Published in final edited form as:

Dev Psychobiol. 2014 April ; 56(3): 317–326. doi:10.1002/dev.21100.

Developmental trajectories of respiratory sinus arrhythmia: Associations with social responsiveness

Michelle A. Patriquin, Jill Lorenzi, Angela Scarpa, and Martha Ann Bell

Department of Psychology, Virginia Tech

Abstract

The present longitudinal study examined relations between respiratory sinus arrhythmia (RSA) development and social responsiveness characteristics associated with autism spectrum disorders. Group-based developmental trajectory modeling was used to characterize RSA development patterns in 106 typically developing children across 5, 10, 24, 36, and 48 months of age. A two-group model fit of RSA development was found: a “typically” and “atypically” developing group. The typical group gradually increased in RSA across 5–48 months of age. The atypical group, however, increased in RSA from 5–24 months and demonstrated a plateau or “delay” in RSA development from 24–48 months. The atypical RSA development group also demonstrated more difficulties in parent-reported social responsiveness at 48 months. The results support current literature that identifies RSA as a marker of social functioning level.

Keywords

developmental trajectory; longitudinal; respiratory sinus arrhythmia; social; childhood; autism

Developmental trajectories of respiratory sinus arrhythmia: Associations with social responsiveness

The intersection of physiological systems, development, and psychopathology is critical in understanding processes that may contribute to the expression of typical and atypical behavior (Insel et al., 2010; Van Praag, Asnis, Kahn, & Brown, 1990). One measure of peripheral physiology, respiratory sinus arrhythmia (RSA), has been linked to both typical and atypical social-emotional and cognitive development (Bal et al., 2010; Gentzler, Rottenberg, Kovacs, George, & Morey, 2011; Gentzler, Santucci, Kovacs, & Fox, 2009; Patriquin, Scarpa, Friedman, & Porges, 2011; Staton, El-Sheikh, & Buckhalt, 2008; Van Hecke et al., 2009; Wetter & El-Sheikh, 2012). At the physiological level, RSA is a measure of heart rate variability (HRV) that occurs at the rate of spontaneous breathing (Porges, 1985; Porges & Bohrer, 1990). That is, RSA is the interval between heart beats that varies at the rate of respiration, and it is associated with parasympathetic activation. Although RSA has been found to increase over infancy and early childhood and reach stable adult levels by 5 years of age (Bornstein & Suess, 2000), the developmental trajectory of RSA during these years has yet to be described in relation to social responsiveness. Thus, the current study examined the developmental trajectory of baseline RSA in children at 5, 10, 24, 36, and 48 months of age. In order to explore associations between RSA and social responsiveness, RSA developmental trajectory groups were then compared on parent-reported social responsiveness measured at 48 months. Because deficits in social responsiveness are often

associated with autism spectrum disorders (ASD), the current study highlights a pattern of RSA that may serve as a potential physiological marker for difficulties in a continuum of ASD-related social behaviors.

Conceptualization of Respiratory Sinus Arrhythmia

Conceptually, RSA indexes the functioning of the vagus nerve (cranial nerve X), which exerts parasympathetic control over the heart (Porges, 1995). For example, when the vagal “brake” is applied, or there is more activity of the vagus nerve, the vagus will slow the human intrinsic heart rate via regulation of the sinoatrial node (“pacemaker” of the heart). In this example, when the vagus exerts more activity on the heart, RSA increases. Conversely, when the vagus nerve withdraws activity from the sinoatrial node, parasympathetic activity to the heart decreases, and heart rate can increase (for the debate on the reciprocal nature of parasympathetic/sympathetic response see Berntson, Cacioppo, & Quigley, 1991). As such, increased vagal activation is thought to reflect parasympathetic functioning, which supports the restoration of calm and physiological functioning when the body is at rest (Porges, 1995).

RSA and the vagus nerve have been theoretically linked to social engagement. The Polyvagal Theory, in particular, is a biobehavioral perspective that outlines central and autonomic physiology that contributes to human response in safe social interactions, danger, and life threat (Porges, 1995, 1998, 2001, 2003, 2007b, 2009; Porges & Lewis, 2009). The neurophysiological circuit hypothesized to support interaction in safe social contexts includes the myelinated branch of the vagus and the nucleus ambiguus of the medulla. When the vagus is active, reflecting parasympathetic activity on the heart, it is hypothesized that this state promotes effective social communication. The theory posits that specific cranial nerves, centrally located in the brainstem, may be more coordinated when an individual is in this physiologically “soothed” and in a parasympathetically-mediated state. More specifically, the Polyvagal Theory outlines five cranial nerves that form a Social Engagement System that regulates the striated muscles of the face and head to help coordinate effective social behavior (i.e., cranial nerves V, VII, IX, X, and XI; see Porges, 2009). RSA provides a broad indicator of the functioning of the Social Engagement System and therefore may give insight to the psychopathologies that affect social behavior (e.g., ASD; Porges, 2007a).

