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Physiological and Emotional Reactivity to Learning and Frustration

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Abstract

This study examined the behavioral (arm, facial) autonomic (heart rate, respiratory sinus arrhythmia [RSA], and adrenocortical axis) reactivity of 56 4-month-old infants in response to contingency learning and extinction-induced frustration. During learning, infants displayed increases in operant arm response and positive emotional expressions. Changes in average $RSA(V_{NA})$ paralleled the observed changes in facial expressions in general and maintained an inverse relation with heart rate throughout most of the session. When frustrated by extinction, infants displayed increases in negative expressions, heart rate, and a brief increase in RSA(V_{NA}) followed by a significant decrease. No significant changes were observed for cortisol. These behavioral and facial responses are consistent with earlier work. The physiological changes, along with the facial expressions and instrumental responses, indicate that the autonomic nervous system functions as a coordinated affect system by 4 months of age.

Lewis and colleagues (Alessandri, Sullivan, & Lewis, 1990; Lewis, Alessandri, & Sullivan, 1990; Lewis, Sullivan, & Brooks-Gunn, 1985; Lewis, Sullivan, & Michalson, 1984; Lewis, Sullivan, Ramsay, & Alessandri, 1992; Sullivan & Lewis, 1988, 1989; Sullivan, Lewis, & Alessandri, 1992) have documented that when young infants learn a contingent response (e.g., pulling a string to produce an audiovisual stimulus), they display increases in positive emotional expressions. When the contingency is taken away and arm responses produce no reward (a brief extinction), infants between the ages of 2 and 8 months react with increased arm responding and negative emotional expressions. The baseline phase, a period of no reward, yields low amounts of emotion except for interest expressions. Although some controversy still surrounds the interpretation of infant facial expressions, during the learning and extinction procedure, they are consistent with the positive and negative action patterns shown by infants who learn and are subsequently frustrated (Sullivan & Lewis, 2003). The learning phase is marked by expressions of surprise and enjoyment that are indicative of stimulus engagement and are, therefore, signs of positive emotion. In contrast, the extinction phase, during which the infant's expectancy of reward is violated, is marked by predominantly anger expressions that are indicative of response to a blocked goal and are, therefore, negative emotion (Alessandri et al., 1990; Lewis & Goldberg, 1969; Lewis et al., 1990; Lewis et al., 1992; Shapiro, Fagen, Priogot, Carroll, & Shalan, 1998; Singer & Fagen, 1992; Sullivan & Lewis, 1989; Sullivan et al., 1992).

We examined physiological responses in addition to facial expression in this study to better understand emotional responses to learning and its frustration. Widely regarded as a basic cognitive skill of infants, contingency learning involves the coordination of multiple behavioral systems, including motor responses, attention, and emotion. Contingency

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learning and its frustration offer an opportunity to observe the coordination between these behavioral systems and their continuous regulation as young infants learn a response and encounter the withdrawal of salient stimulation. Although several studies have explored the relation of resting levels of cardiac physiology to emotion and emotional reactivity (for a review, see Porges, Doussard-Roosevelt, & Maiti, 1994), little is known about the physiological changes corresponding to shifts in emotional tone during contingency learning and subsequent frustration. The phases of a learning and frustration procedure (i.e., baseline, contingency, and extinction) are likely to have a major impact on both attention and emotion due to novelty and increased cognitive demand. Consequently, we expected to observe the greatest changes in the cardiac measures as well as facial expressions at the phase transitions. We chose to study these changes in 4-month-old infants because the majority of infants learn the contingency rapidly at this age and because vagal tone, a measure of respiratory sinus arrhythmia (RSA), shows the expected relations with soothing and engagement by 4 months (Doussard-Roosevelt & Porges, 1999). Therefore, we expected some correspondence among learning behavior, emotion expression, and cardiac regulation to be evident.

Three measures of autonomic nervous system functioning served as assessments of physiological change during learning and frustration. Two measures of cardiac response heart rate (HR) and the amplitude of respiratory sinus arrhythmia (RSA[V_{NA}])-were measured continuously throughout the task. Decreases in HR have often been used as an indicator of orienting and attending, and HR increases have been used as an indicator of sympathetic arousal and parasympathetic inhibition (cf. Lewis, 1974; Porges, 1992; Richards & Casey, 1992). RSA represents the rhythmic changes in HR variability occurring as a result of the interaction in the medulla between respiratory control centers and the nucleus ambiguous, which is one source of vagal input to the heart via the sino-atrial node (Richter & Spyer, 1990). RSA(V_{NA}) is a commonly used measure of psychophysiological regulation as it is considered an accurate and noninvasive index of cardiac vagal tone or, in other words, the parasympathetic neural control exerted on the heart by the vagus nerve (Katona & Jih, 1975; Porges, McCabe, & Yongue, 1982). HR, in contrast, reflects both sympathetic and parasympathetic influences. Most commonly, sympathetic and parasympathetic influences on the heart are reciprocal; however, under certain circumstances (e.g., stress or fear), coactivation or coinhibition of autonomic control may occur (Berntson, Cacioppo, & Quigley, 1991, 1993).

