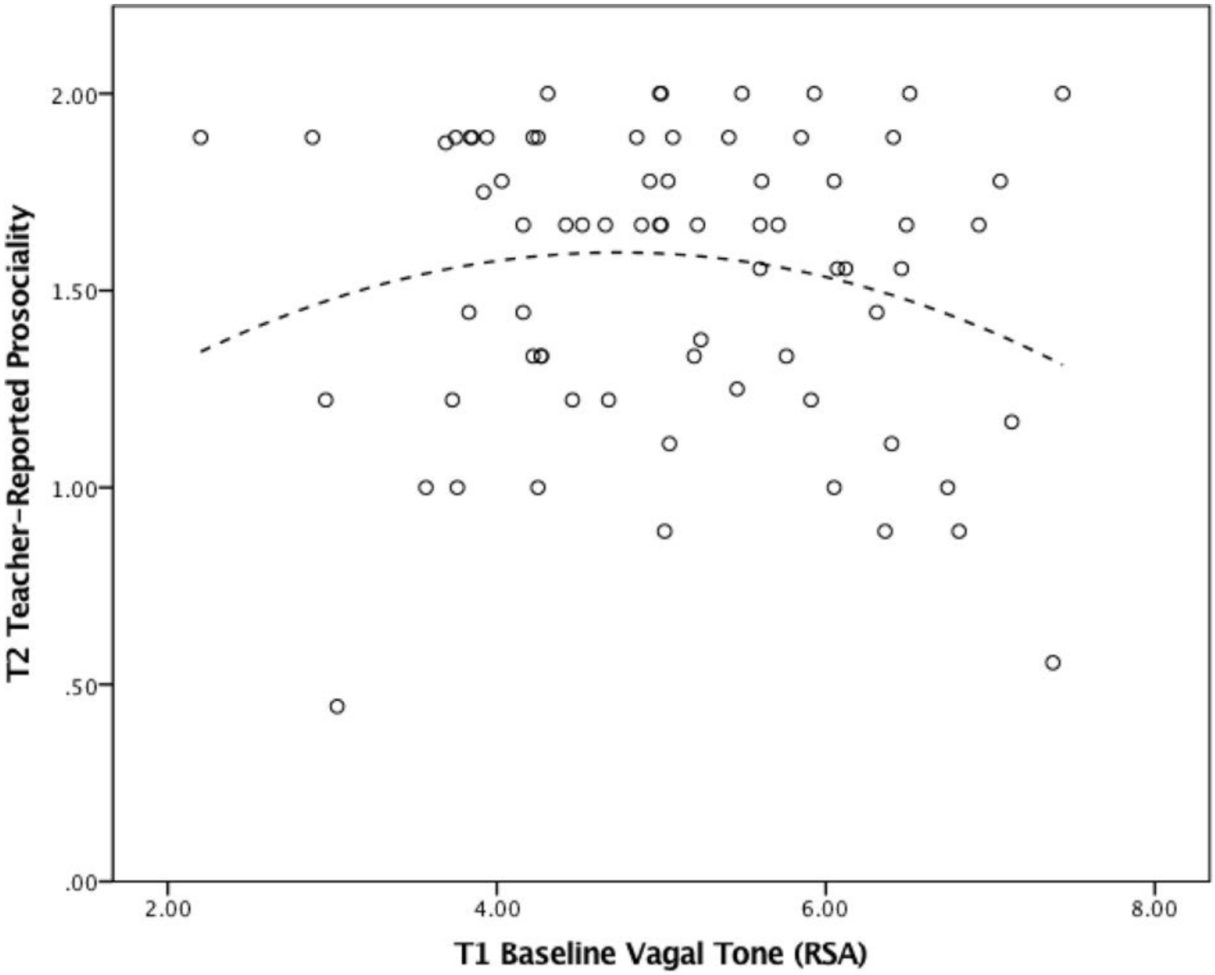

Figure 6.
Quadratic line fit to data to represent relation between baseline RSA at preschool age and children's teacher-reported prosociality 5.5 years later in Study 3.

Table 1

Descriptive Statistics for Study 1, Study 2, and Study 3.

	M	*SD*	Range
Study 1			
1. Age	5.58	1.1	4.08 – 7.37
2. Baseline RSA	6.84	1.11	3.69 – 9.63
3. Self-Reported Prosociality	0.65	0.20	0 – 1.00
Study 2			
1. Age	4.09	0.12	4.00 – 4.25
2. Baseline RSA	6.23	1.28	2.58 – 9.23
3. Empathic Concern in Response to Adult Injury	4.41	1.48	1 – 7
4. Tokens Donated to Sick Children	5.09	6.34	0 – 20
Study 3			
1. T1 Age	3.5	0.75	2.08 – 4.92
2. T2 Age	9.07	0.81	7.50 – 11.67
3. T1 Baseline RSA	5.25	1.35	2.20 – 9.46
4. Early Teacher-Reported Prosociality	3.93	0.87	1.50 – 5.60
5. T2 Child-Reported Prosociality	1.61	0.30	0.80 – 2.00
6. T2 Mother-Reported Prosociality	1.31	0.33	0.38 – 2.00
7. T2 Teacher-Reported Prosociality	1.54	0.37	0.44 – 2.00

Note. RSA = Respiratory sinus arrhythmia.

Table 2

Path Analysis Model Estimates for Study 1, Study 2, and Study 3.

Study 1: Self-Reported Prosociality	**B**	**β**	***C.R.***	***p***
Intercept	0.67			
Linear Term for Baseline RSA	0.01	0.06	0.76	0.45
Quadratic Term for Baseline RSA	−0.02	−0.16	2.1	0.04
Study 2: Observed Empathic Concern	B	β	*C.R.*	*p*
Intercept	4.62			
Linear Term for Baseline RSA	−0.08	−0.07	0.58	0.56
Quadratic Term for Baseline RSA	−0.14	−0.24	2.05	0.04
Study 3: Child-Reported Prosocaility	B	β	*C.R.*	*p*
Intercept	1.38			
Linear Term for Baseline RSA	−0.03	−0.11	1.12	0.26
Quadratic Term for Baseline RSA	−0.03	−0.29	2.94	<.01
Study 3: Mother-Reported Prosociality	B	β	*C.R.*	*p*
Intercept	1.55			
Linear Term for Baseline RSA	−0.02	−0.08	0.82	0.41
Quadratic Term for Baseline RSA	−0.06	−0.41	3.89	<.001
Study 3: Teacher Reported Prosociality	B	β	*C.R.*	*p*
Intercept	1.09			
Linear Term for Baseline RSA	−0.03	−0.09	0.77	0.44
Quadratic Term for Baseline RSA	−0.03	−0.2	1.82	0.07

Note. RSA = Respiratory sinus arrhythmia. C.R. = Critical ratio (unstandardized beta estimate divided by its estimated standard error).

Table 3

Study 2 Zero Inflated Negative Binomial Model Predicting Number of Tokens Donated and Not Giving versus Giving.

	Number of Tokens Donated (counts model component)			Not Giving versus Giving (logistic model component)		
	B	***C.R.***	***p***	**B**	***C.R.***	***p***
Intercept	2.59			1.98		
Sex	−.14	.69	.49	−1.53	2.94	.00
Linear Term for Baseline RSA	−.06	.70	.51	−.18	.82	.41
Quadratic Term for Baseline RSA	−.10	1.98	.05	11	1.03	.30

Note. RSA = Respiratory sinus arrhythmia. C.R. = Critical ratio (unstandardized beta estimate divided by its estimated standard error). Sex is dummy coded (boys = 0, girls = 1).