Development of RSA

Over the first year of life, longitudinal studies have demonstrated that baseline RSA increases and baseline heart period (HP) or heart rate (HR) decreases (i.e., HR slows; Izard et al., 1991; Richards, 1989; Stifter, Fox, & Porges, 1989). In particular, it has been reported that 13 month olds have a mean baseline RSA of 3.7, increasing to a mean baseline RSA of 4.3 at 18 months, and 5.7 at 36 months (Porges, Doussard-Roosevelt, Lourdes Portales, & Suess, 1994). Further, children’s baseline RSA reaches adult baseline RSA levels around 5 years of age (Bornstein & Suess, 2000) and is stable into childhood and adolescence (El-Sheikh, 2005). As RSA increases with development, a child’s physiological and behavioral responses become more organized. Thus, differences in the development of RSA may be related to the development of social-cognitive outcomes.

For example, one study examined associations between changes in baseline RSA from birth to 5 years of age and social-emotional and cognitive development (Feldman & Eidelman, 2009). Both cognitive ability and social engagement increased linearly from birth to 5 years. Significant growth in cognitive skills was seen between 2–5 years of age (e.g., symbolic competence, language) and there were large improvements in social skills (e.g., vocalization, gaze, social initiation) during the first years of life. Further, the effects of RSA

occurred during the periods of the most growth in both social-emotional and cognitive domains. The authors concluded that it might be during periods of dramatic social, emotional, and cognitive changes that a more adaptive or flexible physiological system will promote quicker adaptation to environmental stimuli or social signals.

Yet, some individuals may not develop the physiological organization necessary to promote effective social engagement and cognitive skills. One relevant cluster of disorders, autism spectrum disorders (ASD), are characterized by both social-cognitive difficulties and differences in RSA.

ASD & RSA

ASD is characterized by marked impairments in nonverbal behaviors (e.g., eye-to-eye gaze, facial expression), lack of spontaneous seeking to share enjoyment, interests, or achievement, and the delay in, or total lack of, the development of spoken language (DSM-IV-TR; American Psychiatric Association, 2000). Interestingly, many of the nerves outlined in the Social Engagement System of the Polyvagal Theory support social behaviors that are difficult and symptomatic for individuals with ASD. For instance, the accessory nerve (XI) supports joint attention and the ability to orient to stimuli by innervating in the sternocleidomastoid (neck muscle) and trapezius (back muscle). The facial nerve (VII) supports eyelid opening, movement of facial muscles (facial affect), and listening (e.g., extracting human voice from background noise) by innervating the stapedius (ear muscle) and face muscles. The glossopharyngeal (IX) supports vocalizations and verbalizations by innervating the pharynx. Lastly, the trigeminal nerve (V) may contribute to sensory and hearing difficulties in ASD by innervating the tensor tympani. As hypothesized by Porges, if individuals with ASD demonstrate difficulties producing these behaviors appropriately to environmental stimuli, one other cranial nerve – the vagus (X) – should also demonstrate differences (e.g., Porges, 2007b).

In fact, emerging literature examining RSA in ASD finds exactly this. Specifically, higher baseline RSA may be related to more positive functioning in ASD. A recent study examined baseline RSA, social behavior (i.e., joint attention, conventional gestures), receptive language ability, and response to an attention-demanding stimuli in children aged 4–7 years old with an ASD (Patriquin et al., 2011). This study found that higher amplitude baseline RSA was significantly correlated with better social engagement (i.e., more instances of joint attention and conventional gestures), higher receptive language scores, and more responsivity to attention-demanding stimuli. These results support prior findings that also suggest that higher baseline RSA is associated with better functioning within ASD. For example, children and adolescents with ASD who had higher amplitude RSA at baseline were better at recognizing emotions (Bal et al., 2010). Additionally, children with ASD (aged 8–12) who had higher baseline RSA demonstrated better parent-reported social skills and fewer problem behaviors (Van Hecke et al., 2009). Taken together, these results support the notion that higher baseline RSA can be a marker of more positive functioning within the autism spectrum. Moreover, it is possible that RSA can similarly reflect the range of functioning in social responsiveness that occurs on a continuum in typically developing children as well as children with psychopathology.

To our knowledge, relations between the developmental trajectory of RSA across early development and social responsiveness related to ASD have not been examined. As such, the objectives for this study were two-fold: 1) to examine the trajectories of RSA prospectively in a community sample of children from 5–48 months, and 2) to determine if different RSA trajectories are associated with variations in social responsiveness. This study provides critical insight to the developmental changes in RSA that may be associated with range of variability in social responsiveness that occurs in typically developing children.

Method

Participants

Participants were part of a sample of children and mothers enrolled in a longitudinal study examining cognition and emotion integration across early development. The RSA data acquired during five research lab visits (5, 10, 24, 36, and 48 mo) and maternal report of social responsiveness at 48 months were the focus of the current study. The children in this analysis represent one cohort of the children in the larger longitudinal study and are the only cohort for which social responsiveness data are available. The sample of 106 children (50 boys and 56 girls; ethnicity: 4.7% Hispanic, 95.3% non-Hispanic; race: 87.7% Caucasian, 1.9% African American, 0.9% Asian, 8.5% multi-racial, 0.9% other) were born full-term and had no diagnosed neurological or developmental problems. All parents completed a high school education, with 73% of mothers and 66% of fathers having a college degree. Families were paid for participation in the study and children were given a small gift at each visit.