The cardiac measures, especially RSA(V_{NA}), were expected to vary with the emotional tone of infants' behavior during the learning procedure. According to Porges's polyvagal theory of emotion (Porges, 1995, 1997, 1998), the vagus nerve is part of a complex neurological feedback system regulating the balance between activating demands from the external environment, shown by reductions in RSA(V_{NA}), and the support needed to maintain internal homeostasis for restorative and cognitive processes, shown by increases in RSA(V_{NA}). In particular, Porges posited that situations involving positive emotional engagement with the environment should be accompanied by increased parasympathetic vagal influence to the heart. In Porges's terms, putting on the "vagal brake" (Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996) has a slowing effect on the heart, which is thought to promote not only physiological homeostasis, but also pleasant states, social engagement, and approach behaviors (e.g., looking, listening, positive vocalization, and positive facial expressions).

Changes in RSA(V_{NA}) in response to negative environmental challenges have not been studied extensively in humans. However, as observed by Bazhenova, Plonskaia, and Porges (2001), increased negative emotion should be accompanied by reduced RSA(V_{NA}), that is, a release of the vagal brake, promoting the increases in HR needed to support the increased

metabolic demand for carrying out behavioral mobilization (i.e., fight and flight behaviors). With respect to the study reported here, this theory predicts that the positive expression during contingency learning should be paralleled by an increased $RSA(V_{NA})$ and, therefore, a corresponding decrease in HR. In contrast, increased negative expressions during extinction should be accompanied by a decrease in $RSA(V_{NA})$. Finally, contextual contrast, such as the initial unexpected onset of contingent stimulation during learning and its initial unexpected cessation during extinction, were hypothesized to mark significant directional changes in the reciprocal patterning of physiological responses due to increased demands on infant attention and emotion due to the changing nature of environmental stimulation.

The final physiological measure, adrenocortical reactivity, as indexed by salivary cortisol levels, was assessed both before and after the contingency procedure. It has been shown that the hypothalamic–pituitary–adrenal (HPA) stress system is activated by events that produce high amounts of negative emotion such as inoculations (Lewis & Ramsay, 1995a, 1995b; Lewis & Thomas, 1990; Ramsay & Lewis, 1994) and circumcision (Gunnar, Broderson, Krueger, & Rigatuso, 1996). It is not known, however, if the frustration experienced by infants during the violation of expectancy enlists an HPA response. Psychological stressors (e.g., separation distress) appear to enlist an HPA access in certain groups of toddlers (Gunnar, Mangelsdorf, Larson, & Hertsgaard, 1989; Hertsgaard, Gunnar, Erickson, & Nachmias, 1995). The range of potential psychological stressors is large and not all of them may elicit a cortisol response. Whether learning and extinction are sufficiently stressful to affect this physiological system in young infants is therefore of interest.

Thus, this study attempted to document the dynamic changes taking place in young infants' cardiac, cortisol, and expression responses concurrently with the changing attentional and cognitive demands of learning and a frustration. The three primary goals of this study were (a) to replicate the pattern of behavioral arm response and facial expressions seen in other studies of contingency learning and frustration using the same task (Alessandri et al., 1990; Lewis et al., 1990; Sullivan et al., 1992); (b) to explore the relation between the emotional and physiological, especially cardiac, measures; and (c) to document changes in dynamic cardiac and adrenocortical reactivity that accompany behavioral changes seen in response to the shifting task demands of learning and extinction.

We predicted that (a) contingency learning would produce increases in arm response and positive facial expressions during learning relative to baseline, and loss of contingency during extinction would produce high levels of both arm response and negative facial expressions relative to baseline, as observed in past work; (b) changes in cardiac physiology would parallel the behavioral changes seen; that is, the positive emotional expressions during learning would be accompanied by high, stable $RSA(V_{NA})$ and decreased HR relative to baseline as predicted by polyvagal theory, and the negative expressions during extinction would be accompanied by decreased $RSA(V_{NA})$ and increased HR relative to learning; (c) significant changes in physiology and expression would be evident when alterations in stimulus context are introduced, reflecting increased attention demand; (d) there would be negative correlations between positive and negative facial expressions, as well as between RSA(V_{NA}) and HR, because each pair of measures are commonly regarded as theoretical and conceptual opposites; (e) similarly, there would be positive correlations between positive expressions and RSA(V_{NA}), as well as between negative expressions and HR; and (f) postsession cortisol levels would rise significantly above presession levels, as infants react to the psychological stress of an unexpected contingency and subsequent frustration.

METHOD

Participants

Fifty-six 4-month-old infants (29 girls, 27 boys) participated in the study. The infants ranged in age from 104 to 139 days (M age = 119.6 days, SD = 8.4). Infants were Asian (n = 4), White (n = 51), and Hispanic (n = 1). Thirteen additional participants were excluded due to equipment failure (n = 4), fussy behavior (n = 3), and failure to meet the learning criterion for the task (n = 6). The learning criterion is described fully in the Behavioral Measures section.

