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Physiological Responses to Social and Physical Challenges in Children: Quantifying Mechanisms Supporting Social Engagement and Mobilization Behaviors

ABSTRACT: *Physiological response patterns to laboratory-based social and physical challenges were investigated in 37 typically-developing 3- to 5-year-old children. The study was conducted to determine whether the response profiles during each challenge were similar and whether individual differences in the response profiles to the challenges were correlated. Results demonstrated challenge specific physiological response strategies. In response to the social challenge, respiratory sinus arrhythmia and heart period increased and motor activity decreased. In contrast, in response to the physical challenge, respiratory sinus arrhythmia and heart period decreased and motor activity increased. Neither challenge reliably elicited changes in salivary cortisol. Only heart period responses were correlated between the challenges. © 2008 Wiley Periodicals, Inc.* Dev Psychobiol 50: 171–182, 2008.

Keywords: *respiratory sinus arrhythmia; heart rate; heart rate variability; cortisol; children; exercise*

INTRODUCTION

Children physiologically react to social and physical challenges. Studies have demonstrated that young children react with reliable physiological responses to both social (Alkon, Goldstein, Smider, Essex, Kupfer, & Boyce, 2003; Boyce, Quas, Alkon, Smider, Essex, Kupfer & MacArthur Assessment Battery Working Group of the MacArthur Foundation Research Network on Psychopathology and Development, 2001; Bruce, Davis, & Gunnar, 2002; Davis, Donzella, Krueger, & Gunnar, 1999; Dettling, Gunnar, & Donzella, 1999; Doussard-Roosevelt, Montgomery, & Porges, 2003; Kagan, Reznik, & Snidman, 1999; Rubin, Hastings, Stewart, Henderson, & Chen, 1997; Schmidt, Fox, Rubin, Sternberg, & Gold, 1999; Zimmermann & Stansbury, 2004) and physical challenges (Filaire, Bonis, & Lac, 2004; Jansen et al., 1999). However, no published study has contrasted the physiological response profiles during social and physical challenges in children. Since similar physiological parameters can be monitored during both classes of challenges (e.g., respiratory sinus arrhythmia (RSA), heart rate, salivary cortisol), it is possible to determine whether the response magnitude (i.e., reactivity) elicited by these two classes of challenges are correlated or if the response profiles represent task-specific neurophysiological adjustments.

The Polyvagal Theory (Porges, 1995, 2001a, 2003) provides a framework to interpret physiological responses during various challenges. The theory describes the evolution of the neural regulation of the autonomic nervous system in vertebrates and how phylogenetic changes in the

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autonomic nervous system are related to social behavior. Specifically, based on vertebrate phylogeny, the Polyvagal Theory describes three hierarchically organized neural ''circuits'' that regulate the autonomic nervous system and foster distinct behavioral strategies. In the most phylogenetically recent circuit, a myelinated vagus provides the neural regulation of the heart to support behavioral strategies associated with social engagement. The myelinated vagus can be conceptualized as a ''brake,'' (Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996) that decreases heart rate below the intrinsic rate of the pacemaker to promote a calm physiological state during normal conditions. When the vagal brake is released, heart rate increases. An index of the dynamic influence of the myelinated vagus on the heart can be estimated by quantifying the changing amplitude of RSA. Thus, it is hypothesized that a social challenge would recruit a neural circuit to support social engagement behaviors by increasing RSA and the physical challenge would recruit a neural circuit to support mobilization behaviors by decreasing RSA. Both neural circuits are related to the sympathetic-adrenal system, as the neural circuit which supports social engagement behaviors suppresses sympathetic-adrenal activity, while the neural circuit which supports mobilization increases sympathetic-adrenal activity. Increased sympathetic-adrenal activity is often indexed by increased heart rate, decreased RSA, and increased glucocorticoids, such as cortisol.

Cortisol plays an important role in supporting mobilization behavior. In general, the functioning of the adrenal cortex and the secretion of cortisol appears to be integrated into the mobilization function of the autonomic nervous system by increasing sympathetic activation and circulating catecholamines. These effects suggest that, consistent with the phylogenetic approach described in the Polyvagal Theory (see Porges, 1995, 2001a,b), cortisol secretion may be related to the maintenance of mobilization (i.e., the conversion of norepinephrine into epinephrine) for flight–flight behaviors and in the recovery from the lactate build up that may contribute to a functional oxygen debt (i.e., gluconeogenesis). Vagal activity has been implicated in the function of the adrenal cortex, which produces cortisol. Reports suggest that afferents originating in the subdiaphragmatic vagus exhibit an inhibitory influence on the HPA-axis and reduce cortisol secretion (e.g., Bueno et al., 1989; Miao, Janig, Green, & Levine, 1997). Other research has demonstrated a covariation between increases in cortisol and decreases in cardiac vagal tone (Gunnar, Porter, Wolf, Rigatuso, & Larson, 1995), which, consistent with the removal of the vagal brake and the stimulation of the sympathetic nervous system, would promote mobilization. Similarly, psychological stressors that reduce cardiac vagal tone have been reported to increase cortisol plasma level (e.g., Cacioppo et al., 1995). Thus, in several situations there appears to be a coordinated response that functions to promote metabolic activity to support mobilization behaviors by withdrawing of the vagal ''brake'' and activating both the sympathetic nervous system and the HPA-axis.

