Developmental Psychology
2012, Vol. 48, No. 4, 918–931

0012-1649/12/$12.00 DOI: 10.1037/a0026901

Individual Differences in Adolescents' Sympathetic and Parasympathetic Functioning Moderate Associations Between Family Environment and Psychosocial Adjustment

Lisa M. Diamond, Christopher P. Fagundes, and Matthew R. Cribbet
University of Utah

The present study tested whether individual differences in autonomic nervous system functioning interact with environmental risk factors to predict adolescents' psychosocial functioning. The authors assessed skin conductance and respiratory sinus arrhythmia at rest and during laboratory stressors in 110 14-year-olds. Subsequently, adolescents and their mothers provided both questionnaire and daily diary data (over 10 days) on emotional and interpersonal functioning. The authors found stronger associations between environmental risk factors (having a single-mother household or a mother with high internalizing problems) and psychosocial outcomes (externalizing problems, daily negative affect, and daily interaction quality) among youths with specific patterns of tonic and stress-induced sympathetic and parasympathetic nervous system activity, but the pattern of moderating effects differed between boys and girls. The findings support the notion that individual differences in autonomic functioning index variation in youth's susceptibility to environmental risk factors.

Keywords: autonomic reactivity, RSA, SCL, adolescence, psychosocial adjustment

A growing body of research has investigated whether individual differences in autonomic nervous system (ANS) functioning predispose children to be differentially sensitive to their environmental contexts. Most of this research has adopted a diathesis-stress or "dual-risk" perspective, positing that negative rearing environments have disproportionately negative effects on children with exaggerated ANS responses to stress (reviewed by Boyce & Ellis, 2005). Yet recently, an alternative perspective has emerged, denoted *differential susceptibility* (Belsky, Bakermans-Kranenburg, & van Ijzendoorn, 2007; Belsky & Pluess, 2009; Del Giudice, Ellis, & Shirtcliff, 2011; Ellis, Boyce, Belsky, Bakermans-Kranenburg, & Van Ijzendoorn, 2011) positing that the same factors that render children susceptible to negative environments also render them susceptible to positive environments. Hence, both dual-risk and differential susceptibility (DS) perspectives predict that children with certain patterns of ANS functioning will show disproportionately negative outcomes in negative environmental contexts (as shown by Boyce, Chesney, Alkon, & Tschann, 1995; Bubier, Drabick, & Breiner, 2009; Cummings, El-Sheikh, Kouros, & Keller, 2007; El-Sheikh, Keller, & Erath, 2007; El-Sheikh et al., 2009; Katz, 2007), but the DS perspective additionally predicts that these children will show disproportionately positive outcomes in positive environments (reviewed in Belsky et al., 2007; Belsky & Pluess, 2009). In the present study, we examined whether this is the case by testing whether individual differences in baseline and stress-induced ANS functioning moderate adolescents' sensitivity to family environmental factors (specifically, two-parent vs. single-parent family structure and mothers' internalizing problems). We tested for moderating effects involving three different psychosocial outcomes—externalizing problems, daily negative affect, and daily mother-perceived interaction quality—and we compared the applicability of a dual-risk versus a DS perspective for different combinations of ANS moderators, environmental factors, and outcomes.

Autonomic Nervous System Functioning and Child-Adolescent Outcomes

Individual differences in resting and stress-induced ANS functioning have received increasing attention as predictors of child adjustment. The ANS has two branches—the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). During stress, SNS engagement (typically measured via skin conductance, or SCL) produces increased heart rate and blood pressure. Excessive SNS reactivity has been posited as a potential marker of children's hypersensitivity to environmental challenges (Boucsein, 1991), and has been found to predict reactive aggression (Hubbard et al., 2002), anxiety (Weems, Zakem, Costa, Cannon, & Watts, 2005), and internalizing and externalizing problems (El-Sheikh et al., 2007).

In contrast to the SNS, the PNS provides for tonic inhibitory control of cardiac output. Individuals with high tonic PNS regulation are conceptualized as having nervous systems that respond

This article was published Online First January 23, 2012.

Lisa M. Diamond, Christopher P. Fagundes, and Matthew R. Cribbet, Department of Psychology, University of Utah.

Christopher P. Fagundes is now at the Ohio State University School of Medicine.

This project was supported by W. T. Grant Foundation Grant 2610, awarded to Lisa M. Diamond.

Correspondence concerning this article should be addressed to Lisa M. Diamond, Department of Psychology, University of Utah, 380 South 1530 East, Room 502, Salt Lake City, UT 84112-0251. E-mail: diamond@psych.utah.edu

quickly and flexibly to—and recover more effectively from—environmental demands (Porges, 1991; Thayer & Lane, 2000). Tonic PNS functioning is typically assessed via resting levels of *respiratory sinus arrhythmia* (RSA), which refers to the regular variations in heart rate that are attributable to the respiratory cycle (increasing with inhalation and decreasing with exhalation). Variability in heart rate has numerous sources (Akselrod, Gordon, Snidman, Shannon, & Cohen, 1985), but the high-frequency component of variability that corresponds to the respiratory cycle has been found to be a reliable index of parasympathetic control of heart rate. Children and adults with low resting RSA show ineffective behavioral coping in response to stress (Fabes, Eisenberg, & Eisenbud, 1993) as well as higher levels of anger, hostility, mental stress, and generalized anxiety (reviewed in Brosschot & Thayer, 1998). During stress, there is typically a "suppression" of PNS activity that facilitates increased cardiovascular activity to meet stressor demands (e.g., Pieper, Brosschot, van der Leeden, & Thayer, 2007). This pattern allows for a rapid increase in heart rate without requiring energy-costly SNS mobilization and is thought to reflect the capacity to use attentional strategies to engage appropriately with the environment to mount an organized response to challenge (Bornstein & Suess, 2000a). Accordingly, children with greater stress-induced RSA suppression have shown greater social competence (Calkins & Keane, 2004; Doussard-Roosevelt, Montgomery, & Porges, 2003; Graziano, Keane, & Calkins, 2007), greater emotion regulation (Hessler & Katz, 2007), and fewer externalizing problems (Calkins & Dedmon, 2000).Yet, some studies (usually of adults) have found the opposite—namely, that greater RSA suppression during stress is associated with *poorer* psychosocial outcomes (Austin, Riniolo, & Porges, 2007; Calkins, Graziano, & Keane, 2007; Egizio et al., 2008; J. W. Hughes & Stoney, 2000). One possible explanation for these contradictory findings is that there may be an optimal range of PNS suppression that balances preparedness for challenge with active self-regulation in service of prosocial engagement, which has been found to be associated with increased PNS activity (Beauchaine, 2001; Egizio et al., 2008; Thayer & Lane, 2000). Developmental changes must also be considered, given that most studies finding associations between RSA suppression and negative outcomes have been conducted among adults.

Interactions Between ANS Functioning and Environmental Factors

Researchers have increasingly examined patterns of SNS and PNS activity as moderators of environmental influences, in line with dual-risk and differential susceptibility models. For example, Boyce and Ellis (2005) have advanced a model of *biological sensitivity to context*, which is essentially a differential susceptibility model focusing specifically on biological indices of susceptibility. Boyce et al. (1995) found that among 3– to 5-year-old children, higher cardiovascular activity predicted higher susceptibility to respiratory illness among children living in stressful environments, but not among those living in normal environments. In a prospective study of preadolescent girls, El-Sheikh et al. (2007) found that parents' marital conflict predicted increases in externalizing and internalizing problems over time among girls with heightened SCL reactivity to stress, but this association was less pronounced for girls with lower SCL reactivity to stress. Cummings et al. (2007) found a similar pattern when focusing on links between child adjustment and parental depression: Specifically, children with elevated SCL reactivity showed heightened vulnerability to their parent's depression. In a recent study, Erath, El-Sheikh, Hinnant, and Cummings (2011) examined SCL reactivity as a moderator of links between harsh parenting and growth in externalizing symptoms from ages 8 to 10. They found that among boys with lower SCL reactivity and harsh parents, high externalizing problems tended to emerge early and to persist over time, whereas among boys with harsh parents and elevated SCL reactivity, externalizing problems tended to increase over time (although this effect was not found among girls; girls with elevated SLC reactivity and harsh parenting showed declines in externalizing problems from ages 8–10).

Regarding PNS functioning, Gordis, Feres, Olezeski, Rabkin, and Trickett (2010) found that youths with low baseline RSA were more sensitive than youths with high baseline RSA to the detrimental effects of maltreatment on aggression. A similar result was found in a study by El-Sheikh and colleagues (El-Sheikh, Harger, & Whitson, 2001) on the negative implications of interparental conflict for child adjustment. Specifically, the tendency for children living with interparental conflict to show greater internalizing and externalizing problems, greater anger and anxiety, and lower self-worth was more pronounced among children with lower baseline RSA. Bosch and colleagues (Bosch, Riese, Ormel, Oldehinkel, & Verhulst, 2009) studied links between adolescents' anxiety levels and their exposure to stressful life events. They found that among adolescents with high stressful life events, those with lower baseline RSA showed greater anxiety than those with higher baseline RSA. Katz and Gottman (1995) found stronger associations between parents' marital conflict and children's externalizing behavior among children with low baseline RSA, paralleling findings by El-Sheikh and colleagues (El-Sheikh et al., 2001). Regarding RSA, Katz (2007) found that children with a combination of a violent home environment and less RSA suppression in response to stress showed elevated conduct problems (Katz, 2007).