All infants were full-term at birth, had no history of birth complications or sensory and neurological deficits, and were healthy at the time of observation. Participants were recruited through telephone calls to parents following a previous contact made in the maternity unit at a local university teaching hospital.

Apparatus

Infants were tested in a three-sided booth while sitting in a reclining infant seat. The seat faced a rear-projection screen (18 cm square) mounted in the rear wall of the booth. The seat was placed 45 cm from the screen during training and testing. Auditory feedback (at a level of 50 dB) was provided by a cassette player placed behind the screen. A string was attached to the infant's wrist via a terrycloth elastic wristband and was connected to a leaf switch (Zygo Industries, CM-2) mounted behind the booth. When pulled, the string activated a 3-sec stimulus presentation of a color slide of an infant's smiling face, accompanied by a recording of children's voices singing. Infant arm responses were recorded by a Laser 128 Apple-compatible personal computer.

During the session, infants' faces were continuously monitored in close-up by a Burle TC292 color video camera mounted just below the screen, and videotaped on a Sony EVC200 Hi8 videocassette recorder. A digital readout of time, in seconds, was simultaneously encoded on the videotape. Subsequently, the videocassette recorder was used in slow motion for coding facial behaviors.

A Grass Polysomnograph (Model 78F, Quincy MA) was used for monitoring the infant's electrocardiogram (ECG) throughout the entire session via three infant Ag/AgCl disposable electrodes (Vermont Medical Inc., Bellows Falls, VT) attached to the chest in a triangular configuration: one on the right shoulder, one on the left side, and the ground lead on the lower abdomen. The ECG signal was recorded onto tape by an FM tape recorder (Model D, A. R. Vetter Co., Rebersburg, PA), and the output was quantified offline by using a vagal tone monitor (Delta Biometrics Inc., Bethesda, MD).

Procedure

The session was scheduled at an alert or play time as designated by the infant's parent. On arrival at the laboratory, a baseline saliva sample was collected by placing an absorbent dental cotton roll in the infant's mouth. The infant was then seated in the apparatus and the ribbon was attached to the right wrist. A parent sat behind the infant throughout the entire contingency session, out of the child's view.

The session consisted of three phases: baseline, learning, and extinction. The baseline phase involved a 2-min period of nonreinforcement during which the operant level of arm responses was recorded. The learning phase was a 6-min period of contingent stimulation during which arm responses activated the audiovisual stimuli. This time interval was chosen to be sufficient to observe learning, but brief enough to preclude boredom or crying (Lewis

et al., 1985). This session length was determined by analyzing the individual performance of 3-month-olds in a foot-kick contingency task (Hitchcock & Rovee-Collier, 1996) and 4-month-olds in the arm response task (Lewis et al., 1985). The extinction phase consisted of a 2-min period of nonreinforcement (procedurally identical to the baseline phase). The second saliva sample was taken 20 min after the end of the session. This is the standard interval used to detect the peak cortisol response to stress and arousal in most infants (Lewis & Ramsay, 1995a, 1995b; Lewis & Thomas, 1990; Ramsay & Lewis, 1994). Both pre- and postsession cortisol samples were immediately frozen and stored at -42 °F for later analysis.

Behavioral Measures

Arm response rate—Responses were continuously and automatically recorded during the experimental session. To be included in the final sample, each infant had to meet the criterion of an average arm rate equal to or greater than 1.5 times his or her original baseline rate in at least 2 of 3 consecutive minutes during the learning phase. This is a standard learning criterion used in infant learning research (see Rovee-Collier, 1996). All 56 infants reached this learning criterion during the learning phase.

Facial expressions—Facial movements were coded from the videotaped sessions using Affex (Izard, Dougherty, & Hembree, 1983), the whole face version of the Maximally Discriminative Facial Movement Coding System (MAX; Izard, 1995). Three coders were trained by an experienced MAX coder using both MAX training tapes and precoded slides of infants from earlier studies using the same procedures.

Faces were viewed in slow motion, second by second. Based on MAX formulae, coders noted the occurrence of the MAX codes for expressions of joy (00-00/33-52), surprise (20-30-00/50), anger (25-33-00/54/55), sadness (23-33-00/56), and anger/sad blends (25-33-56 or 23-33-54/55). Interest expressions, which represent a large heterogeneous category of expressions in MAX, were not coded. Instead, we coded only the raised brow, eyes wide components that characterize MAX surprise expressions and also some variants of MAX interest. The frequency of each expression was tabulated for each 30 sec of the session. Reliability was assessed by computing kappa statistics on a random sample of 9 participants (16%) scored by two coders. The average kappa coefficient for the ratings of all five facial expressions combined over the total session was .86 (range: joy, $\kappa = .92$; surprise, $\kappa = .69$; anger, $\kappa = .87$; sadness, $\kappa = .93$; anger/sad blends, $\kappa = .91$). All kappas indicated above-chance agreement for all expressions scored.