Procedures

Upon arrival at the research laboratory for each of the five visits, participants and their mothers were greeted, procedures were described, and signed consent was obtained from the mothers. Prior to the 48-month visit, mothers were mailed the Social Responsiveness Scale (Constantino, 2002) and the completed questionnaire was collected at the lab visit.

RSA acquisition—After parental consent at each age, children were given an opportunity to acclimate to the research lab and the experimenter. Then electrocardiogram (ECG) electrodes were applied and a baseline recording procedure began. ECG was measured from two disposable electrodes using modified lead II alignment (right collarbone and lower left rib; Stern, Ray, & Quigley, 2001), grounded at the scalp near electrode site Fz. The cardiac electrical activity was amplified using a SA Instrumentation Bioamp (San Diego, CA) and bandpassed from 0.1 to 100 Hz. The QRS complex was displayed on the acquisition computer monitor and digitized at 512 samples per second. The acquisition software was Snapshot-Snapstream (HEM Data Corp.; Southfield, MI) and the raw data were stored for later R-wave detection and RSA analyses.

Baseline electrophysiology was recorded for 1 minute during each of the infant lab visits (5 months, 10 months) while the infant sat on the mother's lap. During the baseline recording, a research assistant manipulated a toy containing brightly colored balls on top of the testing table, 1.1 m in front of the infant. This procedure quieted the infant and yielded minimal gross motor movements. Mothers were instructed not to talk to infants during the baseline recording. This is our typical baseline for infant electrophysiology research (e.g., Bell, 2012; Cuevas & Bell, 2011)

During the toddler (24 months) and preschool (36 months, 48 months) visits, baseline electrophysiology was recorded as each child sat quietly for 2 minutes and watched a clip from the Disney film, *Finding Nemo* (sea turtles riding the East Australian Current). This procedure quieted the child and yielded minimal gross motor movements. Mothers sat in a chair beside the child and did not interact with the child during the recording. This is our typical baseline for toddler and preschooler electrophysiology research (e.g., Cuevas, Raj, & Bell, 2012; Morasch & Bell, 2012)

RSA analysis—ECG data were examined and analyzed using IBI Analysis System software developed by James Long Company (Caroga Lake, NY). First, R waves were detected offline with a four-pass peak detection algorithm, resulting in a data file with onset times for each detected R-wave. Next, the ECG signal was viewed on a computer monitor

along with tick marks representing the onset times of the IBI software detected R-waves. For undetected visible and obscured R-waves, the tick marks were inserted manually. Movement artifact was designated by the absence of at least three consecutive R-waves. These artifact-scored epochs were eliminated from all calculations. The edited R-wave was converted to heart period (i.e., time between heart beats).

Spectral analysis was used to calculate high frequency variability (i.e., RSA) in the heart period data, using a discrete Fourier transform with a 16-second Hanning window and 50% overlap. The frequency band for quantification of RSA at each age was 0.24 – 1.04 Hz. This frequency band is appropriate for all age groups between infancy and early childhood (Bar-Haim, Marshall, & Fox, 2000). The RSA data were transformed using natural log to normalize the distribution.

Social Responsiveness—Social responsiveness was measured at 48 months using maternal-report on the Social Responsiveness Scale (SRS; Constantino, 2002). SRS is a 65-item questionnaire focused on various dimensions of social behaviors associated with autism spectrum disorders. Mothers rate specific, observable aspects of social behavior on a scale from one (not true) to four (almost always true). The value of using SRS in this study is that the items can be used to form a single social responsiveness total score that is continuously distributed in the general population (Constantino, Przybeck, Friesen, & Todd, 2000; Constantino & Todd, 2003). A higher score indicates greater social impairment. For our sample, the SRS total score had an internal consistency of $\alpha = .87$.

In addition to a total score, the SRS also has five subscales. The *social awareness* scale focuses on detection of social cues and sensory aspects of reciprocal social behavior. The *social cognition* scale involves social information processing or cognitive-interpretive aspects of reciprocal social behavior. *Social communication* includes the capacity for reciprocal expressive social communication, while *social motivation* includes anxiety, inhibition, and empathy. Finally, the *autistic mannerisms* scale includes stereotypical, repetitive behaviors or highly restricted interests that are characteristic of autism.

Data analysis—Group-based trajectory analyses were conducted on baseline RSA data collected from the children at 5, 10, 24, 36, and 48 months using SAS macro PROC TRAJ (<http://www.andrew.cmu.edu/user/bjones/>; Jones, Nagin, & Roeder, 2001; Nagin, 2005). Model selection involved a two-stage selection process of identifying both the optimal number of trajectory groups and the optimal order of polynomial that best described the trajectory of each group identified in the first step. Baseline RSA trajectory group assignments then allowed for the examination of group differences on subsequent SRS total and subscale scores according to Jones and Nagin's (2007) Extension 5 (Relating Trajectory Groups to a Subsequent Outcome Variable).