Importantly, however, few of these studies have specifically tested the key prediction of DS models, which is that the same biological risk indices that predict poorer adjustment in poorer environments predict better adjustment in enhanced environments. Also, most of the aforementioned studies have found significant gender differences in ANS moderating effects (e.g., El-Sheikh et al., 2001; Gordis et al., 2010), and the specification of gender-differentiated patterns of differential susceptibility has been identified as an important direction for future research (Bornstein & Suess, 2000b; Cummings & Davies, 2002). For example, El-Sheikh and colleagues (El-Sheikh et al., 2007) found stronger associations between parents' marital conflict and children's internalizing and externalizing problems among girls with heightened SCL reactivity, but among boys lower SCL reactivity predicted stronger associations between parental conflict and externalizing problems. Regarding PNS activity, El-Sheikh and colleagues (2001) found that boys—but not girls—with less stress-induced suppresssion of RSA showed stronger associations between interparental conflict and externalizing problems. Both boys and girls with less stress-induced suppression of RSA showed greater associations between interparental conflict and internalizing problems, but over a 2-year period, this moderating effect was only preserved for girls (El-Sheikh & Whitson, 2006). On the basis of such findings, El-Sheikh and Whitson (2006) have suggested that girls' and boys' different social-developmental experiences may contribute to gender differences in sensitivities to environmental factors. Collectively, such considerations indicate the importance of comprehensively testing for gender differences in the moderating effects of ANS functioning, and specifically determining whether moderating effects fit a dual-risk versus a DS model.

The Present Study

We assessed both resting levels and stress-induced changes in SNS and PNS functioning in a community sample of 110 14-year-old adolescents, and tested whether individual differences in these parameters moderated associations between youths' family environments (single-parent vs. two-parent household, mother's internalizing symptoms) and their psychosocial functioning (mother-reported externalizing problems, adolescent-reported daily negative affect, and mother-reported daily interaction quality). We focused on externalizing rather than internalizing problems because of the extensive prior literature on ANS functioning and externalizing problems, and because we expected that mother reports would be more reliable for externalizing problems. The negative affectivity manifested in internalizing problems is captured by our measure of adolescent-reported daily negative affect. We collected 10-day diary data on negative affect to increase the reliability and ecological validity of this measure and to ensure that it was independent of youths' emotional state during the laboratory assessment of ANS functioning. Mothers' perceptions of their daily interactions with their child were assessed using the 10-day diary to provide a reliable and ecologically valid index of the degree to which the youths' social competence is manifested in interactions experienced by the other person as enjoyable, close, and responsive. Although this measure does not provide a direct index of the youth's interpersonal skills, we expect that mothers of more socially competent youths will experience daily mother–child interactions as more positive and responsive. We focused on the environmental context of family structure based on previous research showing that children growing up in single-parent households often show heightened adjustment problems (Breivik & Olweus, 2006; Pan & Farrell, 2006). The adolescent years can be particularly challenging in single-parent households (Richards & Schmiege, 1993), given that these households typically contain higher levels of mother–child conflict, lower parental monitoring, and deficits in parenting style (Breivik, Olweus, & Endresen, 2009; Pan & Farrell, 2006). Similar phenomena have been observed when mothers suffer from anxiety and depression, even at subclinical levels (E. K. Hughes & Gullone, 2010; Judd, Paulus, Wells, & Rapaport, 1996), and hence daily interactions with mothers who have high internalizing problems are likely to create chronic day-to-day stress for adolescents.

Consistent with both dual-risk and differential-susceptibility perspectives, we expect that adolescents with greater SCL stress reactivity (Hypothesis 1), lower baseline RSA (Hypothesis 2), and less RSA suppression (Hypothesis 3) will show stronger associations between negative family environmental (single-parent household, high-internalizing mothers) and negative outcomes (greater externalizing problems, greater day-to-day negative affect, poorer mother-perceived interaction quality). We do not advance specific hypotheses regarding gender differences, given the mixed findings of previous research, but we plan to systematically test for gender differences in the hypothesized moderating effects, and to examine whether effects prove more consistent with dual-risk versus DS models. Both models predicts that youths with ANS indices of susceptibility should show more negative outcomes when raised in negative environments, but the DS model additionally predicts that high-susceptible youths should show more positive outcomes when raised in positive environments.

Method

Participants

Participants were 110 14-year-old youths (56 boys and 54 girls) participating in a longitudinal study of adolescent relationships and development. Recruitment announcements (describing the study as an investigation of adolescent well-being and relationships involving questionnaire and psychophysiological assessments) were mailed to parents of all ninth graders in a large urban school district in the United States and distributed to local charter and private schools. Approximately 20% of families receiving announcements contacted our office to request additional information. Participants had to be 14 years of age and living with their natural or adopted mother. Youths with major psychiatric illness, endocrine or cardiovascular disorders, or who were taking medications with cardiovascular or endocrine side effects were excluded. The average age of mothers was 45 ($SD = 6.7$). In all, 82% of participants were White, 3% were African American, 1% were Asian American, 7% were Latino/Latina, and 7% had another or mixed ethnicity. Regarding household income, 13% of families had a household income of less than $20,000, 25% had incomes between $20,000 and $50,000, 29% had incomes between $50,000 and $75,000, and 31% had incomes over $75,000. In all, 31% of youths were living in single-parent households (all of which had experienced parental divorce), and 12% of youths were living with their mother and either a stepfather or a cohabiting male partner. Boys and girls were equally distributed among these residency types.

Procedure

All participants were instructed to refrain from eating, smoking cigarettes, or consuming caffeinated beverages 2 hr before the assessment (verified at the laboratory). During informed consent, participants were informed that the psychophysiological assessment involved the completion of several psychologically challenging tasks. The adolescent was fitted with physiological equipment (described below) and seated alone on a couch, where he or she sat quietly for 5 min to become accustomed to the equipment. Then participants rated their liking of landscape photographs for 3 min (to engage their attention in a restful, pleasant task, following Jennings, Kamarck, Stewart, & Eddy, 1992). SCL during this 3-min epoch served as the measure of baseline SCL. Then they spent 6 min breathing in time with a prerecorded tape (4 s of inhalation and 4 s of exhalation). The last 3 min of this epoch served as the measure of resting RSA (pacing respiration is recommended for accurate assessment of tonic RSA, given associations between RSA and respiratory frequency; Grossman, Stemmler, & Meinhardt, 1990).

After the baseline assessment, an adult male experimenter wearing a lab coat (whom the adolescent had not previously seen) entered the room to administer the stress tasks. He adjusted several video cameras so that they were pointed directly at the participant and informed the participants that their verbal and mathematical skills were about to be evaluated by trained raters. The first task was a mathematical challenge, in which participants had to subtract the number 13 from the number 9,000, in their head, periodically reporting the number that they had reached when a buzzer sounded. During this 5-min task, the research assistant routinely reminded the participant to increase his or her speed and accuracy. Afterward, the adolescent completed emotion-rating scales (serving as a manipulation check for the stressful nature of the tasks). Then the verbal task was initiated. Participants were instructed to prepare a short speech discussing their best qualities and their most significant weaknesses, and were informed that their thoroughness, clarity, and honesty would be compared by trained raters with other adolescents of the same age. After 2 min of preparation, the adolescent discussed her or his positive and negative qualities for 4 min. The research assistant periodically interrupted the participant and asked for more detailed examples. Participants completed another round of emotion ratings after the task was finished. Then the experimenter left the room, and the original research assistant who had greeted the adolescent reentered to unhook and debrief the participant. Participants and their mothers then filled out several additional questionnaires and completed a social interaction task (reported elsewhere). Before leaving, they were instructed on using Palm Pilots for the subsequent 10-day diary assessment. Diary reports were provided each night at bedtime, and the date and time of each entry was automatically recorded. Each family had their own research assistant to check in with them every few days and to be on call to answer questions. In all, only 9% of the nearly 26,000 individual items were missing, and analyses revealed no significant patterns to the missing data. At the completion of the study, adolescents received $90, and their mothers received $60.

Measures

Means, standard deviations, and ranges for all measures are presented in Table 1, stratified by gender (there were no gender differences), and correlations between all study measures are presented in Table 2. Mothers reported on their child's externalizing behaviors using a parent-report version of the Youth Self-Report (Achenbach, 2001). The scale for externalizing behaviors includes 22 items assessing rule-breaking and aggression, measured on a 1–3 scale (a borderline clinical score would be 2.8, and less than 1% of our participants had scores at that level). Reliability for the index was .84. Mothers reported on their own internalizing problems using the Adult Self-Report (Achenbach & Rescorla, 2003). The scale for internalizing problems contains 28 items assessing anxiety, withdrawal, depression, and physical symptomology, rated on a 1–3 scale (a borderline clinical score would be 2.65, and less than 10% of our participants had scores at that level). Reliability for the index was .87. For both measures, higher scores represent greater problems. The Adult Self-Report also assesses annual household income with a 1–5 scale, with the following cutpoints: less than $20,000, $20,000–35,000, $35,000–$50,000, $50,000–75,000, and over $75,000. Preliminary analyses revealed that this variable had a normal distribution, and so it was modeled in continuous form.