For each expression, the frequency per minute was calculated. These scores were then averaged across expressions to yield a composite score of average positive emotional expression (joy and surprise) and average negative emotional expression (anger, sadness, anger/sad blends) per minute.

Physiological Measures

HR—The raw ECG signal was played layed back through the vagal tone monitor to digitize the signal at a rate of 1,000 Hz and to detect the peak of each R-wave. Sequential heart periods (R-R intervals) were timed to the nearest millisecond and the output was stored as an ASCII file. Heart period (HP) data were then edited using MXedit software (Delta Biometrics, Bethesda, MD). This PC-based program allows visual inspection of the R-R intervals and permits the editing of faulty R-wave detections. Aberrant values were adjusted by integer addition and division of the sequential R-R intervals to fit the preceding and following intervals. Less than 1% of the data were adjusted in this way.

Mean values were computed for each 30-sec epoch and then averaged over each minute of the session, yielding scores for mean HP per minute. HR values were then calculated from the HP data using the formula HR = 60,000 msec/HP, or the standard conversion of HP to a per-minute rate.

RSA(V_{NA})—MXedit was also used to calculate RSA(V_{NA}), a statistic representing the amplitude of RSA at a band of frequencies characteristic of breathing as an index of cardiac vagal tone (Porges, 1991, 1992). This index, RSA(V_{NA}), is an estimate of the vagal influence on the heart originating in the nucleus ambiguus. For this study, a frequency range of 0.24 to 1.04 Hz was used, which is equivalent to the normal rate of spontaneous breathing in infants under 1 year of age (Porges, 1991, 1992). The algorithm for calculating RSA(V_{NA}) involved two steps. First, a 21-point moving polynomial was applied to the R-R interval data, which was sampled every 250 msec to remove complex trends and slower heart rhythm periodicities. A 25-point symmetrical bandpass filter was then applied to the respiratory frequencies. The resulting RSA(V_{NA}) statistic was the natural logarithm of the variance expressed in units of log_emsec2. Mean values were computed in 30-sec epochs and then averaged over each minute of the session, yielding scores for mean RSA(V_{NA}). To facilitate comparisons by phase, the values were averaged within each phase.

Cortisol level—The collected samples of frozen saliva were shipped in dry ice to Covance Laboratories (Vienna, VA) for radioimmunoassay to detect the amount of unbound salivary cortisol (reported in µg/dl).1 To maintain sample size and to decrease variability, the data were inspected for outlying values, defined as any value greater than three standard deviations from the mean level for the entire sample (cf. Lewis & Ramsay, 1995a). These were replaced by calculating a proportion score (i.e., taking a known within-range value from the same infant and dividing it by the group mean for that value). The proportion score was then multiplied by the reciprocal of the group mean for the missing value. This yielded a value based on the group mean, assigning the infant a rank order from a set of values that were within 3 standard deviations of the group mean. Only 5 values out of 112 (4%) were adjusted in this way. There were no differences in the results whether or not the data for the adjusted outliers were included in the subsequent analyses.

RESULTS

Strategy for Data Analysis

To explore changes over the experiment, repeated measures analyses of variance (ANOVAs) were conducted for the minute-to-minute arm rate, cardiac, and facial expression measures. The analysis focuses on systematic trends over time across baseline, learning, and extinction. To focus on changes over time, trend analyses were used to examine changes in each measure across baseline, learning, and extinction. In addition, we also used planned contrasts to examine the minutes of greatest contextual change, those minutes corresponding to the between-phase transitions (i.e., the first minute of learning and the first minute of extinction) in relation to preceding and subsequent minutes. Because the first minute of these two phases represents a demand for increased attention, we expected the greatest behavioral and physiological change to occur when a new phase was introduced.

²Minutes 7 and 8, learning minutes, differed only from Minute 10, an extinction minute.

¹This laboratory's quality-control procedures have been described previously (Lewis & Thomas, 1990).

All multivariate *F*s are based on Wilks's criterion. Unless indicated otherwise, subsequent post hoc mean comparisons were conducted using Helmert and reverse Helmert contrasts within groups. All pairwise comparisons used Bonferroni's adjustment for multiple comparisons. Confidence levels were set at 95%. There were no significant main effects of gender. All of the measures, with the exception of cortisol, showed significant changes over the experimental session.

Changes in Arm Response Over Time

Figure 1 shows arm rate increased over baseline, learning, and extinction. As can be seen, arm responses increased over minutes, F(9, 46) = 13.89, p < .001, by repeated measures ANOVA. Within-subjects contrasts revealed a strong linear, which can also be seen in the figure, F(1,44) = 4.94, p < .05. Arm responses during the second minute of learning were significantly greater than during either baseline minute. All subsequent minutes also were significantly above baseline (planned contrasts; all ps < .001). The average arm response during extinction was greater than the average rate during learning t(55) = 3.22, p < .01.