The current study was conducted to examine the relation between physiological responses to social and physical challenges. The study addresses five primary questions: (1) Do social and physical challenges elicit similar physiological response patterns? (2) Is there a synergistic relation between decreases in vagal influences on the heart and increases in salivary cortisol in response to the physical challenge? (3) Are physiological base levels related to response patterns? (4) Are the systematic changes in heart period and RSA due to challenge related changes in activity? (5) Are individual differences in response strategies to the social challenge related to parental perception of a child's behavior?

Children between the ages of 3 and 5 years were tested, since children of this age have rapid developmental shifts in their social skills (e.g., Koblinsky, Gordon, & Anderson, 2000; National Research Council Institute of Medicine, 2000) and display a broad range of individual differences in regulating emotion in social settings (e.g., Denham, 1998; Eisenberg & Fabes, 1992; National Research Council Institute of Medicine, 2000; Sroufe, 1996). The broad range of individual differences in social behavior and emotional regulation commonly observed in children (e.g., Cole, Zahn-Waxler, Fox, Usher, & Welsh, 1997; Galyer & Evans, 2002; National Research Council Institute of Medicine, 2000; Rubin, Coplan, Fox, & Calkins, 1995) provides an optimal opportunity to evaluate the relation between physiological response profiles during different domains of challenge and also to relate these physiological response parameters to individual differences in behavior.

Both a social and a physical challenge were included to determine whether there was a common physiological reaction to both challenges, whether responses to the social and physical challenges use similar mechanisms, or whether the response profile was context-specific. The social challenge was designed to place children in a physically safe environment that could nonetheless elicit a broad range of reactions to a novel adult. In this study, the social challenge consisted of the child remaining in the research playroom, while the parent exited the room and a researcher (i.e., novel adult) entered the room and conducted hearing tests. Through this design, children were placed in a physically safe environment (i.e., research play-room), but subjected to an experience of the parent being absent and an unfamiliar adult being present. The physical challenge consisted of rapid pedaling of a stationary bicycle. RSA, heart period (i.e., the reciprocal of heart rate), and motor activity were continuously monitored during both challenges. Saliva was sampled six times during the study. Heart period, was recorded as an overall measure of cardiac function and metabolic processes. Heart period was used instead of heart rate because the duration between sequential heart beats monotonically increases with vagal influences to the cardiac pacemaker (Berntson, Cacioppo, & Quigley, 1995). RSA, an index of the functioning of the myelinated vagus at the level of the heart (i.e., the vagal brake) was statistically derived from the beat-to-beat heart period data. Since the myelinated vagal efferent fibers to the pacemaker have a respiratory rhythm (Jordan, Khalid, Schneiderman, & Spyer, 1982), the functional impact of the neural transmission through these vagal fibers can be assessed dynamically by evaluating the amplitude of RSA. Salivary cortisol was collected as an indicator of HPA-axis activation convergent with the mobilization strategy described in the Polyvagal Theory (see Porges, 2001b) and because salivary cortisol has been reported to be responsive to social challenges, such as the Trier Social Stress Test (Kirschbaum, Pirke, & Hellhammer, 1993). Since the neural regulation of the heart is influenced by changing metabolic demands required by increases and decreases in movement, motor activity level was recorded. In addition, the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2000) was administered, since child behavior patterns and clinical dimensions have been related to physiological reactivity (e.g., Boyce et al., 2001; Borger & van der Meere, 2000; Garralda, Connell, & Taylor, 1991; Mangeot et al., 2001; Monk et al., 2001; Ortiz & Raine, 2004; Pine et al., 1998, 2000; Sampei, Dakeishi, Wood, & Murata, 2006).

METHODS

Participants

Fifty eight 3- to 5-year olds were recruited from the Chicago area via public solicitation (e.g., newspaper, magazine, announcements at area preschools). Analyses were conducted on participants with complete physiological and parent questionnaire data ($N = 37$, $M = 53.1$ months, $SD = 10.3$). The most common sources of incomplete data were insufficient amount of saliva for hormone analysis ($n = 10$), uneditable heart period data for one or more conditions ($n = 8$) or equipment problems ($n = 3$). There were no differences in gender, age or parental assessment of anxiety for children with complete and incomplete data. Inclusion criteria included normal hearing and physical ability to use arms to manipulate a bicycle-like device. Participants were excluded if they were taking medications or had a medical condition that could interfere with the physiological data.

The participants with complete data (19 females, 18 males) represented a broad range of socioeconomic levels and culturally diverse backgrounds. Fifty four percent of the participants were Caucasian, 13.5% were African-American, 13.5% were Hispanic, 8.1% were Asian, 8.1% were Caucasian and Hispanic and 2.7% were described as "other." Three percent of the primary caregivers had completed high school, 24.3% had completed some college, 37.8% held a bachelor's degree, 2.7% held a master's degree and 32.4% held advanced degrees (Ph.D., J.D., or M.D.) Eighty-one percent of parents reported an annual household income above \$50,000, 16.2% reported an annual income below \$50,000 and 2.7% reported receiving public assistance.