Youths' daily negative affect was measured with the Positive and Negative Affect Schedule (Watson, Clark, & Tellegen, 1988). Reliability for the 10 negative affect items was .89. Ratings were made on a 1–5 scale, with higher scores representing greater negative affect, and aggregated across the 10 days of assessment. Youths' mothers completed daily ratings of the quality of their most important interaction with their child that day, using a measure adapted from Reis, Sheldon, Gable, Roscoe, and Ryan (2000). In all, 92% of the interactions were described as "talking with child," 15% as conflicts, 34% as having a meal together, 24% as doing household chores or tasks together, 36% as driving or riding together, 18% as watching television or a movie together, and 15% as going out together, such as for dinner or a movie (participants could endorse more than one of these categories). Mothers rated (on a 1–5 scale) the extent to which the interaction was enjoyable, how much it made them feel close to their child, and how much they felt their child understood and appreciated them. Higher scores represent higher perceived quality. Cronbach's alpha was .85. Ratings were aggregated across the 10 days of assessment. Table 1 shows that the 10-day averages for negative affect and

Table 1
Means and Standard Deviations for Study Variables

	Girls			Boys		
Variable	*M*	*SD*	Range	*M*	*SD*	Range
Externalizing problems (mother-reported)	1.3	.2	(1–2.1)	1.3	.2	(1–1.9)
Average daily negative affect (child-reported)	2.0	.4	(1.3–2.8)	1.8	.5	(1–3.3)
Average daily mother–child interaction quality (mother-reported)	1.3	.3	(1–2.3)	1.3	.5	(1–3.7)
Household income	3.5	1.5	(1–5)	3.6	1.4	(1–5)
Mother's internalizing problems	1.3	.2	(1–1.9)	1.3	.3	(1–1.9)
Baseline RSA (in ms, logged)	5.3	.4	(4.3–6.1)	5.3	.6	(3.6–7.6)
RSA reactivity (task minus baseline)	–1.2	.5	(−2.3–−.03)	–.9	.6	(−3–.1)
Respiration reactivity (task minus baseline)	–2.5	1	(−4.6–.1)	–2.7	1.4	(−5.1–.3)
Baseline SCL (in microSiemens)	6.5	3.8	(1.6–17.5)	8.2	5.7	(.13–19.6)
SCL reactivity (task minus baseline)	1.5	1.3	(4.3–6.2)	2.0	1.7	(−1.4–5.7)

Note. RSA = respiratory sinus arrhythmia; SCL = skin conductance.

perceived interaction quality were relatively low (to facilitate interpretation, a rating of 1 on both scale corresponds to *not at all*, and a rating of 2 corresponds to *a little*).

To assess RSA and SCL, continuous recordings of electrocardiogram (ECG), respiration, and electrodermal activity were amplified and filtered through a James Long Company (Caroga Lake, NY) 4-channel bioamplifier, model LMD-04, with the ECG channel high-pass filter set to .1 Hz and a low-pass filter set to 1000 Hz. ECG was recorded with disposable electrodes placed on the participant's chest in a lead-II configuration. Respiration frequency (i.e., number of seconds for a complete respiratory cycle) was measured by a latex rubber pneumatic bellows girth sensor fitted around the participant's chest. All physiological signals were fed into an A/D interface box and stored on an IBM-compatible computer. The sampling rate was 1000 Hz for all channels. Data analysis was implemented with the James Long Company PHY General Physiology Analysis System software, which permits visual inspection and manual editing of artifacts (Berntson & Stowell, 1998). Approximately 1% of data were edited for artifacts using interpolation of adjacent points. RSA was assessed on the basis of the ECG and respiration data. Interbeat intervals (IBIs) were calculated as the time in milliseconds between successive R waves in the electrocardiogram, and the "peak-to-valley" method was used to derive RSA on the basis of these IBIs. This method computes the heart period difference, in milliseconds, between inspiration onset and expiration onset. For each separate epoch, RSA is calculated as the sum of these "peak-to-valley" measurements (in milliseconds) divided by the number of breaths. Peak-to-valley methods are widely used and show high correlations with other methods of assessing RSA (Grossman, van Beek, & Wientjes, 1990). Following standard practice, RSA values were logged to normalize their distribution.

To measure SCL, James Long Company silver/silver chloride SCL electrodes were placed on the medial phalanges of the first and second fingers of the participant's nondominant hand and fixed in place with velcro cuffs. The area of skin in contact with the electrode was delineated with James Long Company double-sided adhesive collars with a 1-cm diameter hole. James Long Company SCL gel consisting of a citrate salt in propanediol carboxylate polymer base and having a pH of 6.25 was used as the electrolyte medium. A 0.5 V root-mean-square 30 Hz sine wave excitation signal was applied to the skin, and conductance was recorded with a low-pass filter of 10 Hz. Readings were amplified and filtered through the same 4-channel bioamplifier mentioned above, fed into an A/D and stored on an IBM-compatible computer. The sampling rate was 1000 Hz per channel. SCL level is recorded in microsiemens.

Preliminary analyses revealed high consistency in youths' physiological responses to the three different phases of the stress assessment (the 5-min subtraction task, the 2-min speech preparation, and the 4-min speech delivery). Reliability was .92 for RSA and .99 for SCL. Hence, we averaged youths' responses across these three tasks to provide a single "stress task" measure (as recommended by Kamarck et al., 1992). Baseline activity was then subtracted from stress task activity to provide reactivity indices. Because RSA typically declines during stress, larger negative change scores reflect greater RSA suppression, and positive change scores reflect less RSA suppression. To control for the association between RSA and respiration, all analyses included task-minus-baseline change scores for respiratory frequency.

Results

To test our hypotheses, we calculated regression models for three separate psychosocial outcomes: child's externalizing problems (as reported by the child's mother), day-to-day negative affect (reported by the child across the 10-day daily diary assessment), and day-to-day interaction quality (reported by the mother across the 10-day diary assessment). In each case, we tested whether individual differences in baseline and stress-induced ANS functioning moderate adolescents' sensitivity to family environmental factors (specifically, two-parent vs. single-parent family structure and mothers' internalizing problems). We used simple slope tests to compare the applicability of a dual-risk versus a DS perspective for different combinations of ANS moderators, environmental factors, and outcomes. Table 3 presents the results of our prediction models, and Table 4 summarizes the results of the simple slope tests. We calculated regression models using full information maximum likelihood (FIML) estimation (implemented with AMOS structural equation software; Arbuckle, 2006), which is superior to listwise deletion for handling missing data (Enders, 2001; Jeličič, Phelps, & Lerner, 2009). FIML is robust to departures from normality assumptions and performs well even with low sample sizes (Graham, 2009). Models included both males and females (for a total $N = 110$), and in addition to testing for two-way interactions between ANS parameters and environmental factors (using cross-product terms), we tested for three-way interactions involving gender. All continuous variables were centered, and to facilitate tests of interactions between family structure and gender, they were both effect coded (two-parent households were coded $-.5$, and single-parent households were coded .5; males were coded $-.5$, and females were coded .5). Household income was included in all models as a covariate (it did not interact with other variables in the model, nor were there significant interactions among the ANS parameters).

Before presenting the results of these models, several significant associations among study variables bear mention: Specifically, mothers of adolescents in single-parent households had greater internalizing problems, $t(109) = 4.3$; lower household incomes, $t(109) = -5.5$; and described their children as having higher externalizing problems, $t(109) = 2.6$, all $ps < .01$. Youths with greater externalizing problems had higher daily negative affect, and their mothers gave higher ratings of the quality of day-to-day mother–child interactions. Mothers with greater internalizing problems also gave higher ratings of the quality of daily mother–child interactions. An additional partial correlation analysis established that the correlation between youths' externalizing problems and mother's perceptions of interaction quality was attributable to their joint association with mother's internalizing problems. The fact that mothers with greater internalizing problems reported higher quality mother–child interactions might reflect the fact that high-internalizing mothers may deliberately seek comfort and reassurance from family interactions. For both SCL and RSA, youths with higher baseline levels showed higher reactivity. Such correlations are common (Berntson, Uchino, & Cacioppo, 1994), which is why it is standard practice to include baseline measures as covariates when analyzing reactivity.

Table 2
Correlations Among Study Variables

Variable	1	2	3	4	5	6	7	8	9
1. Externalizing problems (mother-reported)	—								
2. Average daily negative affect (child-reported)	.26**	—							
3. Average daily mother-perceived interaction quality	.25**	.08	—						
4. Household income	−.16	.09	−.15	—					
5. Mother's internalizing problems	.32**	.09	.29**	.40**	—				
6. Baseline RSA	.07	.25*	−.10	−.05	.07	—			
7. RSA reactivity	.11	−.10	.08	−.03	.10	−.54**	—		
8. Respiratory reactivity	.13	.13	.15	−.09	−.03	−.15	.57**	—	
9. Baseline SCL	−.10	.20	.04	.21*	−.21*	.13	−.26*	−.13	—
10. SCL reactivity	.05	.09	−.07	.05	−.13	.26*	−.04	.07	.52

Note. RSA = respiratory sinus arrhythmia; SCL = skin conductance.
* $p < .05$. ** $p < .01$.