Arm Response to Phase Transitions

Table 1 presents the means and standard errors for arm responses and other measures during the transition minutes. When the effect of the transition to a new phase was examined, the planned contrasts showed that arm response in the first minute of learning (a) did not differ from the immediately preceding baseline minute, and (b) was lower than the following learning minute (p < .05). Likewise, the initial minute of extinction did not differ from the final minute of learning or the subsequent extinction minute. Thus, infants did not learn the arm response immediately, nor did they react immediately to extinction. Therefore, any corresponding changes in emotion and physiology during the initial minute of learning and extinction are due to their detection of contextual change and not learning per se.

Changes in Cardiac Responses Over Time

Figure 2 shows both HR and RSA(V_{NA}) changes over time. The repeated measures ANOVA conducted on minute-to-minute changes in HR was significant, F(9, 46) = 13.72, p < .001. HR showed a significant cubic trend over minutes, F(1, 54) = 4.85, p < .04. After an initial increase during baseline, HR remained relatively stable from the onset of the learning phase, increasing gradually. There was a significant increase during the 2 min of extinction. The change in HR from the final minute of baseline to the first learning minutes was not significant. All learning minutes were significantly different from one or both extinction minutes2 (planned comparisons; all ps < .05 or better). Average HR during extinction was higher than during baseline and the average HR during the first 4 min of learning (planned contrasts; all ps < .01).

As shown in Figure 2, RSA(V_{NA}) also showed a significant change over minutes, F(9, 46) = 4.11, p < .01. These changes described a complex function with a significant fifth-order trend, F(1, 54) = 16.91, p < .001.3 RSA(V_{NA}) declined significantly from the first to the second baseline minute, but increased significantly again during the first minute of learning (both ps < .01). It declined significantly from the first minute of learning to the second (p < .001) and remained at this level during all subsequent learning minutes (all values significantly less than the first minute, $ps \le .05$). Following this relatively stable level during learning, RSA(V_{NA}) increased again at the onset of extinction. Learning Minute 8 and extinction Minute 9 did not differ significantly from each other or the final baseline minute,

³Linear and quadratic trends were marginally significant (both ps < .08).

but extinction Minutes 9 and 10 were each greater than the first baseline minute (both ps < . 10).

Cardiac Response to Phase Transitions

The pattern of the cardiac measures across the changing contextual demands of the experimental phases is presented in Figure 3. The means with standard errors appear in Table 1. Figure 3 summarizes the changes occurring in the two major transition minutes (the first minute of learning and the first minute of extinction) and both the prior and subsequent minutes of each phase transition. These minutes mark the critical changes in contextual conditions. This analysis allows us to examine the fifth-order trend more closely as well as to observe the reciprocal patterning of HR and RSA(V_{NA}), which is central to the hypotheses under study. That is, these minutes can be examined separately, because HR and RSA(V_{NA}) were relatively stable during the intervening learning minutes and we neither predicted nor found differences between Learning Minute 2 and Learning Minute 6. The initial baseline minute is not considered in this analysis because it may reflect cardiac reactivity to the novel environment of the experiment, and we did not obtain a preexperimental "resting" level for comparison.

Recall that HR was lower during the transition to learning as opposed to either of the adjacent minutes and that RSA(V_{NA}) shows the reciprocal pattern, as expected. Figure 3 shows this pattern in detail. In contrast, HR showed only a linear increase during the transition to extinction, despite the trend of relatively higher RSA(V_{NA}) at the transition to extinction. Thus, for RSA(V_{NA}), but not for HR, there was no difference in whether the transition was the onset of the contingency during learning or its removal during extinction. We confirmed these trends in a phase (learning, extinction) × minute (3) × sex repeated measures multivariate ANOVA including both the HR and RSA(V_{NA}) measures. The measures differed by minute, overall, F = 11.61, p < 001. Follow-up univariate ate *F* tests on each measure confirmed that there was only a significant linear trend for HR and a significant quadratic trend for RSA, $F_{\text{linear}}(1, 54) = 11.34$; $F_{\text{quadratic}}(1, 54) = 23.16$, both *ps* < .001.

For HR, the multivariate Phase × Minute interaction was also significant. Follow-up univariate *F*s indicated that there was a Phase × Minute interaction, F(2, 108) = 15.67, p < .001. Thus, learning and extinction transitions were marked by different HR patterns by phase. There were quadratic trends in HR during the transition to learning but a linear increase during the transition to extinction. However, for RSA(V_{NA}), we found only a main effect of minute, F(2, 108) = 11.61, p < .001. In contrast to HR, learning and extinction showed the same quadratic pattern of RSA(V_{NA}) across both phases.

Relations between cardiac responses and activity—Although arm responses changed over time, the changes observed in HR and $RSA(V_{NA})$ were not due to increased infant's activity. Table 2 presents the correlations between HR and $RSA(V_{NA})$ as well as the correlations between both arm rate and HR and $RSA(V_{NA})$. The expected modest negative relation between HR and $RSA(V_{NA})$ was present through all phases. Arm rate was only weakly related to HR and $RSA(V_{NA})$. The correlations between HR and $RSA(V_{NA})$ do not change when partial correlations are used to control for arm rate.