Physiological Measures

Cardiac. Heart period was continuously recorded with a Mini-Logger (Bend, OR, Mini-Mitter), a small device the size of a personal digital assistant (PDA) that stores sequential R-R intervals timed to the nearest millisecond. Two Ag/AgCl self-adhering electrodes (Meditrace) were placed on the chest forming a plane across the heart. Heart period data were visually inspected and edited off-line with MXedit software (Brain-Body Center, University of Illinois at Chicago). Editing consisted of integer arithmetic (i.e., dividing intervals when detections were missed or adding intervals when spuriously invalid detections occurred). RSA was calculated with MXedit consistent with the procedures developed by Porges (1985). The Porges method quantifies the amplitude of RSA with age-specific parameters, sensitive to the maturational shifts in the frequency of spontaneous breathing. Steps include: (1) R–R intervals are timed to the nearest millisecond to produce a time series of sequential heart periods; (2) sequential heart periods are resampled into 250 ms intervals to produce time-based data; (3) the time-based series is detrended by a 21-point cubic moving polynomial (Porges & Bohrer, 1990) that is stepped through the data to create a smoothed template and the template is subtracted from the original time-based series to generate a detrended residual series; (4) the detrended time series is bandpassed to extract the variance in the heart period pattern associated with spontaneous breathing (i.e., 0.24–1.04 Hz); and (f) the natural logarithm of the variance of the bandpassed time series is calculated as the measure of the amplitude of RSA (Riniolo & Porges, 2000). These procedures are mathematically equivalent to frequency domain methods (i.e., spectral analysis) for the calculation of the amplitude of RSA when heart period data are stationary (Porges & Byrne, 1992). Five minutes of heart period data during each challenge condition and 2 min of heart period data during each baseline condition were edited. RSA and heart period were quantified during each sequential 30-s epoch and the averages within each condition were used in the data analyses.

Activity. Activity level was recorded via an Actigraph (Manufacturing Technology, Inc., Fort Walton Beach, FL). The Actigraph contains an accelerometer and records movements that range in acceleration from .05 to 2 G's. The acceleration signal is band pass filtered (between 0.25 and 2.5 Hz) and digitized (8 bit A/D converter at 10 samples per second). The Actigraph was fastened around the wrist of the child's dominant hand to record movements. Movement data were converted to movements per minute within each condition.

Salivary Cortisol. Saliva was collected to assay cortisol. A minimum of 1 ml of saliva was collected at six time points: (1) at the beginning of the protocol; (2) pre-social challenge; (3) post-social challenge; (4) pre-physical challenge; (5) post-physical challenge; and (6) at the conclusion of the protocol. Children were asked to chew on small pieces of cotton dental rolls for approximately 20–30 s. The cotton pieces were placed in a plastic needleless syringe and the saliva was expressed in a cryogenic vial. Children were asked to chew multiple pieces of cotton until 1 ml of saliva had been collected. Most children chewed 4–5 cotton pieces to obtain the 1 ml saliva. Sufficient saliva was obtained in approximately 3–5 min. HS Cortisol High Sensitivity Salivary Cortisol Enzyme Immunoassay Kits (Salimetrics LLC) were used to assay the saliva samples. All samples were assayed in duplicate using multiple plates. Samples differing by 5% were re-assayed. The lower limit of sensitivity was $<.007$ μg/dl and the intra- and inter-assay coefficients of variation were less than 6% and 3%, respectively.

Behavioral Measure

Parental perception of child behavior was assessed with the Child Behavior Checklist 1½–5. The checklist is well validated, has high test-retest reliability, and has high stability over a 12-month period (Achenbach & Rescorla, 2000). The CBCL is a 99-problem item checklist designed to assess the parental perception of the child's typical behaviors. The checklist produces seven syndrome scales: Emotionally Reactive, Anxious/Depressed, Somatic Complaints, Withdrawn, Sleep Problems, Attention Problems, and Aggressive Behavior. The Internalizing Scale is a sum of scores on all the problem items within the following subscales: emotionally reactive, anxious/depressed, somatic complaints, and withdrawn. The Externalizing Scale is a sum of scores on all the problem items within the following subscales: attention problems and aggressive behavior. The Total Problems Scale composite score is the sum of scores on all the problem items of a form.

Procedure

Parental consent was obtained prior to start of the study. The study was conducted in a research room at the Brain-Body Center and began at approximately 9:30 a.m. Upon entering the research room the physiological monitoring equipment and method for saliva collection were demonstrated to the parents and children. After demonstrating the physiological monitoring equipment and the method for collecting saliva, sensors were attached to the child. The researcher attached the activity monitor around the wrist of the child's dominant hand with a Velcro strap and placed two self-adhesive electrodes on either side of the child's heart. After ensuring that the parent/guardian and child were comfortable with the equipment, the study proceeded. An initial baseline measure of heart period (2 min) was collected while the child sat in a chair at a table. During this and subsequent baselines, the child was encouraged to minimize motor activity by engaging in the "quiet game" with the researcher. The object of the "quiet game" was to remain quieter with less movement than the other player. After each quiet game and at the end of the study, the child was asked to provide a saliva sample.