As shown in Table 3, the final regression model for externalizing problems contained a total of 17 predictors, and two significant three-way interactions (Gender × Family Structure × SCL Reactivity and Gender × Family Structure × RSA Reactivity). The model *R* squared was .38 (without the interaction terms, the model *R* squared was .18). The final model for daily negative affect contained a total of 19 predictors and two significant three-way interactions (Gender × Mother's Internalizing Problems × SCL Reactivity and Gender × Family Structure × RSA Reactivity). The model *R* squared was .47 (without the interaction terms, the model *R* squared was .18). The final model for mother-perceived interaction quality contained a total of 18 predictors and two significant three-way interactions (Gender × Mother's Internalizing Problems × Baseline RSA and Gender × Family Structure × SCL Reactivity). The model *R* squared was .54 (without the interaction terms the *R* squared was .18). For each moderating effect, we conducted simple slope tests (defining "high" and "low" groups as 1 *SD* above and below the sample mean) to test our specific hypotheses within the gender showing the interaction effect. None of the standardized coefficients for the final models were greater than 1.0 (an indicator of model misspecification).

Moderating Effects of SCL Reactivity

Hypothesis 1 predicted that adolescents with greater SCL stress reactivity would show stronger associations between negative environments and negative outcomes than adolescents with low SCL reactivity. We found support for this prediction for boys' externalizing problems, girls' mother-perceived interaction quality, and girls' day-to-day negative affect. Specifically, living in a single-mother household was positively associated with externalizing problems among boys with high SCL reactivity ($b = .44$, $p < .05$), but negatively associated with externalizing problems among boys with low SCL reactivity ($b = -.27$, $p < .05$). Similarly, living in a single-mother household was negatively associated with mother-perceived interaction quality among girls with high SCL reactivity ($b = -.43$, $p < .05$), but positively associated with interaction quality among girls with low SCL reactivity ($b = .53$, $p < .05$). Finally, mothers' internalizing problems were positively associated with day-to-day negative affect among girls with high SCL reactivity ($b = 1.8$, $p < .05$), but negatively associated with negative affect among girls with low SCL reactivity ($b = -8.1$, $p < .001$). Figures 1, 2, and 3 display these effects: Each graph displays regression slopes relating youths' outcomes (respectively, boys externalizing problems, girls' mother-perceived interaction quality, and girls' negative affect) to their family environments (family structure for Figures 1 and 2, mothers' internalizing problems for Figure 3) stratified by SCL reactivity. According to the guidelines of Belsky et al. (2007), the interaction effects depicted in Figures 1 and 2 appear consistent with a dual-risk perspective, whereas the crossover interaction in Figure 3 appears to fit a DS perspective. Simple slope tests confirmed these impressions (summarized in Table 4). Within single-mother households, SCL reactivity was positively associated with boys' externalizing problems ($b = .20$, $p < .05$), and negatively associated with girls' mother-perceived interaction quality ($b = -.39$, $p < .05$), but the direction of these associations was not reversed in two-parent households, contrary to a DS perspective ($b_{\text{boys' externalizing}} = -.01$, *ns*; $b_{\text{girls' interaction quality}} = -.02$, *ns*). Yet in households with high-internalizing mothers, SCL reactivity was positively (but not significantly) associated with negative affect among girls ($b = .2$, *ns*), and this effect was reversed in households with low-internalizing mothers ($b = -.29$, $p < .05$), consistent with a DS perspective.

There was an additional unexpected moderating effect of SCL reactivity for girls' externalizing problems: Living in a single-mother household was positively associated with externalizing problems among girls with low SCL reactivity (rather than high SCL reactivity, as we had predicted; $b = .35$, $p < .05$), but unassociated with externalizing problems among girls with high SCL reactivity ($b = -.08$, *ns*). Figure 4 displays regression slopes relating girls' externalizing problems to family structure, stratified by SCL reactivity. Additional simple slope tests found that the association between SCL reactivity and externalizing problems was not reversed for single-mother versus two-parent households. Rather, these associations were not statistically significant in either household ($b_{\text{single parent}} = -.09$, $b_{\text{two parent}} = .05$, *ns*).

Table 3
Results of Regression Models Predicting Youth's Externalizing Problems, Daily Negative Affect, and Daily Mother–Child Interaction Quality

Independent variable	*b*	*SE*	95% CI
Externalizing problems			
Intercept	1.3***	.02	[1.25, 1.34]
Gender	−.05	.05	[−.14, .05]
Household Income	.002	.02	[−.03, .03]
Family structure	.1	.06	[−.01, .21]
Mother's internalizing problems	.28**	.10	[.09, .48]
Baseline RSA	.04	.05	[−.06, .14]
RSA reactivity	.08	.06	[−.04, .20]
Respiration reactivity	.02	.02	[−.02, .07]
Baseline SCL	.001	.01	[−.01, .01]
SCL reactivity	.03	.03	[−.03, .09]
Family Structure × SCL Reactivity	.02	.06	[−.09, .13]
Family Structure × RSA Reactivity	.12	.08	[−.04, .28]
Gender × Family Structure	.06	.10	[−.14, .26]
Gender × SCL Reactivity	−.12*	.05	[−.22, −.02]
Gender × RSA Reactivity	−.28***	.08	[−.43, −.12]
Gender × Family Structure × SCL Reactivity	−.35***	.10	[−.55, −.15]
Gender × Family Structure × RSA Reactivity	.31*	.17	[−.02, .64]
Average daily negative affect			
Intercept	1.9***	.05	[1.81, 1.99]
Gender	.27**	.10	[.08, .46]
Household income	.05	.04	[−.02, .13]
Family structure	.06	.12	[−.18, .30]
Mother's internalizing problems	.31	.25	[−.17, .79]
Baseline RSA	.34*	.14	[.07, .60]
RSA reactivity	.19	.14	[−.08, .47]
Respiration reactivity	.05	.05	[−.05, .14]
Baseline SCL	.01	.01	[−.02, .03]
SCL reactivity	−.01	.05	[−.09, .09]
Mother's Internalizing × SCL Reactivity	.39	.25	[−.10, .89]
Family Structure × RSA Reactivity	−.38*	.19	[−.75, −.01]
Gender × Mother's Internalizing	.09	.50	[−.88, 1.06]
Gender × Family Structure	.25	.22	[−.18, .68]
Gender × SCL Reactivity	−.06	.08	[−.22, .10]
Gender × RSA Reactivity	.82***	.24	[.36, 1.29]
Gender × Baseline RSA	.73**	.27	[.19, 1.26]
Gender × Mother's Internalizing × SCL Reactivity	1.49**	.51	[.50, 2.48]
Gender × Family Structure × RSA Reactivity	1.12**	.36	[.41, 1.84]
Mother-perceived interaction quality			
Intercept	1.4***	.04	[1.32, 1.48]
Gender	−.04	.09	[−.22, .14]
Household income	.03	.03	[−.03, .09]
Family structure	.12	.11	[−.09, .33]
Mother's internalizing problems	.66***	.18	[.31, 1.01]
Baseline RSA	.14	.10	[−.34, .05]
RSA reactivity	−.17	.11	[−.39, .04]
Respiration reactivity	.12*	.04	[.04, .19]
Baseline SCL	.02*	.01	[.01, .04]
SCL reactivity	−.08	.06	[−.19, .03]
Mother's Internalizing × Baseline RSA	−2.1***	.39	[−2.9, −1.37]
Family Structure × SCL Reactivity	−.08	.10	[−.28, .12]
Gender × Mother's Internalizing	−.69	.33	[−1.34, −.03]
Gender × Family Structure	−.13	−.20	[−.53, .26]
Gender × SCL Reactivity	−.26*	.10	[−.46, −.06]
Gender × Baseline RSA	.55***	.16	[.24, .86]
Gender × Mother's Internalizing × Baseline RSA	2.7***	.79	[1.2, 4.3]
Gender × Family Structure × SCL Reactivity	−.60**	.19	[−.97, −.23]

Note. CI = confidence interval; RSA = respiratory sinus arrhythmia; SCL = skin conductance.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Table 4
Summary of Simple Slope Tests Comparing Dual-Risk Versus Differential Susceptibility (DS) Perspectives

Perspective				Poorer environment predicts poorer outcome in high-susceptible group?	Poorer environment predicts poorer outcome in low-susceptible group?	Susceptibility predicts poorer outcomes in poorer environments?	Susceptibility predicts better outcomes in better environment?
Dual-risk model predictions				yes	yes or no	yes	no
DS predictions				yes	no	yes	yes
Moderator	Environment	Outcome	Gender				
SCL reactivity	Two-parent vs. single parent	Externalizing	Boys	yes	no	yes	no
	Two-parent vs. single parent	Mother-perceived interaction quality	Girls	yes	no	yes	no
	Mother's internalizing	Negative affect	Girls	yes	no	yes	yes
	Two-parent vs. single parent	Externalizing	Girls	no	yes	No	no
Baseline RSA	Mother's internalizing	Mother-perceived interaction quality	Boys	no	no	No	no
RSA reactivity	Two-parent vs. single parent	Externalizing	Girls	yes	no	no	yes
	Two-parent vs. single parent	Negative affect	Boys	no	no	no	no

Note. SCL = skin conductance; RSA = respiratory sinus arrhythmia.

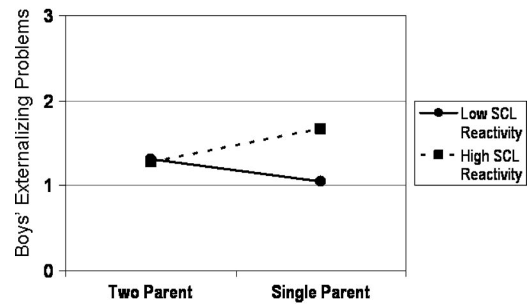

Figure 1. Estimated slopes relating boys' externalizing problems to family structure, stratified by skin conductance (SCL) reactivity.