Changes in Emotional Reactivity by Phase

Figure 4 shows the minute-to-minute changes in positive and negative emotional reactivity as indexed by facial expression. Separate repeated measures ANOVAs conducted for positive and negative expressions revealed a significant change over minutes for positive and negative expressions, F(9, 46) = 7.57, p < .001, and F(9, 54) = 7.34, p < .001,

respectively. A quadratic trend was observed in the amount of positive expressions over phase, F(1, 54) = 36.58, p < .001. Positive expressions during each minute of learning were significantly greater than baseline, but they decreased significantly from the final learning minute to extinction (all ps < .001). For negative expressions, we observed a linear increase over minutes, F(9, 54) = 49.79, p < .001. There were virtually no negative expressions during baseline, and the maximum level occurred during the final minute of extinction.

Positive and Negative Expressions During Phase Transitions

Table 1 summarizes the means and standard deviations of facial expressions during the transition to learning and extinction. The transition to learning was associated with significant mean differences in positive expression. Positive expressions were significantly greater during the initial minute of learning than during the prior or subsequent minute (both $ps \le .01$). Positive expressions declined significantly during the initial minute of extinction and remained at this very low level thereafter (p < .001).

For negative expressions, although the means show an increasing trend, there were no significant differences during the transition to learning. In contrast, the transition to extinction was marked by a significant increase in negative expressions, followed by a further significant increase (both ps < .001).

Relations to cardiac measures—Positive and negative expressions were inversely correlated across all minutes of the learning phase. To explore the relations between all the measures of facial expression and cardiac responses, correlations were calculated across the session minutes. Table 3 presents these correlation measures by phase with transition minutes shown in bold. Contrary to prediction, there was no relation between positive expressions and RSA(V_{NA}), or between positive expressions and HR. Instead, negative expressions were positively and significantly related to HR during the last minute of baseline, most learning minutes, and during both minutes of extinction. Except for the first minute of extinction, there was little relation between negative expressions and RSA(V_{NA}). Controlling for arm responses had no effect on the relation between the cardiac measures and emotion.

Cortisol Level

Infants' mean cortisol levels before and after the session showed no significant increase from presession level (M = .67 (µg/dl) to postsession level (M = .69 (µg/dl), indicating the learning and frustration experience was not stressful enough to involve the HPA axis. There also were no significant correlations between cortisol levels and any other measure.

DISCUSSION

This study confirms previous findings that contingency learning yields increases in both arm responses and positive emotional expressions, whereas the removal of the contingency during a brief extinction phase produces increased negative expressions as well as decreased positive expressions (Lewis et al., 1990). Baseline, a time when the context is novel but demands little of the infant, is a time of lower motor, emotional, and physiological engagement. During the first minutes of learning, infants initially responded to the contingency with calm attentiveness indexed by increased RSA(V_{NA}), decreased HR, and increased positive expressions. These expressions and relatively stable cardiac autonomic patterns were maintained even as significantly increased motor activation occurred. The extinction phase, marked by the loss of the expected contingency, was characterized by increased negative expressions, decreased positive expressions, and initially refocused attention as indexed by increases in both HR and RSA(V_{NA}). Subsequently, sympathetic

arousal, indexed by $RSA(V_{NA})$ withdrawal and continued HR increase, presumably marked the beginning of disengagement. At this time, negative arousal was at its greatest, most infants were fussing actively, and the highest levels of arm responses and negative expression were observed.

There are three major findings for $RSA(V_{NA})$. First, $RSA(V_{NA})$ generally showed the reciprocal relations with HR predicted by the vagal brake model, both in the mean patterns observed at the phase transitions and in correlations over time. $RSA(V_{NA})$'s trajectory also generally paralleled HR changes during learning, and the negative correlations between the measures were significant during this time. That is, when HR did not vary significantly during learning, $RSA(V_{NA})$ also remained stable and negatively related to HR. $RSA(V_{NA})$ therefore does show the predicted suppressing influence on HR during periods of heightened activity that might otherwise lead to HR acceleration.

Second, as predicted, the most significant increases in $RSA(V_{NA})$ occurred at the phase transitions, or the first minute of learning and extinction relative to the adjacent minutes. In these transition minutes, a salient change in the stimulus context occurred, whether it was the introduction of the contingency or its unexpected cessation. The salience of these changes most likely led to increases in $RSA(V_{NA})$, which were independent of arm response and not sustained in subsequent minutes. The high initial level of $RSA(V_{NA})$ during the first minute of baseline can also be understood as a response to the introduction to the novel experimental situation, and so is consistent with these data.