Results

Descriptive Statistics and Inter-Correlations

Table 1 presents means and standard deviations for key variables of interest, while Table 2 presents inter-correlations for the same variables. As expected, there were several significant positive correlations between baseline RSA at the different time points. There were few significant correlations, however, between baseline RSA and SRS *T*-scores, including the time point at which the SRS was completed (48 months).

Trajectory Analysis of Baseline RSA

Results from the group-based trajectory analysis indicated that a two-group quadratic trajectory model best fit baseline RSA over the five different time points (Figure 1; Table 3). This model was preferable to a model with only one group, as well as to models with more than two groups. The Bayesian Information Criterion (BIC) is commonly used to inform decisions regarding model selection (Kass & Raftery, 1995; Schwarz, 1978). Table 4 presents BIC values for models with number of groups between one and five, as well as statistics for model comparisons. Kass and Raftery (1995) and Schwarz (1978) recommend choosing the model with the largest BIC value, which supported the selection of the two-group model. Additionally, an approximation for the BIC log Bayes factor, $2(\Delta\text{BIC})$ (where $\Delta\text{BIC} = \text{BIC for more complex model} - \text{BIC for simpler model}$), also supported the selection of the two-group model (for more information, see Jones, Nagin, & Roeder, 2001). The two-group model also evidenced conceptual interpretability in terms of “typical” and “atypical.” A model with an additional group (three groups in total) evidenced one trajectory group that was very similar to a previously identified group, which did not lead to increased interpretability.

The two-group quadratic trajectory model was also preferable to two-group models with any trajectory other than quadratic. The decision regarding the polynomial order began at the lowest order for both groups; polynomial terms were added to each group so long as the coefficients remained significant. For both groups, both the linear and quadratic terms were significant, but the cubic term was significant for neither group, so it did not remain in the final model.

The estimated population group proportions for the two-group quadratic trajectory model were 90.6% for a “typical” group (Group 1) whose average baseline RSA tended to increase gradually during the period from five months to 48 months of age, and an estimated 9.4% for an “atypical” group (Group 2) whose average baseline RSA tended to increase greatly between 5 and 24 months of age, but then demonstrated a plateau between 24 and 48 months of age. For this particular sample, of the 105 participants with usable baseline RSA data, 98 (93.3%) were assigned to Group 1, while 7 were assigned to Group 2 (6.7%). The estimated population proportions approximate the sample membership proportions, supporting good model fit. Additionally, average posterior probabilities of group membership were very high (.97 for membership in Group 1, .99 for membership in Group 2). These probabilities exceed the threshold of .7 recommended by Nagin (2005), which suggests that distinct groups are present and that this model fits well.

Comparison of SRS Scores by Trajectory Group

Based on the results of the trajectory analysis that identified two distinct groups, Jones and Nagin’s (2007) Extension 5 was used to relate baseline RSA trajectory groups to subsequent SRS scores (*T*-scores for Total score and the five subscales). Of the participants assigned to Group 1 (“typical”) in the trajectory analysis, 56 had SRS data at 48 months. Of the participants assigned to Group 2 (“atypical”), 6 had SRS data at 48 months. Table 5 presents 95% confidence intervals comparing Group 1 and Group 2 on SRS scores. According to these results, *T*-scores for Total score and the subscales of social cognition and social communication differed significantly by baseline RSA trajectory group, with Group 2 evidencing significantly higher scores on all three. This suggests that the two distinct baseline RSA trajectory groups also evidenced significant differences in their total SRS scores and in two SRS subscales at the age of 48 months. Group 1 and Group 2 did not differ significantly on the subscales of social awareness, social motivation, or autistic mannerisms.

Exploratory Analyses with Two and Three Observations

Supplemental analyses were also conducted to determine whether group-based trajectory analyses would reveal similar groups with only two or three observations. Specifically, since the baseline RSA observations at 24, 36, and 48 months evidenced the greatest differentiation between the two assigned groups (with less differentiation at 5 and 10 months), different combinations of these three observations were analyzed to then consider group differences on the SRS. A group-based trajectory analysis of only the 24 and 48 month baseline RSA observations did not reveal group differences on any of the outcome variables (SRS Total *T*-score and all five subscales). Likewise, a similar analysis of only the 24 and 36 month baseline RSA observations did not reveal group differences on any of the outcome variables.

However, a group-based trajectory analysis of only the 36 and 48 month baseline RSA observations revealed a significant group difference on the social awareness subscale of the SRS (95% confidence intervals: Group 1 [51.14, 56.49], Group 2 [56.75, 68.99]), but not on any other outcome variables. Likewise, a similar analysis of only three observations (baseline RSA at 24, 36, and 48 months) revealed a significant group difference on the social cognition subscale of the SRS (95% confidence intervals: Group 1 [49.46, 53.84], Group 2 [55.14, 68.73]), but not on any of the other outcome variables. As such, while some significant differences emerged based on analyses with only two or three baseline RSA observations, the analysis with all five observations identified the greatest number of significant group differences in SRS scores.