Moderating Effects of Baseline RSA and RSA Reactivity

Hypothesis 2 predicted that adolescents with lower baseline RSA would show stronger associations between negative environments and negative outcomes. This prediction was not supported. We detected only one interaction effect involving baseline RSA, and this effect was unexpected. Specifically, among boys with low baseline RSA, mothers' internalizing problems was positively associated with day-to-day mother-perceived interaction quality (contrary to the predicted negative association; $b = 2.7$, $p < .01$), yet among boys with higher baseline RSA, mothers' internalizing problems were negatively associated with day-to-day mother-perceived interaction quality ($b = -.89$, $p < .01$). Figure 5 displays the slopes relating mother-perceived interaction quality to mothers' internalizing problems, stratified by boys' baseline RSA. Simple slope tests examined whether the association between boys' baseline RSA and mother-perceived interaction quality was reversed for boys with low-internalizing versus high-internalizing mothers and found that this was the case. Baseline RSA was positively associated with mother-perceived interaction quality for boys with low-internalizing mothers ($b = .36$, $p < .05$), but negatively associated with interaction quality for boys with high-internalizing mothers ($b = -1.2$, $p < .01$). There was also a significant interaction between gender and baseline RSA in predicting negative affect: Among girls, baseline RSA was positively associated with negative affect ($b = .68$, $p < .01$), but this was not the case for boys ($b = -.06$, *ns*).

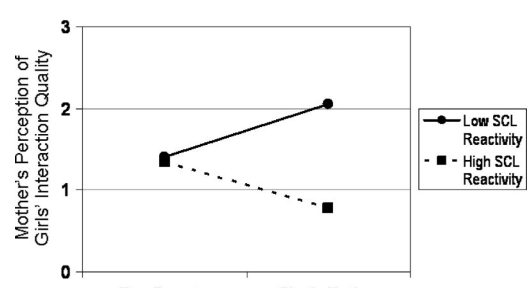

Figure 2. Estimated slopes relating girls' daily mother-perceived interaction quality to family structure, stratified by skin conductance (SCL) reactivity.

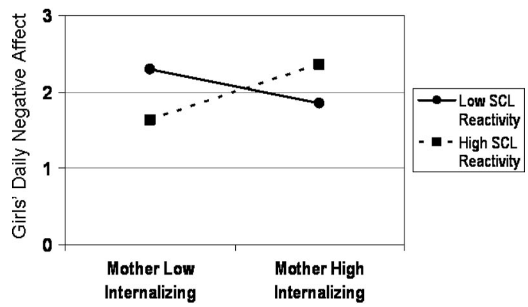

Figure 3. Estimated slopes relating girls' daily negative affect to their mothers' internalizing problems, stratified by skin conductance (SCL) reactivity.

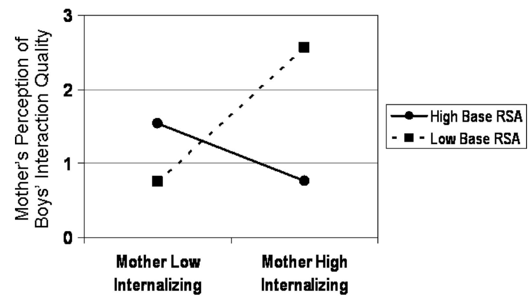

Figure 5. Estimated slopes relating boys' daily mother-perceived interaction quality to their mothers' internalizing problems, stratified by baseline respiratory sinus arrhythmia (RSA).

Hypothesis 3 predicted that youths with less RSA suppression (i.e., more positive task-minus-baseline change scores) would show stronger associations between environmental risk factors and psychosocial outcomes. Support for this prediction was found for girls' externalizing problems: Specifically, living in a single-mother household was positively associated with externalizing problems among girls with less RSA suppression ($b = .36$, $p < .01$), but unassociated with externalizing problems among girls with greater RSA suppression ($b = -.10$, *ns*). Figure 6 displays the slopes relating girls' externalizing problems to family structure, stratified by RSA suppression. Additional simple slope tests were conducted to examine whether the association between RSA suppression and externalizing problems was reversed for two-parent versus single-parent households: Partially consistent with the DS model, less RSA suppression (i.e., more positive RSA reactivity) was not significantly associated with externalizing problems in single-parent households ($b = .13$, *ns*), but it was negatively associated with externalizing problems in two-parent households ($b = -.34$, $p < .01$). Lastly, among boys, we found an unexpected interaction between RSA suppression and negative affect: Living in a single-mother household was inversely associated with negative affect among boys with less RSA suppression (contrary to the positive association that we had predicted; $b = -.65$, $p < .01$), but positively associated (albeit only at trend level) with negative affect among boys with greater RSA suppression ($b = .43$, $p < .10$). Figure 7 displays the slopes relating boys' negative affect to family structure, stratified by RSA suppression. Additional simple slope tests examined whether the association between RSA suppression and negative affect was reversed for two-parent versus single-parent households: Less RSA suppression (i.e., more positive RSA reactivity scores) was unassociated with externalizing problems in two-parent households ($b = .26$, *ns*), but it was negatively associated with negative affect in single-parent households ($b = -.7$, $p < .001$).

Discussion

The present research demonstrates that the degree to which individual differences in ANS functioning moderate adolescents' susceptibility to negative and positive family environments depends on the specific combination of outcomes, contexts, and moderators, and also varies by gender. Overall, moderating effects involving family structure were more consistent with a dual-risk than a DS approach, whereas moderating effects involving mothers' internalizing problems showed limited support for a DS perspective (as summarized in Table 4). All of the moderating effects were gender specific, consistent with a growing body of evidence for distinct gender differences in links between ANS activity and children's psychosocial functioning (El-Sheikh et al., 2001; El-Sheikh et al., 2007; Erath et al., 2011; Gordis et al., 2010; Greaves-Lord et al., 2010; Sloan et al., 2001). These findings suggest that individual differences in SNS and PNS functioning do not function as global sensitivity factors, but have gender-specific implications for youths' psychosocial functioning in different domains and within different environments.

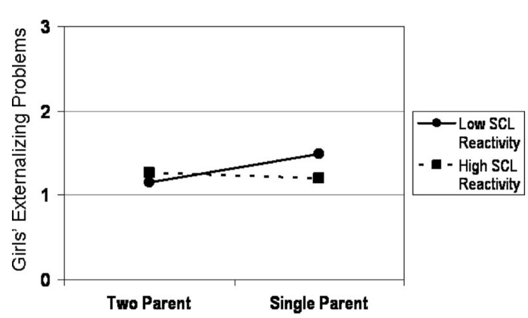

Figure 4. Estimated slopes relating girls' externalizing problems to family structure, stratified by skin conductance (SCL) reactivity.

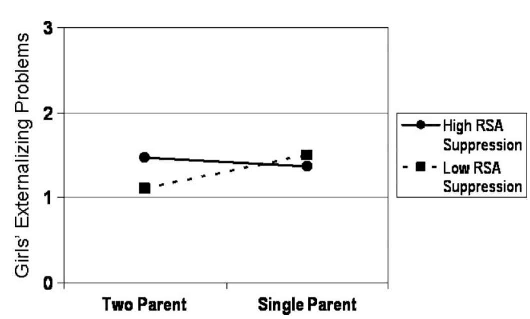

Figure 6. Estimated slopes relating girls' externalizing problems to family structure, stratified by respiratory sinus arrhythmia (RSA) suppression.

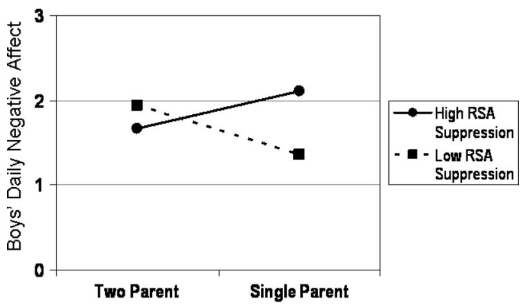

Figure 7. Estimated slopes relating boys' daily negative affect to family structure, stratified by respiratory sinus arrhythmia (RSA) suppression.

Moderating Effects of SNS Functioning

Our findings support the notion that adolescents with heightened SNS reactivity to stress, manifested here by heightened SCL reactivity, show greater vulnerability to negative environmental contexts. Youths with elevated SCL reactivity showed more negative psychosocial outcomes (lower mother-perceived interaction quality among girls and higher externalizing problems among boys) if they lived in single-parent versus two-parent households. These patterns parallel similar research on children, for example, showing that children with elevated SCL reactivity show heightened vulnerability (with respect to internalizing and externalizing problems) to parental depression and conflict (Cummings et al., 2007; El-Sheikh et al., 2007) and more growth in externalizing problems over time when exposed to harsh parenting (Erath et al., 2011). Yet notably, the patterns we detected are more consistent with a dual-risk than a DS moderating effect. According to the DS model, youths with elevated SCL reactivity should not only show poorer outcomes in poorer environments, but they should also demonstrate more positive outcomes in more positive environments. The latter was not found to be the case with respect to elevated SCL reactivity.