The protocol sequence is outlined in Table 1. At the beginning of the social challenge, the parent/guardian was asked to temporarily leave the testing room and accompany the familiar researcher to an adjacent room, wherein the parent/guardian was invited to watch the child via video monitoring equipment. The social challenge began when the child realized that the parent would be leaving the room and an unfamiliar researcher entered the room to conduct 2 hearing tests (results not presented in this paper). During the hearing tests, children were asked to sit motionless during administration of a tympanometer test and an audiogram. The duration of

Table 1. Timeline for Experimental Procedures

9:30	Baseline heart rate and saliva collection
9:35	Quiet play for 20 min
9:55	Pre-social challenge heart rate and saliva collection
10:00	Social challenge for 15 min
10:15	Post-social challenge heart rate and saliva collection
10:20	Quiet play for 20 min
10:40	Pre-physical challenge heart rate and saliva collection
10:45	Physical challenge for 10 min
11:05	Post-physical challenge heart rate and saliva collection
11:10	Quiet play for 25 min
11:35	Final saliva collection

the social challenge was 10 min. The social challenge ended when the parent returned to the room with the familiar researcher.

During the physical challenge, the child was asked to pedal a stationary bicycle (SimCycle, Eloton 2001) with his/her arms for 8–10 min. To motivate the child to pedal the bicycle fast, the bicycle was connected to an interactive video game (Need for Speed: Porsche Unleashed, EA Sports 2002) that requires rapid pedaling in order to play the game. The video game was presented on a computer monitor that was positioned in front of the stationary bicycle, thus allowing the child to watch the video screen while pedaling. Due to the nature and duration of the task, as well as the age group of the participants, some children fatigued before the challenge session was over. If the child reported feeling fatigued before the end of the physical challenge, the child was allotted a 5 s break from pedaling and then encouraged to continue. Fewer than 10% of the children requested a break, and each child was allotted no more than 2 breaks. During quiet play, videos, books, and toys were provided to entertain the child without requiring excessive physical activity that could interfere with the cortisol measurements. The timing and duration of events in the protocol were selected to capture cortisol reactivity to specific events. After completion of the study, the physiological sensors were removed from the child and the parent/guardian and child were thanked. Parents/Guardians were compensated for their time ($10) and for their travel expenses. Children were given a $25 bookstore gift certificate.

RESULTS

Heart period, RSA, and activity were quantified during seven conditions (initial baseline, social pre-baseline, social challenge, social post-baseline, physical pre-baseline, physical challenge, and physical post-baseline). A square root transformation was used to normalize the distribution of activity data. Salivary cortisol was quantified at six time points (beginning of the protocol, pre-social challenge, post-social challenge, pre-physical challenge, post-physical challenge, end of protocol). A logarithm transformation was used to normalize the distribution of cortisol values.

The means and standard deviations of the physiological variables during each condition are listed in Table 2. There were no gender effects in any of the physiological variables during either challenge or during the baseline. There were no age effects in heart period, RSA, activity, or cortisol during baseline or social challenge. During the physical challenge, there were age effects for activity, $F(4, 68) = 9.82$, $p < .001$. The youngest children were most active during the pre- and post-baselines, while the oldest children were most active during the physical challenge.

Stability Across Baselines

To evaluate the stability of each variable across baselines within the experimental session, correlations were calculated. All baseline measures of RSA, heart period and activity were highly correlated across the session (see Tab. 3). Cortisol level at the beginning of the protocol was highly correlated with cortisol level before and after the social challenge, but was not correlated with cortisol level before or after the physical challenge. The other cortisol measures were highly correlated with one another.

Response Patterns During Challenge Conditions

Repeated measures ANOVAs were calculated to assess response pattern of each variable (RSA, heart period,

Table 2. Means (Standard Deviations) for Respiratory Sinus Arrhythmia, Heart Period, Activity, and Cortisol ($n = 37$)

	Respiratory Sinus Arrhythmia[a]	Heart Period[b]	Activity[c]	Cortisol[d]
Initial baseline	6.55 (1.24)	614.46 (85.52)	20.14 (14.71)	−2.33 (.56)
Social pre-BL	6.28 (1.28)	606.65 (71.81)	30.19 (16.90)	−2.49 (.59)
Social challenge	6.70 (1.18)	623.04 (76.56)	22.73 (10.12)	
Social post-BL	6.38 (1.27)	610.94 (75.99)	30.25 (13.73)	−2.54 (.60)
Physical pre-BL	6.52 (1.19)	614.81 (67.56)	33.40 (13.75)	−2.61 (.66)
Physical challenge	3.59 (1.18)	467.39 (48.05)	111.79 (17.79)	
Physical post-BL	6.24 (1.09)	598.34 (56.27)	35.57 (14.46)	−2.59 (.63)
Final baseline				−2.57 (.64)

[a] $\ln (ms)^2$.
[b] ms.
[c] Square root (movements per minute).
[d] ln (nmol/L).