Discussion

This study examined the developmental trajectories of RSA in typically developing children across 5, 10, 24, 36, and 48 months of age and the association with social responsiveness. Our findings suggest the possibility of a developmental “delay” or plateau of RSA development in one RSA trajectory group that is related to more difficulties with social responsiveness (particularly, social cognition and social communication). These results highlight the importance of examining how developmental trajectories of RSA throughout infancy/childhood may be associated with social responsiveness difficulties that are considered to be characteristic of ASD.

Our group-based developmental trajectory analyses, based on Nagin (2005), revealed a two-group quadratic trajectory model fit best. The “typical” group (93.3% of the sample) demonstrated a gradual increase in RSA from 4–48 months of age, which is similar to findings in typically developing infants and children (i.e., RSA increases, HR slows; Izard et al., 1991; Porges et al., 1994; Richards, 1989; Stifter et al., 1989). Our group-based trajectory model also revealed a second, “atypical,” group (6.7% of the sample). Instead of exhibiting the gradual increase in RSA across development, this group showed an increase in RSA from 5–24 months and a plateau between 24–48 months. The plateau illustrated by our group-based trajectory modeling seems consistent with a developmental “delay” in the autonomic nervous system (i.e., vagal development). We speculate that the “typical” RSA trajectory group may gradually increase in RSA until age 5 (Bornstein & Suess, 2000), potentially surpassing the “atypical” RSA trajectory group in RSA development due to the atypical group’s plateau (or delay). Yet, we stress that this is a point for future research and the data herein cannot confirm/disconfirm this hypothesis. Without typical physiological organization and development (i.e., gradual increase in RSA), however, the “atypical” RSA trajectory group infants/children may demonstrate less physiological flexibility to environmental/social stimuli contributing to more social-cognitive and attentional difficulties (Porges, 2003).

In particular, the five cranial nerves (i.e., trigeminal, facial, accessory, glossopharyngeal, and vagus) that comprise the Social Engagement System (e.g., Porges & Lewis, 2009) may not be developed in a coordinated manner, suggesting a compromised ability to engage properly in the social world. The two-group trajectory model that emerged in this study may be one broad indicator of the coordination of the Social Engagement System as it develops across infancy and early childhood. In prior studies, this has been retrospectively hypothesized by findings of RSA differences in children/adolescents with ASD (Bal et al., 2010; Patriquin et al., 2011; Van Hecke et al., 2009), whose social impairments are a primary characteristic of their diagnosis (American Psychiatric Association, 2000; Kanner, 1943). Notably, this study was conducted on typically developing infants/children, but we did examine the differences of the typical and atypical trajectory groups on the Social Responsiveness Scale (SRS), which is highly correlated with a gold-standard assessment measure of ASD, the Autism Diagnostic Interview, Revised (Constantino et al., 2003).

When compared to the typical RSA development group, the atypical RSA development group demonstrated significantly higher scores on the SRS total score and on the social cognition and social communication subscale scores. On the SRS, a higher score indicates more difficulty in that domain. Therefore, the infants/children that demonstrated atypical patterns in their physiological development (i.e., development of RSA/vagal regulation) across 24–48 months demonstrated more social responsiveness difficulties. In contrast to the typical group, which showed a gradual increase in RSA development, the steep increase in vagal regulation for the atypical group and then delay, or plateau, in development may contribute to more difficulties in the coordination of Social Engagement System cranial nerve development and to more difficulties in social responsiveness.

There are limitations to this study. The atypical RSA development group did not demonstrate significant differences on the social awareness, social motivation, and autistic mannerisms subscales of the SRS, although the scores were in the hypothesized direction (i.e., atypical group had higher scores on both subscales relative to the typical group). These differences may be due to the number of participants allocated in the group-based trajectory modeling to the atypical group. In the trajectory modeling, 98 children were assigned to the typical group and 7 to the atypical group. Further, because only 7 individuals were allocated to the atypical group, the quadratic fit for the atypical developers and the reliability of these findings are currently unknown. In relating trajectory group assignments to subsequent SRS data, only 56 children in the typical group and 6 in the atypical group had complete SRS data. In addition, we found that five observations (at 5, 10, 24, 36, 48 months) identified the greatest number of significant group differences on the SRS compared to combinations of two or three observations (at 24, 36, 48 months). The two or three group analyses, however, may have also been underpowered due to a small sample size. Future researchers, who are interested in designing longitudinal studies that examine RSA developmental patterns and symptoms associated with ASD, should take into account these findings and attempt to recruit a larger sample to achieve the variability necessary to examine atypical RSA developmental trajectories, potentially with fewer observations.