Third, positive emotion predominated when $RSA(V_{NA})$ was in a reciprocal relation with HR, but negative emotion predominated when a nonreciprocal relation occurred. Increases in positive expressions, predominantly surprise, accompanied increased $RSA(V_{NA})$ only during the transition to contingency. Thereafter, positive emotions remained stable as long as $RSA(V_{NA})$ and HR remained stable, but there was little relation between positive emotion and either cardiac measure. Thus, higher $RSA(V_{NA})$ marks heightened attention and interest during contextual transitions, but similar levels of positive expressions also occur at lower vagal tone levels. Increases in vagal tone, therefore, may set the stage for increased positive emotional tone, whereas lower, stable $RSA(V_{NA})$ was characteristic of sustained positive emotional tone.

Contemporary models of cardiac physiology show that parasympathetic and sympathetic influences on the heart can work independently or synergistically, although reciprocity is the modal pattern of autonomic control (Berntson et al, 1991). Nonreciprocal patterns between HR and RSA(V_{NA}) may reflect independent sympathetic activation, independent parasympathetic withdrawal, the coactivation of both systems, or their simultaneous withdrawal or coinhibition (Berntson et al., 1991). The nonreciprocal model explains why sympathetic activity is sometimes seen in the absence of vagal inhibition (Brooks, 1983; Grossman, 1983; Koizumi, Terui, & Kollai, 1983). In this study, both reciprocal and nonreciprocal patterns were seen. Nonreciprocal relations between RSA(V_{NA}) and HR marked the transition to negative emotion. Relations among RSA(V_{NA}), HR, and negative expression were apparent during extinction, and relations with positive expressions were notably absent at this time. During the initial minute of extinction, the typical reciprocal relation between $RSA(V_{NA})$ and HR was disrupted and both measures rose significantly relative to their levels in the preceding minute. That is, we found simultaneous significant increases in both cardiac indexes at the transition to extinction, when negative expressions had also increased significantly. This was followed by a return to the expected reciprocal pattern of the vagal brake. The significant decrease in RSA(V_{NA}) during the final minute of extinction was again accompanied by the highest observed levels of both HR and negative emotion and a reciprocal decline in RSA(V_{NA}). The increases in HR at this time were

unrelated to arm movement. Past findings have demonstrated that negative behavioral reactivity can be, at times, associated with high parasympathetic activity (see Stifter & Fox, 1990). Nonreciprocal modes of autonomic control (i.e., coactivation or coinhibition of the parasympathetic and sympathetic systems) have been typically observed in animals under conditions of either stress or fear and avoidance (Berntson et al., 1991).

One example of nonreciprocal cardiac patterns reported for human infants is the simultaneous coinhibition of HR and RSA(V_{NA}) during highly focused, vigilant attention. During focused attention, the normal opposing relation between HR and RSA(V_{NA}) does not occur (cf. Lewis, 1974; Richards & Casey, 1992). Usually, simultaneous depression in both RSA(V_{NA}) and HR occurs in older children and adults (Porges & Raskin, 1969; Suess & Bornstein, 2000; Suess, Newlin, & Porges, 1997; Weber, van der Molen, & Molenaar, 1994) and in infants when using fairly uncomplicated tasks involving visual attention (Richards & Casey, 1991) or habituation (Suess & Bornstein, 2000). This finding has been explained by likening sustained attention to the freezing behavior that accompanies sudden heightened arousal and attention in animals. Although behaviorally quiet, they are in a state of preparation for action and using metabolic resources to support the demands of the sustained cognitive processing (Porges, 1992; Richards & Casey, 1991; Suess & Bornstein, 2000). Studies using more complex tasks involving emotional engagement have found increases in RSA(V_{NA}) during sustained attention (e.g., Bazhenova et al., 2001; DiPietro, Porges, & Uhly, 1992). During the transition to extinction in this study, however, increases in both cardiac measures (coactivation) were accompanied by the increase of negative expressions of anger, sadness, and their blends. This pattern fits a stress rather than a fear or focused attention interpretation.

There was no significant increase in cortisol response in this study, suggesting that despite HR increases and negative expression, extinction was not sufficiently stressful to enlist the HEA system. The cardiac measures were more sensitive in this regard. Although it might be argued that coming to the laboratory itself might be sufficiently stressful to increase cortisol, this is unlikely. The values of cortisol observed in this study are comparable to those observed at this age on arrival at pediatric offices prior to inoculation (Lewis & Ramsay, 1999). Cortisol increases above waiting room baseline levels are reliably observed in response to inoculation in pediatric settings. Therefore, the stress of travel and arrival at the laboratory cannot have masked a cortisol rise. Rather, the failure to observe an increase is likely due to the less stressful nature of the procedures than to a ceiling effect. Moreover, the lack of a behavioral–cortisol relation is consistent with findings that there is at best only a modest relation between cortisol response and behavioral responses to stress (e.g., Lewis & Ramsay, 1995a; Lewis, Ramsay, & Kawakami, 1993; Lewis & Thomas, 1990; Ramsay & Lewis, 1994).