Table 3. Correlations Among Baseline Measures ($n = 37$)

	Initial BL	Social Pre-BL	Social Post-BL	Physical Pre-BL
RSA				
Social pre-BL	.91*			
Social post-BL	.87*	.91*		
Physical pre-BL	.84*	.88*	.88*	
Physical post-BL	.80*	.83*	.85*	.86*
Heart period				
Social pre-BL	.93*			
Social post-BL	.93*	.95*		
Physical pre-BL	.85*	.89*	.90*	
Physical post-BL	.83*	.84*	.84*	.89*
Activity				
Social pre-BL	.59*			
Social post-BL	.49*	.54*		
Physical pre-BL	.48*	.38**	.50*	
Physical post-BL	.57*	.59*	.57*	.64*
Cortisol				
Pre-social	.70*			
Post-social	.51*	.80*		
Pre-physical	.11	.49*	.53*	
Post-physical	.05	.39**	.44*	.76*

*$p < .01$.
**$p < 0.05$.

activity, and cortisol) during each challenge (social and physical). When necessary, a Huynh-Feldt correction was used to adjust for sphericity violations. As illustrated in Figure 1, there were condition effects during the social challenge for RSA, $F(2, 72) = 9.57$, $p < .001$, heart period, $F(1.60, 57.53) = 4.33$, $p < .03$, and activity, $F(2, 72) = 5.52$, $p < .006$. During the social challenge, RSA and heart period increased from pre-baseline to challenge and decreased from challenge to post-baseline. Activity increased from pre-baseline to challenge and decreased from challenge to post-baseline. Cortisol did not significantly change from pre-social challenge to post-social challenge, $F(1, 36) = .07$, $p < .80$.

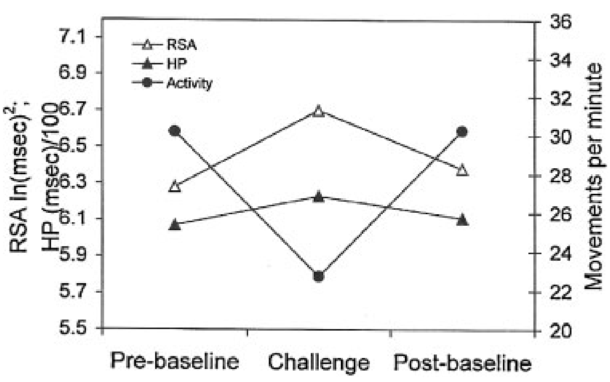

FIGURE 1 RSA, heart period (HP) and activity during social challenge ($n = 37$).

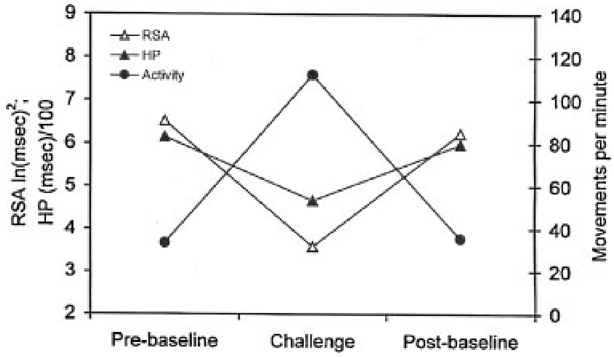

FIGURE 2 RSA, heart period (HP), and activity during physical challenge ($n = 37$).

As illustrated in Figure 2, there were significant condition effects during the physical challenge for RSA, $F(1.43, 51.51) = 172.81$, $p < .001$, heart period, $F(1.31, 47.24) = 135.63$, $p < .001$, and activity, $F(1.32, 47.49) = 322.99$, $p < .001$. During the physical challenge, RSA and heart period decreased from pre-baseline to challenge and increased from challenge to baseline and activity increased from pre-baseline to challenge and decreased from challenge to post-baseline. Cortisol did not significantly change from pre-physical challenge to post-physical challenge, $F(1, 36) = .64$, $p < .43$.

Response Patterns Among Variables Within Challenges

To evaluate reactivity of RSA, heart period, and activity to each challenge, change scores (challenge minus pre-baseline) were calculated. To evaluate cortisol reactivity, change scores (post-challenge minus pre-challenge) were calculated. The means (standard deviations) of the change scores during the social challenge were: RSA [.42 (.67)], heart period [16.39 (39.73)], activity [−7.46 (17.56)] and cortisol [−.05 (.37)]. The means (standard deviations) of the change scores during the physical challenge were: RSA [−2.93 (1.18)], heart period [−147.42 (73.36)], activity [78.39 (22.32)], and cortisol [.02 (.45)]. In general, the change scores in response to each challenge for RSA, heart period, and activity were significantly correlated with their respective baselines (social challenge: RSA, $r = -.41$, $p < .01$, heart period, $r = -.15$, $p < .37$, activity, $r = .83$, $p < .001$; physical challenge: RSA, $r = -.51$, $p < .001$, heart period, $r = -.77$, $p < .001$, activity, $r = -.60$, $p < .001$). Thus, to remove the statistical dependence between baseline and change, residualized change scores adjusted for the pre-baseline value were calculated with regression analyses. To maintain the metric for each variable, unstandardized residuals were used.