In contrast, the interaction effect between girls' SCL reactivity and their mother's internalizing problems in predicting daily negative affect is consistent with the DS model. Specifically, heightened SCL reactivity was associated with elevated daily negative affect among girls with high-internalizing mothers, but lower daily negative affect among girls with low-internalizing mothers. Hence, as argued by Boyce and Ellis (2005), heightened SNS stress reactivity does not appear to function as a global risk factor for girls' adjustment problems; rather, its implications depend on girls' environments, and also on the outcome in question. For girls' externalizing problems, we found that it was lower rather than higher SCL reactivity that predicted higher risk for girls in single-parent homes, consistent with research by El-Sheikh and colleagues (2007), who found that lower SCL reactivity predicted stronger associations between parents' marital conflict and boys' externalizing problems.

Taken together, all but one of the SCL moderating effects involved family structure, and these effects conformed to the dual-risk perspective (as summarized in Table 4). Notably, even the unexpected vulnerability conferred by lower SCL reactivity for girls' externalizing problems fit the dual-risk model, given that this association was not reversed for girls in two-parent versus single-parent homes. In contrast, the crossover interaction effect between SCL reactivity and mothers' internalizing problems fits the DS model (as specified by Belsky et al, 2007). One possible interpretation is that contrasting two-parent and single-parent homes does not provide sufficient variation regarding the positive features of family environments to fully test the DS model. Considering the range of positive and negative characteristics that occur in two-parent households, this group is more accurately considered "neutral" (in comparison to single-parent families) rather than "enhanced." In contrast, comparing mothers who are extremely high or low on internalizing problems provides for a more valid examination of the DS model, because low-internalizing mothers are lower *than average* (although all mothers were within a normal range of functioning: Mothers' scores for internalizing problems were comparable to published norms for nonreferred women in the same age group, and only 10% had scores at a borderline clinical range; Achenbach & Rescorla, 2003). Hence, future testing of the DS model requires assessing a broader range of positive family environmental characteristics.

A key question for future research involves pinpointing the specific psychobiological mechanisms by which heightened SNS stress reactivity relates to heightened environmental susceptibility, and determining why the implications of SNS reactivity are specific to certain domains of functioning. Notably, in adults heightened SNS reactivity has been linked to repressive coping and emotional suppression (Diamond, Hicks, & Otter-Henderson, 2006; Roisman, Tsai, & Chiang, 2004). Hence, one possibility is that youths with heightened SNS reactivity possess a general predisposition to avoid stress and a repressive coping style, which may render them vulnerable to adverse psychosocial outcomes when exposed to the sustained stressors that accompany single-parent households and/or mothers with high internalizing problems.

Moderating Effects of PNS Functioning

Our findings for PNS functioning were sharply differentiated by gender. First, our analyses of baseline RSA detected only one moderating effect, and the nature of this effect was unexpected. Among boys with low baseline RSA, mothers' internalizing problems were positively associated with mother-perceived interaction quality (contrary to the negative association that we predicted among low-RSA boys). Given that the ratings of interaction quality were provided by mothers, this unexpected finding might have more to do with mothers of sons with low baseline RSA than with the sons themselves: Recall that low baseline RSA has been associated with restricted emotionality, poor affective information processing, and lower empathy (reviewed in Thayer & Lane, 2000). Perhaps these characteristics make boys with low baseline RSA "easier" interaction partners for mothers with high internalizing problems. In contrast, boys with higher baseline RSA might be more likely to convey and detect cues of emotional distress in their mothers during social interactions, which might prove taxing to mothers struggling with internalizing problems. On this point, it is notable that the expected positive association between baseline RSA and mother-perceived interaction quality was detected for boys with low-internalizing mothers. Hence, it was only high-internalizing mothers who perceived interactions with low-RSA sons more positively than interactions with high-RSA sons. This finding suggests the importance of understanding the fit between a youth's capacities and needs and those of other family members when evaluating the quality of family interactions.

As for RSA reactivity to stress, we expected that adolescents with less RSA suppression during stress who lived in more negative family environments would show more negative psychosocial outcomes. This was found for girls, but not for boys. Among girls with less RSA suppression, living in a single-parent household was associated with greater externalizing problems, whereas this was not the case for girls with greater RSA suppression. Furthermore, consistent with the DS model, lower levels of RSA suppression predicted more *positive* outcomes (i.e., lower internalizing problems) in the more positive environment of two-parent homes. Among boys with less RSA suppression during stress, however, there was a negative association between living in a single-parent home and day-to-day negative affect, and a positive association between these variables for boys with greater RSA suppression. This pattern is directly contrary to that observed in girls and is particularly notable given that previous research on both children and adults has yielded a mixed pattern of findings regarding whether failure to suppress RSA during stress indexes emotion-regulation deficits (Hessler & Katz, 2007; Neumann, Sollers, Thayer, & Waldstein, 2004) or whether it reflects heightened regulatory effort in the service of social engagement (Beauchaine, 2001; Egizio et al., 2008; Thayer & Lane, 2000). Our findings suggest that the answer to this question depends on the youth's environment and also on gender. Among girls, higher levels of RSA during stress may reflect deficits in the capacity to flexibly respond to stress with a withdrawal of PNS activity, indicative of autonomic rigidity. Among boys, however, higher levels of RSA during stress might indicate the engagement of active regulatory effort aimed at maintaining adaptive functioning in the face of challenge. Katz (2007) has argued that the heightened attentiveness and regulatory effort facilitated by increased PNS activity might help children in challenging environments to monitor their surroundings for changes in key parameters (such as a parent's negative mood) and to maintain effective control over emotions and behavior. Accordingly, children in stressful environments might develop a chronic pattern of stress-induced increases in PNS activity.

Yet, if increased PNS activity is specifically adaptive for individuals coping with chronic regulatory challenges, it might not prove so adaptive for individuals in more normative environments. In particular, many researchers conceptualize regulatory capacity as relatively finite, analogous to a muscle that tires upon repeated use (reviewed in Vohs, Baumeister, & Ciarocco, 2005). Hence, children and adolescents who routinely respond to stress with increased regulatory effort (indexed by increased PNS activity) might eventually experience regulatory "fatigue," leaving them vulnerable to eventual failures of self-control and poorer socioemotional outcomes. Hence, individual differences in children's RSA suppression during stress may reflect "trade-offs" between autonomic flexibility versus effortful self-control, and the implications of these individual differences may be highly specific to the child's environment. Examining the conditions under which high versus low RSA suppression under stress indicates vulnerability versus resilience in the face of environmental challenge, and the implications of these patterns for socioemotional functioning in diverse environments is a key direction for future research comparing dual-risk versus DS models. Along these lines, it is also notable that we found that girls with higher *baseline* RSA had higher day-to-day negative affect, inconsistent with the notion of baseline RSA as an index of effective emotion regulation. As suggested by Katz (2007), this might reflect the fact that girls attempting to cope with adjustment challenges (potentially manifested by their high-externalizing problems) may develop chronically elevated levels of RSA over time.

Our gender-differentiated results for PNS functioning concord with previous research documenting gender differences in the links between PNS functioning and child and adolescent outcomes (Graziano et al., 2007; Greaves-Lord et al., 2010; Sloan et al., 2001). Some have explained these gender differences by arguing that girls typically receive more explicit socialization pressures than boys with respect to the regulation of negative emotions such as anger, and over time this might moderate links between their underlying physiological capacities and their expressive behavior (Fabes & Eisenberg, 1992; Graziano et al., 2007). Hence, the aforementioned trade-off between autonomic flexibility (RSA suppression) and effortful self-control (increased RSA) might be weighted differently for adolescent boys versus girls. There may also be basic biological sex differences to consider, given that there appear to be sex differences in the neural modulation of parasympathetic regulation of heart rate (Åhs, Sollers, Furmark, Fredrikson, & Thayer, 2009).

Limitations and Directions for Future Research

Our research makes important contributions to the present literature on ANS functioning and adolescent development for several reasons: (a) We tested moderating effects for both SNS and PNS activity, during rest and during laboratory-induced stress; (b) we examined two salient environmental factors—family structure and mother's internalizing problems; (c) we included a diverse and ecologically valid set of outcomes—externalizing problems, day-to-day negative affect, and daily mother-perceived interaction quality—drawing on questionnaire and daily diary data collected from both youths and their mothers; (d) we examined whether each moderating effect was more consistent with a dual-risk versus a DS model (as summarized in Table 4).

Nonetheless, our research has several limitations that must be taken into account when interpreting the findings. First, our sample is predominantly White, reflecting the demographics of the state in which we collected the data. Future research should seek to replicate these findings in families with different ethnic, cultural, and class backgrounds, especially given cultural variations in the parenting and family roles of mothers versus fathers (Coleman & Ganong, 2004). Larger sample sizes are also important: Although our study had sufficient power to detect moderate effects, some DS effects involving different environmental domains may be small in magnitude, requiring larger studies to ensure adequate power. It is also important to replicate our findings in families with a broader range of family functioning. Overall, our participants were fairly well adjusted (as noted above, very few had levels of internalizing or externalizing problems that approached standard clinical cutoffs), and it is possible that some of the hypothesized moderating effects would be more discernable in families with greater intrapsychic and interpersonal challenges. We also do not know the degree to which our participants faced childhood adversity, which may have interacted with ANS reactivity to shape their adjustment trajectories. Also, because the majority of our single-mother households had experienced a divorce, we could not robustly disentangle effects of single parenthood from effects of divorce, which is obviously a salient stressor for children and adolescents.