Despite the limitations, these initial findings provide a valuable illustration of the developmental trajectories of RSA and how a specific developmental pattern may be related to difficulties in social responsiveness. Our findings also emphasize the importance of designing longitudinal studies that prospectively examine the development of RSA and the correlates of RSA development, particularly in the context of psychopathologies that have been associated with differences in RSA, including ASD. Moreover, since the present study did not specifically recruit individuals who were at-risk (e.g., showed developmental delays), this highlights the variability of social responsiveness skills and RSA patterns on a

continuum in the general population, and supports the notion of examining psychopathologies from a domain-specific, dimensional perspective (Insel et al., 2010).

In conclusion, with our data, we add to the literature that describes the connection between difficulties in social behavior and RSA. Our findings also stress the importance of examining symptoms of psychopathology from a biobehavioral, dimensional perspective to gain objective insight to typical and atypical development.

Acknowledgments

This research was supported by grants HD049878 and HD043057 from the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development (NICHD) awarded to Martha Ann Bell. The content of this manuscript is solely the responsibility of the authors and does not necessarily represent the official views of the NICHD or the National Institutes of Health. We are grateful to the families for their participation in our research. The assistance of Denise Adkins, Lisa Bunomano, Annie Cardell, Anjolie Diaz, Morgan Hubble, Kacey Morasch, Vinaya Raj, and Christy Wolfe with data collection and coding is greatly appreciated. We also thank Bobby Jones for his assistance with data analysis.

References

- American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders (DSM-IV-TR). 4th ed. Washington, DC: American Psychiatric Association; 2000. text rev. ed.
- Bal E, Harden E, Lamb D, Van Hecke AV, Denver JW, Porges SW. Emotion recognition in children with autism spectrum disorders: Relations to eye gaze and autonomic state. *Journal of Autism and Developmental Disorders*. 2010; 40(3):358–370. [PubMed: 19885725]
- Bar-Haim Y, Marshall P, Fox N. Developmental changes in heart period and high-frequency heart period variability from 4 months to 4 years of age. *Developmental Psychobiology*. 2000; 37(1):44–56. [PubMed: 10937660]
- Bell MA. A psychobiological perspective on working memory performance at 8 months of age. *Child Development*. 2012; 83(1):251–265. [PubMed: 22103396]
- Berntson G, Cacioppo J, Quigley K. Autonomic determinism: The modes of autonomic control, the doctrine of autonomic space, and the laws of autonomic constraint. *Psychological Review*. 1991; 98(4):459–487. [PubMed: 1660159]
- Bornstein MH, Suess PE. Child and mother cardiac vagal tone: Continuity, stability, and concordance across the first 5 years. *Developmental Psychology*. 2000; 36(1):54. [PubMed: 10645744]
- Constantino J. The social responsiveness scale. Los Angeles: Western Psychological Services; 2002.
- Constantino J, Todd R. Autistic traits in the general population: A twin study. *Archives of General Psychiatry*. 2003; 60(5):524. [PubMed: 12742874]
- Constantino JN, Davis SA, Todd RD, Schindler MK, Gross MM, Brophy SL, Reich W. Validation of a brief quantitative measure of autistic traits: Comparison of the social responsiveness scale with the autism diagnostic interview-revised. *Journal of Autism and Developmental Disorders*. 2003; 33(4):427–433. [PubMed: 12959421]
- Constantino JN, Przybeck T, Friesen D, Todd RD. Reciprocal social behavior in children with and without pervasive developmental disorders. *Journal of Developmental and Behavioral Pediatrics*. 2000
- Cuevas K, Bell MA. EEG and ECG from 5 to 10 months of age: Developmental changes in baseline activation and cognitive processing during a working memory task. *International Journal of Psychophysiology*. 2011; 80:119–128. [PubMed: 21338632]
- Cuevas K, Raj V, Bell MA. A frequency band analysis of two-year-olds memory processes. *International Journal of Psychophysiology*. 2012; 83:315–322. [PubMed: 22137966]
- El-Sheikh M. Stability of respiratory sinus arrhythmia in children and young adolescents: A longitudinal examination. *Developmental Psychobiology*. 2005; 46(1):66–74. [PubMed: 15690389]