Correlations were calculated among the residualized change scores within each challenge condition to determine whether there was a coordinated response among the variables. During the social challenge, RSA reactivity was significantly correlated to heart period reactivity, $r = .68$, $p < .001$; a greater increase in RSA was related to a greater increase in heart period (see Tab. 4). During the social challenge, heart period reactivity was significantly correlated to cortisol reactivity, $r = -.34$, $p < .04$; a greater increase in heart period was related to a greater decrease in cortisol (see Tab. 4). During the physical challenge, all correlations among RSA, heart period and activity were significant (see Tab. 4). RSA reactivity was correlated to heart period reactivity, $r = .50$, $p < .001$ and to activity reactivity, $r = -.57$, $p < .001$; a greater decrease in RSA was related to a greater decrease in heart period and greater increase in activity. Heart period reactivity was significantly correlated to activity reactivity during the physical challenge, $r = -.62$, $p < .001$; a greater decrease in heart period was related to a greater increase in activity. Thus, as individual differences in activity increased, there was a parallel decrease in heart period and RSA. Cortisol reactivity was not significantly correlated with the other variables.

Response Patterns Among Physiological Measures Between Challenges

To determine if the response patterns to the two challenges were similar, correlations were calculated between the residualized change scores for each variable on each challenge. Residualized heart period reactivity was correlated between the social and physical challenges, $r = .40$, $p < .01$; a greater reactivity to the social challenge was related to greater reactivity to the physical challenge. The remaining measures of reactivity were not related between challenges (RSA reactivity, $r = .09$, $p < .61$; activity reactivity, $r = .31$, $p < .06$; cortisol reactivity, $r = .08$, $p < .63$).

Table 4. Correlations Among Change Scores (Residualized) During the Social and Physical Challenges ($n = 37$)

	ΔRSA	ΔHP	ΔActivity
Social challenge			
ΔHP	.68*		
ΔActivity	−.14	−.23	
ΔCortisol	−.21	−.34**	−.16
Physical challenge			
ΔHP	.50*		
ΔActivity	−.57*	−.62*	
ΔCortisol	−.28	−.09	.00

*$p < .01$.
**$p < .05$.

Evaluation of Activity as a Potential Covariate of Physiological Patterns During Challenges

To determine whether systematic changes in heart period and RSA were due to challenge-related changes in activity, a repeated-measures ANCOVA was conducted for RSA and heart period during each of the challenges, using baseline activity for each respective challenge as a covariate. During the social challenge, activity was not a significant covariate for RSA, $F(1, 35) = .05$, $p < .82$, or for heart period, $F(1, 35) = .01$, $p < .93$. During the physical challenge, activity was not a significant covariate for RSA, $F(1, 35) = 1.14$, $p < .29$ or for heart period, $F(1, 35) = .05$, $p < .83$.

Relationship Between Response Patterns and Behavior

To determine the relation between response patterns during the challenges and parental perception of child behaviors assessed by the CBCL, correlations were calculated between each residualized change score and each syndrome scale on the CBCL (i.e., anxious-depressed, emotionally reactive, somatic complaints, withdrawn, sleep problems, attention problems, internalizing subscale, externalizing subscale, and total problems) (see Tab. 5). In response to the social challenge, there were significant correlations between change in RSA and several of the scales. Greater decreases in RSA during the social challenge were significantly correlated with higher values on the anxious-depressed, $r = -.43$, $p < .007$, sleep problems, $r = -.41$, $p < .01$, internalizing problems, $r = -.39$, $p < .02$, and total problems scales, $r = -.39$, $p < .02$. Consistent with these findings, greater decreases/less of an increase in heart period during the social challenge was significantly correlated with higher values on the anxious-depressed, $r = -.40$, $p < .01$, sleep problems, $r = -.40$, $p < .02$, and total problems scales, $r = -.33$, $p < .05$. In addition, decreases in heart period were correlated with higher scores on the emotionally reactive scale, $r = -.34$, $p < .04$, increases in cortisol were correlated with higher scores on the anxious-depressed subscale, $r = .40$, $p < .01$, and increases in activity were correlated with higher scores on the attention problems subscale, $r = .39$, $p < .02$.

In response to the physical challenge, only change in heart period was correlated with aggressive behavior, $r = .37$, $p < .03$, as individuals with more aggressive behaviors demonstrated smaller decreases in heart period in response to the physical challenge.

An exploratory stepwise regression, sequentially applying additional variables, was used to determine the most parsimonious model for predicting scores on the syndrome scales of the CBCL that were correlated with

Table 5. Correlations Between Residualized Change Scores (Social/Physical Challenges) and Syndrome Scales on the CBCL (*t*-Scores; *n* = 37)

	ΔRSA	ΔHP	ΔActivity	ΔCortisol
Social challenge				
Emotionally reactive	−.25	−.34**	−.13	.30
Anxious/depressed	−.43*	−.40**	−.02	.40**
Somatic complaints	−.21	−.12	−.01	.17
Withdrawn	−.28	−.25	.13	−.05
Sleep problems	−.41**	−.40**	.11	.04
Attention problems	.08	.08	.39**	−.18
Aggressive behavior	−.01	−.05	.01	.13
Internalizing problems	−.39**	−.21	−.06	.19
Externalizing problems	−.25	−.27	.18	.04
Total problems	−.39**	−.33**	.07	.13
Physical challenge				
Emotionally reactive	−.06	.04	−.04	.06
Anxious/depressed	−.18	−.11	.06	.16
Somatic complaints	.10	.04	−.15	.06
Withdrawn	.06	−.07	.06	−.13
Sleep problems	.19	−.13	−.18	−.10
Attention problems	.14	−.02	.08	.07
Aggressive behavior	.07	.37**	−.11	−.25
Internalizing problems	.06	.05	−.06	−.03
Externalizing problems	.13	.24	−.23	−.07
Total problems	.16	.17	−.21	−.07

*$p < .01$.
**$p < .05$.

response patterns during either challenge. For the CBCL scales, the following predictors were entered into the model: residualized changes in RSA, heart period, activity, and cortisol for each challenge separately. Only for the anxious-depressed scale did the stepwise regression analysis select more than one variable and in this case change in both RSA and cortisol change during the social challenge were the strongest predictors $F(2, 36) = 6.93$, $p < .003$.