Another important direction for future research concerns the timing of the moderating effects we detected. For example, if heightened SNS activity exacerbates the deleterious consequences of living in a single-mother household at age 14, do these effects persist? On one hand, perhaps the tendency for biologically susceptible children to develop poorer outcomes in the face of environmental stress gets progressively larger over time, as youths' emotion regulation resources are consistently overtaxed. Alternatively, perhaps such children eventually adapt to environmental stressors, albeit perhaps at a slower rate than other children. Future longitudinal research is necessary to investigate this question. A key weakness of the present study is our inability to specify causal pathways between autonomic functioning and adjustment outcomes (i.e., whether adolescents develop certain patterns of ANS reactivity in the process of coping with environmental stressors or whether their coping responses are influenced by their ANS patterns). These possibilities require long-term longitudinal investigation.

Such investigations should also take care to incorporate key measures of positive environmental factors as well as environmental risks. DS models emphasize the fact that high-reactive children might show heightened sensitivity to both positive and negative features of their environments. Hence, in households where environmental "negatives" (economic stress, divorce, etc.) are coupled with "positives" (high-quality parenting, warm contact with extended family members, etc.), the tendency for high-reactive youths to show poorer outcomes in the face of contextual risks might be "counteracted" by their responsiveness to *positive* environmental characteristics over time. Support for this possibility is provided by research showing that highly supportive mothering can buffer many youths from the potential negative consequences of living in a single-parent household (Pan & Farrell, 2006). Charting relations among ANS functioning and a range of positive and negative contextual factors is critical for understanding the mechanisms underlying child and adolescent adjustment in different environments over time.

Conclusion

The present research provides strong support for the notion that individual differences in youths' ANS functioning moderate their sensitivity to family environment characteristics. Our findings are particularly valuable for clarifying how such moderating effects vary across different *combinations* of contexts and autonomic parameters, and also by gender. This variability is consistent with previous research on children (e.g., El-Sheikh et al., 2007) and highlights the importance of testing dual-risk and DS models across a wide variety of outcomes and environmental challenges. This research contributes to ongoing efforts to develop nuanced, multifactorial models of adolescent psychosocial development that systematically integrate information on youths' biologically based individual differences and their environmental risks and supports in order to explain variation in developmental trajectories.

References

Achenbach, T. M. (2001). *Manual for the ASEBA Youth Self-Report and Profiles.* Burlington: University of Vermont, Research Center for Children, Youth, & Families.

Achenbach, T. M., & Rescorla, L. A. (2003). *Manual for the ASEBA Adult Self-Report and Profiles.* Burlington: University of Vermont, Research Center for Children, Youth, & Families.

Åhs, F., Sollers, J. J., III, Furmark, T., Fredrikson, M., & Thayer, J. F. (2009). High-frequency heart rate variability and cortico-striatal activity in men and women with social phobia. *NeuroImage, 47,* 815–820. doi:10.1016/j.neuroimage.2009.05.091

Akselrod, S., Gordon, D., Snidman, N., Shannon, D. C., & Cohen, R. J. (1985). Hemodynamic regulation: Investigation by spectral analysis. *American Journal of Physiology: Heart and Circulatory Physiology, 85,* 867–875.

Arbuckle, J. L. (2006). Amos (Version 7.0) [Computer program]. Chicago, IL: SPSS.

Austin, M. A., Riniolo, T. C., & Porges, S. W. (2007). Borderline personality disorder and emotion regulation: Insights from the Polyvagal Theory. *Brain and Cognition, 65,* 69–76. doi:10.1016/j.bandc.2006.05.007

Beauchaine, T. P. (2001). Vagal tone, development, and Gray's motivational theory: Toward an integrated model of autonomic nervous system functioning in psychopathology. *Development and Psychopathology, 13,* 183–214. doi:10.1017/S0954579401002012

Belsky, J., Bakermans-Kranenburg, M. J., & van Ijzendoorn, M. H. (2007). For better and for worse: Differential susceptibility to environmental influences. *Current Directions in Psychological Science, 16,* 300–304. doi:10.1111/j.1467-8721.2007.00525.x

Belsky, J., & Pluess, M. (2009). Beyond diathesis stress: Differential susceptibility to environmental influences. *Psychological Bulletin, 135,* 885–908. doi:10.1037/a0017376

Berntson, G. G., & Stowell, J. (1998). EEG artifacts and heart period variability: Don't miss a beat! *Psychophysiology, 35,* 127–132. doi:10.1111/1469-8986.3510127

Berntson, G. G., Uchino, B. N., & Cacioppo, J. T. (1994). Origins of baseline variance and the Law of Initial Values. *Psychophysiology, 31,* 204–210. doi:10.1111/j.1469-8986.1994.tb01042.x

Bornstein, M. H., & Suess, P. E. (2000a). Child and mother cardiac vagal tone: Continuity, stability, and concordance across the first 5 years. *Developmental Psychology, 36,* 54–65. doi:10.1037/0012-1649.36.1.54

Bornstein, M. H., & Suess, P. E. (2000b). Physiological self-regulation and information processing in infancy: Cardiac vagal tone and habituation. *Child Development, 71,* 273–287. doi:10.1111/1467-8624.00143

Bosch, N. M., Riese, H., Ormel, J., Oldehinkel, A. J., & Verhulst, F. (2009). Stressful life events and depressive symptoms in young adolescents: Modulation by respiratory sinus arrhythmia? The TRAILS study. *Biological Psychology, 81,* 40–47. doi:10.1016/j.biopsycho.2009.01.005

Boucsein, W. (1991). *Electrodermal activity.* New York, NY: Plenum Press.

Boyce, W. T., Chesney, M., Alkon, A., & Tschann, J. M. (1995). Psychobiologic reactivity to stress and childhood respiratory illnesses: Results of two prospective studies. *Psychosomatic Medicine, 57,* 411–422.

Boyce, W. T., & Ellis, B. J. (2005). Biological sensitivity to context: I. An evolutionary-developmental theory of the origins and functions of stress reactivity. *Development and Psychopathology, 17,* 271–301. doi:10.1017/S0954579405050145

Breivik, K., & Olweus, D. (2006). Adolescents' adjustment in four post-divorce family structures: Single mother, stepfather, joint physical custody and single father families. *Journal of Divorce & Remarriage, 44,* 99–124. doi:10.1300/J087v44n03_07

Breivik, K., Olweus, D., & Endresen, I. (2009). Does the quality of parent-child relationships mediate the increased risk for antisocial behavior and substance use among adolescents in single-mother and single-father families? *Journal of Divorce & Remarriage, 50,* 400–426. doi:10.1080/10502550902766282

Brosschot, J. F., & Thayer, J. F. (1998). Anger inhibition, cardiovascular recovery, and vagal function: A model of the link between hostility and cardiovascular disease. *Annals of Behavioral Medicine, 20,* 326–332. doi:10.1007/BF02886382

Bubier, J. L., Drabick, D. A. G., & Breiner, T. (2009). Autonomic functioning moderates the relations between contextual factors and externalizing behaviors among inner-city children. *Journal of Family Psychology, 23,* 500–510. doi:10.1037/a0015555

Calkins, S. D., & Dedmon, S. E. (2000). Physiological and behavioral regulation in two-year-old children with aggressive/destructive behavior problems. *Journal of Abnormal Child Psychology, 28,* 103–118. doi:10.1023/A:1005112912906

Calkins, S. D., Graziano, P. A., & Keane, S. P. (2007). Cardiac vagal regulation differentiates among children at risk for behavior problems. *Biological Psychology, 74,* 144–153. doi:10.1016/j.biopsycho.2006.09.005

Calkins, S. D., & Keane, S. P. (2004). Cardiac vagal regulation across the preschool period: Stability, continuity, and implications for childhood adjustment. *Developmental Psychobiology, 45,* 101–112. doi:10.1002/dev.20020

Coleman, M., & Ganong, L. H. (Eds.). (2004). *Handbook of contemporary families.* Thousand Oaks, CA: Sage.

Cummings, E. M., & Davies, P. T. (2002). Effects of marital conflict on children: Recent advances and emerging themes in process-oriented research. *Journal of Child Psychology and Psychiatry, 43,* 31–63. doi:10.1111/1469-7610.00003

Cummings, E. M., El-Sheikh, C. D., Kouros, C. D., & Keller, P. S. (2007). Children's skin conductance reactivity as a mechanism of risk in the context of parental depressive symptoms. *Journal of Child Psychology and Psychiatry, 48,* 436–445. doi:10.1111/j.1469-7610.2006.01713.x

Del Giudice, M., Ellis, B. J., & Shirtcliff, E. A. (2011). The adaptive calibration model of stress responsivity. *Neuroscience and Biobehavioral Reviews, 35,* 1562–1592. doi:10.1016/j.neubiorev.2010.11.007

Diamond, L. M., Hicks, A. M., & Otter-Henderson, K. A. (2006). Physiological evidence for repressive coping among avoidantly attached adults. *Journal of Social and Personal Relationships, 23,* 205–229. doi:10.1177/0265407506062470

Doussard-Roosevelt, J. A., Montgomery, L. A., & Porges, S. W. (2003). Short-term stability of physiological measures in kindergarten children: Respiratory sinus arrhythmia, heart period, and cortisol. *Developmental Psychobiology, 43,* 230–242. doi:10.1002/dev.10136

Egizio, V. B., Jennings, J. R., Christie, I. C., Sheu, L. K., Matthews, K. A., & Gianaros, P. J. (2008). Cardiac vagal activity during psychological stress varies with social functioning in older women. *Psychophysiology, 45,* 1046–1054. doi:10.1111/j.1469-8986.2008.00698.x

Ellis, B. J., Boyce, W. T., Belsky, J., Bakermans-Kranenburg, M. J., & Van Ijzendoorn, M. H. (2011). Differential susceptibility to the environment: An evolutionary-neurodevelopmental theory. *Development and Psychopathology, 23,* 7–28. doi:10.1017/S0954579410000611

El-Sheikh, M., Harger, J., & Whitson, S. M. (2001). Exposure to interparental conflict and children's adjustment and physical health: The moderating role of vagal tone. *Child Development, 72,* 1617–1636. doi:10.1111/1467-8624.00369

El-Sheikh, M., Keller, P. S., & Erath, S. A. (2007). Marital conflict and risk for child maladjustment over time: Skin conductance level reactivity as a vulnerability factor. *Journal of Abnormal Child Psychology, 35,* 715–727. doi:10.1007/s10802-007-9127-2

El-Sheikh, M., Kouros, C. D., Erath, S., Cummings, E. M., Keller, P., & Staton, L. (2009). Marital conflict and children's externalizing behavior: Interactions between parasympathetic and sympathetic nervous system activity. *Monographs of the Society for Research in Child Development, 74*(1), vii–79.