- Feldman R, Eidelman AI. Biological and environmental initial conditions shape the trajectories of cognitive and social emotional development across the first years of life. *Developmental Science*. 2009; 12(1):194–200. [PubMed: 19120428]
- Gentzler AL, Rottenberg J, Kovacs M, George CJ, Morey JN. Atypical development of resting respiratory sinus arrhythmia in children at high risk for depression. *Developmental Psychobiology*. 2011
- Gentzler AL, Santucci AK, Kovacs M, Fox NA. Respiratory sinus arrhythmia reactivity predicts emotion regulation and depressive symptoms in at-risk and control children. *Biological Psychology*. 2009; 82(2):156–163. [PubMed: 19596044]
- Insel T, Cuthbert B, Garvey M, Heinssen R, Pine DS, Quinn K, Wang P. Research domain criteria (RDoC): Toward a new classification framework for research on mental disorders. *American Journal of Psychiatry*. 2010; 167(7):748. [PubMed: 20595427]
- Izard CE, Porges SW, Simons RF, Haynes OM, Hyde C, Parisi M, Cohen B. Infant cardiac activity: Developmental changes and relations with attachment. *Developmental Psychology*. 1991; 27(3):432.
- Jones BL, Nagin DS. Advances in group-based trajectory modeling and an SAS procedure for estimating them. *Sociological Methods & Research*. 2007; 35(4):542–571.
- Jones BL, Nagin DS, Roeder K. A SAS procedure based on mixture models for estimating developmental trajectories. *Sociological Methods & Research*. 2001; 29(3):374–393.
- Kanner L. Autistic disturbances of affective contact. *Nervous child*. 1943; 2(2):217–230.
- Kass RE, Raftery AE. A reference Bayesian test for nested hypotheses and its relationship to the Schwarz Criterion. *Journal of the American Statistical Association*. 1995; 90:928–934.
- Morasch KC, Bell MA. Self-regulation of negative affect at 5 and 10 months. *Developmental Psychobiology*. 2012; 54:215–221. [PubMed: 21761408]
- Nagin, DS. Group-based modeling of development. Cambridge, MA: Harvard University Press; 2005.
- Patriquin MA, Scarpa A, Friedman BH, Porges SW. Respiratory sinus arrhythmia: A marker for positive social functioning and receptive language skills in children with autism spectrum disorders. *Developmental Psychobiology*. 2011 Advanced online publication.
- Porges, SW. The Vagal Tone Monitor: Application in sleep research; Paper presented at the IEEE Engineering in medicine and biology society; Chicago, IL. 1985 Septmeber. 1985
- Porges SW. Orienting in a defensive world: Mammalian modifications of our evolutionary heritage: A Polyvagal Theory. *Psychophysiology*. 1995; 32(4):301–318. [PubMed: 7652107]
- Porges SW. Love: An emergent property of the mammalian autonomic nervous system. *Psychoneuroendocrinology*. 1998; 23(8):837–861. [PubMed: 9924740]
- Porges SW. The polyvagal theory: Phylogenetic substrates of a social nervous system. *International Journal of Psychophysiology*. 2001; 42(2):123–146. [PubMed: 11587772]
- Porges SW. Social engagement and attachment. *Annals of the New York Academy of Sciences*. 2003; 1008:31–47. [PubMed: 14998870]
- Porges SW. A phylogenetic journey through the vague and ambiguous Xth cranial nerve: A commentary on contemporary heart rate variability research. *Biological Psychology*. 2007a; 74(2):301–307. [PubMed: 17055142]
- Porges SW. The polyvagal perspective. *Biological Psychology*. 2007b; 74(2):116–143. [PubMed: 17049418]
- Porges SW. The polyvagal theory: New insights into adaptive reactions of the autonomic nervous system. *Cleveland Clinic Journal of Medicine*. 2009; 76(Suppl 2):S86. [PubMed: 19376991]
- Porges, SW.; Bohrer, RE. The analysis of periodic processes in psychophysiological research. In: Cacioppo, JT.; Tassinary, LG., editors. *Principles of psychophysiology: Physical, social, and inferential elements*. New York: Cambridge University Press; 1990. p. 708-753.
- Porges SW, Doussard-Roosevelt JA, Lourdes Portales A, Suess PE. Cardiac vagal tone: Stability and relation to difficultness in infants and 3-year-olds. *Developmental Psychobiology*. 1994; 27(5):289–300. [PubMed: 7926281]
- Porges SW, Lewis GF. The polyvagal hypothesis: Common mechanisms mediating autonomic regulation, vocalizations and listening. *Handbook of Behavioral Neuroscience*. 2009:255–264.

- Richards JE. Development and stability in visual sustained attention in 14, 20, and 26 week old infants. *Psychophysiology*. 1989; 26(4):422–430. [PubMed: 2798691]
- Schwarz G. Estimating the dimension of a model. *Annals of Statistics*. 1978; 6:461–464.
- Staton L, El-Sheikh M, Buckhalt JA. Respiratory sinus arrhythmia and cognitive functioning in children. *Developmental Psychobiology*. 2008; 51(3):249. [PubMed: 19107730]
- Stern, RM.; Ray, WJ.; Quigley, KS. *Psychophysiological record*. 2nd ed.. Ney York: Oxford; 2001.
- Stifter CA, Fox NA, Porges SW. Facial expressivity and vagal tone in 5-and 10-month-old infants. *Infant Behavior and Development*. 1989; 12(2):127–137.
- Van Hecke AV, Lebow J, Bal E, Lamb D, Harden E, Kramer A, Porges SW. Electroencephalogram and heart rate regulation to familiar and unfamiliar people in children with autism spectrum disorders. *Child Development*. 2009; 80(4):1118–1133. [PubMed: 19630897]
- Van Praag HM, Asnis GM, Kahn RS, Brown S. Nosological tunnel vision in biological psychiatry: A plea for a functional psychopathology. *Annals of the New York Academy of Sciences*. 1990; 600:501–510. [PubMed: 2252329]
- Wetter EK, El-Sheikh M. Trajectories of children's internalizing symptoms: The role of maternal internalizing symptoms, respiratory sinus arrhythmia and child sex. *Journal of Child Psychology and Psychiatry*. 2012

Figure 1.
Baseline RSA on Age in Months: Observed and Predicted Trajectories.