DISCUSSION

The current study investigated several important questions regarding our understanding of child autonomic and cortisol reactions to two common classes of challenges. Below, the results of the study are evaluated within the context of each of the five primary questions, as described in the Introduction.

Is There a Common Physiological Response Strategy to Both Social and Physical Challenges?

Although both challenges could be described operationally as ‘‘stressing,’’ each challenge elicited a different response profile. In response to the physical challenge, vagal withdrawal, characterized by significant decreases in heart period and RSA, paralleled an increase in activity. These findings reflect the active withdrawal of the vagal ‘‘brake,’’ which is necessary to support the increased metabolic requirements associated with increased activity. Relative to the physical challenge, the response profile to the social challenge was inverted. Heart period and RSA increased and activity decreased. These findings are consistent with the active increase of the vagal brake during social engagement (see Porges, 2001a) and the reduced cardiac output required during quiescent behavioral states (see Porges et al., 1996). However, cortisol did not respond to either challenge.

Although the pattern of reactivity differed between the tasks, there is the possibility that the magnitude of reactivity might be related across the two challenges. For example, a dampened response to physical exercise might be related to a dampened response to a social challenge. Only changes in heart period were correlated between the tasks. Participants who had the greatest increase in heart period to the social challenge had a dampened decrease in heart period during the physical challenge. In contrast, RSA reactivity, a sensitive measure of the dynamic regulation of the vagal brake, was not consistent across the challenges. Likewise, neither activity nor cortisol reactivity were consistent across challenges. The data illustrate that, although the same variables respond to both challenges, the patterns of reactivity were different. Thus, challenges that appear to be stressful in a social context may not be related to the responses elicited by a physical challenge. There may be an important distinction between the neurophysiological mechanisms mediating reactions to these two broad classes of challenges. For example, challenges that require mobilization may elicit well understood neurophysiological systems that promote increases in metabolic resources to fight and to flee. Alternatively, challenges associated with social interaction may be more dependent on a ''neural'' evaluation of safety in the environment and the dampening of mechanisms mediating mobilization. Thus, if the ''neural'' evaluation (i.e., neuroception) detects risk and not safety, the primitive limbic fight/flight mechanisms are not dampened and a physiological state is maintained to support fight/flight behaviors (see Porges, 2003).

Is There a Synergistic Relation Between Reduced Vagal Efferent Influences on the Heart and Increases in Salivary Cortisol?

Unexpectantly, in the current study, salivary cortisol did not parallel changes in activity or cardiac function. Changes in cortisol were not anticipated during the social challenge, as the challenge required only mild cardiac and activity demands. However, it was assumed that the mobilization demands of the physical challenge would elicit a reliable release of cortisol. There are several possible reasons for these negative findings. First, the duration and intensity of the physical challenge may not have been sufficient to trigger the cortisol response. While there are no published studies examining the relation between physical activity and cortisol responses in young children, studies examining this relation in older children and adults have employed a physical challenge of longer durations requiring greater aerobic demands (e.g., Furlan, DeMartinis, Schweizer, Rickels, & Lucki, 2001; Gonzalez-Bono, Moya-Albiol, Martinez-Sanchis, & Salvador, 2002; Jansen et al., 1999). While several participants pedaled intensely throughout the physical challenge, most participants did not pedal with maximal effort. Interestingly, correlations between movement and cortisol reactivity to the physical challenge were not significant although there were significant parallels between the increases activity and decreases in RSA and heart period.

A second possibility for the lack of a reliable cortisol response to the physical challenge might be related to the time of day during which cortisol levels were sampled (morning) and the general effect of circadian rhythms. Due to the circadian rhythm of HPA-axis activity, the pattern of cortisol release fluctuates throughout the day. While there is a marked variability in the circadian profile of cortisol release in healthy, pre-pubertal children, researchers have found that the majority of children demonstrate a sharp peak of cortisol release at approximately 6:00 am. This peak is followed by a rapid decline in cortisol release until approximately 10:00 am, and then by a slower decline until approximately 2:00 am (Knutsson et al., 1997). By scheduling all participants in the morning (i.e., time of peak cortisol release), the experiment might have challenged the system during a period when it was close to maximal output. Thus, the cortisol reactions might have been dampened. Or, even if the challenges altered cortisol release, the amplitude of the response might not be detectable when it is superimposed on the individual's circadian rhythm. Given the highly stable and reproducible pattern of cortisol release within individuals (Knutsson et al., 1997), future studies should assess cortisol reactions to challenges with the circadian rhythm of cortisol levels on a non-experimental day.