El-Sheikh, M., & Whitson, S. A. (2006). Longitudinal relations between marital conflict and child adjustment: Vagal regulation as a protective factor. *Journal of Family Psychology, 20,* 30–39. doi:10.1037/0893-3200.20.1.30

Enders, C. K. (2001). The performance of the full information maximum likelihood estimator in multiple regression models with missing data. *Educational and Psychological Measurement, 61,* 713–740.

Erath, S. A., El-Sheikh, M., Hinnant, B. J., & Cummings, M. E. (2011). Skin conductance level reactivity moderates the association between harsh parenting and growth in child externalizing behavior. *Developmental Psychology, 47,* 693–706. doi:10.1037/a0021909

Fabes, R. A., & Eisenberg, N. (1992). Young children's coping with interpersonal anger. *Child Development, 63,* 116–128. doi:10.2307/1130906

Fabes, R. A., Eisenberg, N., & Eisenbud, L. (1993). Behavioral and physiological correlates of children's reactions to others in distress. *Developmental Psychology, 29,* 655–663. doi:10.1037/0012-1649.29.4.655

Gordis, E. B., Feres, N., Olezeski, C. L., Rabkin, A. N., & Trickett, P. K. (2010). Skin conductance reactivity and respiratory sinus arrhythmia among maltreated and comparison youth: Relations with aggressive behavior. *Journal of Pediatric Psychology, 35,* 547–558. doi:10.1093/jpepsy/jsp113

Graham, J. W. (2009). Missing data analysis: Making it work in the real world. *Annual Review of Psychology, 60,* 549–576. doi:10.1146/annurev.psych.58.110405.085530

Graziano, P. A., Keane, S. P., & Calkins, S. D. (2007). Cardiac vagal regulation and early peer status. *Child Development, 78,* 264–278. doi:10.1111/j.1467-8624.2007.00996.x

Greaves-Lord, K., Tulen, J., Dietrich, A., Sondeijker, F., van Roon, A., Oldehinkel, A., . . . Huizink, A. (2010). Reduced autonomic flexibility as a predictor for future anxiety in girls from the general population: The TRAILS study. *Psychiatry Research, 179,* 187–193. doi:10.1016/j.psychres.2009.04.014

Grossman, P., Stemmler, G., & Meinhardt, E. (1990). Paced respiratory sinus arrhythmia as an index of cardiac parasympathetic tone during varying behavioral tasks. *Psychophysiology, 27,* 404–416. doi:10.1111/j.1469-8986.1990.tb02335.x

Grossman, P., van Beek, J., & Wientjes, C. (1990). A comparison of three quantification methods for estimation of respiratory sinus arrhythmia. *Psychophysiology, 27,* 702–714. doi:10.1111/j.1469-8986.1990.tb03198.x

Hessler, D. M., & Katz, L. F. (2007). Children's emotion regulation: Self-report and physiological response to peer provocation. *Developmental Psychology, 43,* 27–38. doi:10.1037/0012-1649.43.1.27

Hubbard, J. A., Smithmyer, C. M., Ramsden, S. R., Parker, E. H., Flanagan, K. D., Dearing, K. F., . . . Simons, R. F. (2002). Observational, physiological, and self-report measures of children's anger: Relations to reactive versus proactive aggression. *Child Development, 73,* 1101–1118. doi:10.1111/1467-8624.00460

Hughes, E. K., & Gullone, E. (2010). Reciprocal relationships between parent and adolescent internalizing symptoms. *Journal of Family Psychology, 24,* 115–124. doi:10.1037/a0018788

Hughes, J. W., & Stoney, C. M. (2000). Depressed mood is related to high-frequency heart rate variability during stressors. *Psychosomatic Medicine, 62,* 796–803.

Jeličič, H., Phelps, E., & Lerner, R. M. (2009). Use of missing data methods in longitudinal studies: The persistence of bad practices in developmental psychology. *Developmental Psychology, 45,* 1195–1199. doi:10.1037/a0015665

Jennings, J. R., Kamarck, T. W., Stewart, C., & Eddy, M. J. (1992). Alternate cardiovascular baseline assessment techniques: Vanilla or resting baseline. *Psychophysiology, 29,* 742–750. doi:10.1111/j.1469-8986.1992.tb02052.x

Judd, L. L., Paulus, M. P., Wells, K. B., & Rapaport, M. H. (1996). Socioeconomic burden of subsyndromal depressive symptoms and major depression in a sample of the general population. *The American Journal of Psychiatry, 153,* 1411–1417.

Kamarck, T. W., Jennings, J. R., Debski, T. T., Glickman-Weiss, E., Johnson, P. S., Eddy, M. J., & Manuck, S. B. (1992). Reliable measures of behaviorally-evoked cardiovascular reactivity from a PC-based test battery: Results from student and community samples. *Psychophysiology, 29,* 17–28. doi:10.1111/j.1469-8986.1992.tb02006.x

Katz, L. F. (2007). Domestic violence and vagal reactivity to peer provocation. *Biological Psychology, 74,* 154–164. doi:10.1016/j.biopsycho.2005.10.010

Katz, L. F., & Gottman, J. M. (1995). Vagal tone protects children from marital conflict. *Development and Psychopathology, 7,* 83–92. doi:10.1017/S0954579400006350

Neumann, S. A., Sollers, J. J. I., Thayer, J. F., & Waldstein, S. R. (2004). Alexithymia predicts attenuated autonomic reactivity, but prolonged recovery to anger recall in young women. *International Journal of Psychophysiology, 53,* 183–195.

Pan, E., & Farrell, M. P. (2006). Ethnic differences in the effects of intergenerational relations on adolescent problem behavior in US single-mother families. *Journal of Family Issues, 27,* 1137–1158. doi:10.1177/0192513X06288123

Pieper, S., Brosschot, J. F., van der Leeden, R., & Thayer, J. F. (2007). Cardiac effects of momentary access to worry episodes and stressful events. *Psychosomatic Medicine, 69,* 901–909. doi:10.1097/PSY.0b013e31815a9230

Porges, S. W. (1991). Vagal tone: An autonomic mediator of affect. In J. Garber & K. A. Dodge (Eds.), *The development of emotion regulation and dysregulation* (pp. 111–128). New York, NY: Cambridge University Press. doi:10.1017/CBO9780511663963.007

Reis, H. T., Sheldon, K. M., Gable, S. L., Roscoe, J., & Ryan, R. M. (2000). Daily well-being: The role of autonomy, competence, and relatedness. *Personality and Social Psychology Bulletin, 26,* 419–435. doi:10.1177/0146167200266002

Richards, L. N., & Schmiege, C. J. (1993). Problems and strengths of single-parent families: Implications for practice and policy. *Family Relations, 42,* 277–285. doi:10.2307/585557

Roisman, G. I., Tsai, J. L., & Chiang, K-H. S. (2004). The emotional integration of childhood experience: Physiological, facial expressive, and self-reported emotional response during the adult attachment interview. *Developmental Psychology, 40,* 776–789. doi:10.1037/0012-1649.40.5.776

Sloan, R. P., Bagiella, E., Shapiro, P. A., Kuhl, J. P., Chernikhova, D., Berg, J., & Myers, M. M. (2001). Hostility, gender, and cardiac autonomic control. *Psychosomatic Medicine, 63,* 434–440.

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders, 61,* 201–216. doi:10.1016/S0165-0327(00)00338-4

Vohs, K. D., Baumeister, R. F., & Ciarocco, N. J. (2005). Self-regulation and self-presentation: Regulatory resource depletion impairs impression management and effortful self-presentation depletes regulatory resources. *Journal of Personality and Social Psychology, 88,* 632–657. doi:10.1037/0022-3514.88.4.632

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54,* 1063–1070. doi:10.1037/0022-3514.54.6.1063

Weems, C. F., Zakem, A. H., Costa, N. M., Cannon, M. F., & Watts, S. E. (2005). Physiological response and childhood anxiety: Association with symptoms of anxiety disorders and cognitive bias. *Journal of Clinical Child & Adolescent Psychology, 34,* 712–723. doi:10.1207/s15374424jccp3404_13

Received December 21, 2010
Revision received October 18, 2011
Accepted November 1, 2011 ■