Table 1

Means and Standard Deviations for Key Variables of Interest

Variable	<i>N</i>	<i>M</i>	<i>SD</i>
Baseline RSA, 5 months (ln(ms) ²)	91	3.77	0.89
Baseline RSA, 10 months (ln(ms) ²)	94	4.44	1.02
Baseline RSA, 24 months (ln(ms) ²)	60	5.52	1.52
Baseline RSA, 36 months (ln(ms) ²)	56	6.14	1.11
Baseline RSA, 48 months (ln(ms) ²)	56	6.58	1.07
SRS Total <i>T</i> -score	62	52.26	8.37
SRS Social Awareness <i>T</i> -score	62	55.61	8.68
SRS Social Cognition <i>T</i> -score	62	52.73	8.61
SRS Social Communication <i>T</i> -score	62	50.56	8.26
SRS Social Motivation <i>T</i> -score	62	51.10	9.76
SRS Autistic Mannerisms <i>T</i> -score	62	51.37	8.51

Table 2

Inter-correlations for Key Variables of Interest

	Baseline RSA 10 months	Baseline RSA 24 months	Baseline RSA 36 months	Baseline RSA 48 months	SRS Total	SRS Awareness	SRS Cognition	SRS Communication	SRS Motivation	SRS Mannerisms
Baseline RSA 5 months	.31**	.14	.16	.34*	.05	.06	.15	.06	-.06	.03
Baseline RSA 10 months	--	.27*	.32*	.41**	.25	.13	.30*	.24	.17	.17
Baseline RSA 24 months		--	.61***	.39*	.26	.34*	.28	.20	.03	.24
Baseline RSA 36 months			--	.67***	.12	.35*	.11	.10	.01	.05
Baseline RSA 48 months				--	.23	.16	.24	.21	.16	.17
SRS Total					--	--	--	--	--	--
SRS Awareness						--	.46***	.51***	.39**	.47***
SRS Cognition							--	.75***	.53***	.64***
SRS Communication								--	.69***	.69***
SRS Motivation									--	.58***
SRS Mannerisms										--

Note. Pairwise deletion was used.

*
 $p < 0.05$.**
 $p < 0.01$.***
 $p < .001$.SRS Awareness, social awareness subscale T -score; SRS Cognition, social cognition subscale T -score; SRS Communication, social communication subscale T -score; SRS Motivation, social motivation subscale T -score; SRS Mannerisms, autistic mannerisms subscale T -score; SRS total, total SRS T -score.

Table 3

Summary of Group-Based Trajectory Analysis on Baseline RSA

	Intercept <i>B</i> (SE)	Linear <i>B</i> (SE)	Quadratic <i>B</i> (SE)	Predicted RSA 10 months (ln(ms) ²)	Predicted RSA 24 months (ln(ms) ²)	Predicted RSA 36 months (ln(ms) ²)	Predicted RSA 48 months (ln(ms) ²)
Group 1: Typical	3.36 (0.15)	0.09*** (0.02)	<0.01* (<0.01)	4.24	5.25	5.91	6.38
Group 2: Atypical	2.25 (0.51)	0.36*** (0.06)	-0.01*** (<0.01)	5.37	8.03	8.73	7.97

Note. Linear and quadratic terms reflect change in baseline RSA (ln(ms)²) per month of age.

* $p < 0.05$.

*** $p < 0.001$.

Table 4

Bayesian Information Criterion (BIC) and Model Comparison Statistics for Determining Optimal Number of Groups

<i>Number of Groups</i>	BIC <i>(n = 357)</i>	<i>Null Model</i>	2(ΔBIC)
1	-556.79		
2	-544.42	1	24.74
3	-547.05	2	-5.26
4	-548.09	3	-2.08
5	-560.83	4	-25.48

Table 5

95% Confidence Intervals Comparing Mean SRS Total and Subscale T-Scores Between Baseline RSA Trajectory Groups

	<i>M</i>	95% Confidence Interval
Total Score		
Group 1	51.18	[48.90, 53.46]*
Group 2	60.83	[54.17, 67.48]*
Social Awareness		
Group 1	54.79	[52.52, 57.06]
Group 2	62.46	[55.57, 69.35]
Social Cognition		
Group 1	51.50	[49.28, 53.71]*
Group 2	62.71	[56.19, 69.24]*
Social Communication		
Group 1	49.58	[47.45, 51.72]*
Group 2	58.65	[52.23, 65.06]*
Social Motivation		
Group 1	50.45	[47.89, 53.02]
Group 2	56.57	[48.71, 64.42]
Autistic Mannerisms		
Group 1	50.77	[48.54, 53.01]
Group 2	56.47	[49.66, 63.29]

Note. Group 1 *n* = 56; Group 2 *n* = 6.

* = non-overlapping (significant) confidence intervals