Are Individual Differences in Baseline Physiological State (i.e., RSA) Related to the Response Patterns?

Higher baseline RSA was related to greater reductions in RSA during the physical challenge and attenuated increases during the social challenge. Higher baseline activity was related to greater decreases in activity during the physical challenge and to greater increases in activity during the social challenge. Longer baseline heart period (i.e., slower heart rate) was related to larger decreases in heart period during the physical challenge. Baseline salivary cortisol was not related to changes during either challenge. Thus, the initial levels of the autonomic variables were most clearly related to the magnitude of the reactivity to the physical challenge, with greater cardiac vagal tone (i.e., higher amplitude RSA and longer heart periods) during baseline being related to larger decreases during the physical challenge. These findings provide additional support for the use of residualized change scores to enable the study of reactivity independent of initial levels. The importance of base level on the magnitude of autonomic reactivity was initially described by Wilder (1931) in his ''law of initial values'' (1931/1976), and regression methods were proposed as a corrective strategy several years ago by Benjamin (1967).

Are Individual Differences in the Physiological Responses Due to Changes in Activity?

Since the autonomic response profiles to each challenge covaried with activity, we investigated whether changes in activity determined the changes in RSA and heart period.

Only during the physical challenge did the individual differences in the autonomic variables covary with changes in activity, as increases in activity correlated with decreases in RSA and heart period. These findings are consistent with the physiological mechanisms required to increase cardiac output to support mobilization behaviors by withdrawing vagal influences. To explore further the possibility that autonomic reactivity was driven by activity, change in activity was used as a covariate in analyses of variance evaluating the challenge effects on heart period and RSA. However, activity was not a significant covariate for either variable during either challenge, thus demonstrating that autonomic reactivity was not driven by activity.

Are Individual Differences in Response Strategies to the Challenges Related to Parental Perception of a Child's Behavior?

Physiological reactivity to the challenges was related to parental perceptions of anxiety/depression, emotional reactivity, sleep problems, attention problems, aggressive behavior, internalizing problems, and total problems. The findings replicate previous studies which have likewise demonstrated a relationship between physiology and anxiety (Boyce et al., 2001; Monk et al., 2001; Pine et al., 1998, 2000), emotional disorders (Garralda et al., 1991), sleep duration (Sampei et al., 2006), ADHD (Borger & van der Meere, 2000), and antisocial behavior (which includes aggressive behavior; Ortiz & Raine, 2004).

However, only scores on the anxious/depressed subscale were predicted by RSA and cortisol reactivity to the social challenge (less of an increase in RSA and a greater increase in cortisol during the social challenge predicted more symptoms of anxiety-depression). The behavioral dimension of anxiety is of theoretical interest, as the Polyvagal Theory interprets social behavior as an emergent property of a specific neurophysiological state. The neurophysiological state of individuals higher on the anxiety-depression scale may inappropriately promote mobilization behaviors, instead of social engagement behaviors. While all individuals in the current study were within the typical range for all syndrome scales, including the anxious/depressed syndrome scale, the data indicate that individual differences in physiological reactivity specifically to the social challenge are related to the parent perception of child behavior. Importantly, the data suggest that reactivity to a social challenge can yield important information regarding the mechanisms of typical behavior in children that could potentially be applied to study atypical behavior in children and adults (i.e., anxiety and/or depression). Future studies could also include behavioral data to examine the relationship among parental perception of a child's behavior, the child's behavior, and the child's physiological reactivity during the social challenge.

The study has several limitations. First, due to the difficulty of collecting physiological data from young children, the final sample size was small. The small sample size limits the generalizability of the findings, especially for cortisol which has a small effect size. Second, the social challenge used in the study might not generalize to the social interactions that the child would normally experience. During the social challenge, children were not only exposed to an unfamiliar person in the absence of parents, but were also exposed to the unfamiliar equipment and procedures used to conduct the hearing tests. Thus, the physiological reactivity monitored during the social challenge represents a response to the complex features of the task. Future studies investigating social behavior could address this confound and evaluate whether the social interaction between the child and an unfamiliar person in the absence of novel equipment would elicit a similar physiological response pattern.

To summarize, the study demonstrates several important points. First, physiological reactions to social and physical challenges were not correlated. Second, although both challenges reliably produced effects in heart period and RSA, cortisol was insensitive. Third, as proposed approximately 75 years ago by Wilder (1931/1976), the magnitude of autonomic reactions to challenge was dependent on baseline values (i.e., law of initial values). Thus, the data provide additional evidence for the importance of applying residualized change scores or other regression methods (e.g., partial correlation, analysis of covariance, regression transformation) to study specific "reactivity" processes. These strategies to study autonomic reactivity to psychological manipulations, proposed at the time psychophysiology was emerging as a discipline, are still valid and crucial to current research (e.g., Benjamin, 1967). Fourth, the changes in autonomic reactivity to social and physical challenges are, in part, dependent on the changing metabolic demands associated with task related activity. These findings suggest that measurement of movement is critical when studying autonomic responses and useful in providing a functional interpretation of reported changes in autonomic state. Fifth, autonomic reactivity to the social challenge may provide an experimental portal to study the mechanisms of anxiety and/or depression in children.

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