Collectively, these findings provide qualified support of the polyvagal theory of emotion. The theory predicts calm, emotional engagement with the environment supported by increased vagal influence on the heart (Bazhenova et al., 2001; Porges, 1995, 1997, 1998). We found that the transition minutes, or initial minutes of learning and extinction, were particularly marked by sharp increases in RSA(V_{NA}). The greatest increases in RSA(V_{NA}) and the predicted reciprocal relations with HR in this study were most related to the introduction of a novel context and to the relative balance of positive to negative expression rather than to positive tone per se. With the exception of the first minute of extinction, when increases in both cardiac measures and negative expression were observed, increased RSA(V_{NA}) was accompanied by lower HR, as expected, and more positive than negative expression. In contrast, a nonreciprocal autonomic pattern, the simultaneous increase in both cardiac responses during extinction, was accompanied by rapidly increasing negative expressions and appears to index a stress-related response. Contextual changes therefore

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appear to be a potent activator of changes in RSA(V_{NA}), but the balance of positive and negative emotion appears related to the reciprocity of autonomic response. Bazhenova et al., following Vygotsky (1935/1983), suggested that infant cognitive functioning is dependent on emotion. Consequently, young infants may show high levels of $RSA(V_{NA})$ due to attention to discrepant or novel events. However, thee nature of the relation between cardiac measures may be dependent on the infant's emotional response to those novel events and especially the degree to which negative emotion is present. Because the infants showed a similar increase in $RSA(V_{NA})$ at the start of learning when new stimulation was introduced, the stimulus governing the vagal brake is likely to be the sudden contrast in the nature of the environmental stimulation that elicits a refocus of attention. The difference is the relative amount of positive versus negative expression. Consequently, RSA(V_{NA}) might be influenced by a cognitive-emotional mechanism that can briefly override competing metabolic demands (e.g., motor behavior and negative arousal) to support sudden demands for heightened attention to the environment. A similar argument has been made by Bazhenova et al. to explain observed $RSA(V_{NA})$ increases independent of motor activity, as was observed throughout this study. They suggested that increases in RSA(V_{NA}) may be a component of a physiological state supporting attention to the environment regardless of other metabolic demands. The positive correlations between negative emotion and $RSA(V_{NA})$ and between negative emotion and HR, seen only during the transition to extinction, support this view.

The expected negative correlation between positive (surprise and enjoyment) and negative expressions was evident across transitions. At best, however, this relation was modest. It was weakest during baseline when both positive and negative expressions were low and during extinction when negative expressions dominated. This suggests that at extremes of arousal, positive and negative reactivity are somewhat independent.

The results suggest that the nature of the positive engagement related to $RSA(V_{NA})$ is one of stimulus approach and an emotional balance favoring positively as opposed to negatively toned arousal rather than increased positive emotionality per se. Cardiac responses during learning are related to demands for attention to contextual changes (i.e., contingency onset and removal) that challenge infants to attend, learn, and modify their behavior. Independent of infant arm responses, they are related to the balance between positive and negative expressivity. The only time that the expected reciprocal relation between HR and RSA(V_{NA}) was disrupted was during extinction, minutes marked by sudden stimulus loss and increased negative arousal. The regulation of expressions and state in response to the cognitive challenge of contingency learning and its frustration is a process involving continuous coordination among somewhat independent behavioral, emotional expression, and physiological systems.

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FIGURE 1.

Minute-to-minute changes in arm rate over 2 min of baseline (B), 6 min of learning (L), and 2 min of extinction (E) in 56 infants. Standard errors are shown.



FIGURE 2.

Cardiac measures, HR, and $RSA(V_{NA})$ over 2 min of baseline (B), 6 min of learning (L), and 2 min of extinction (E) in 56 infants.



FIGURE 3.

Vagal reactivity and heart rate during the transition to learning and extinction (N = 56). Minutes L1 and E1 are the critical transition minutes.



FIGURE 4.

Positive and negative expressions over 2 min of baseline (B), 6 min of learning (L), and 2 min of extinction (E) in 56 infants.

TABLE 1

Transitions
Phase
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Mean

			Base to L	earning				Le	arning to l	Extinctic	и	
	B_2		L_{I}		L_2		L_6		E_I		E_2	
	М	SE	Μ	SE	М	SE	Μ	SE	Μ	SE	М	SE
Arm rate	4.60	0.40	5.10_{a}	0.40	$6.90_{ m b}^{\dagger}$	0.60	8.50	0.57	8.80	0.58	¢09.6	0.80
Cardiac												
HR	$155.33_{\rm a}$	1.25	$153.56_{\rm a}$	1.26	$154.65_{\rm a}^{\not T}$	1.433	$156.30_{\rm b}$	1.37	$160.65_{\rm c}$	1.42	$62.89_{\rm c}^{ \dot{\tau}}$	1.60
$RSA(V_{\rm NA})$	2.76_{a}	0.13	$3.16_{\rm b}$	0.96	$2.74_{ m a}^{\sharp}$	0.12	2.76_{ab}	0.13	$2.99_{\mathrm{ab+}}$	0.11	$2.72_{\mathrm{a+}}$ ‡	0.14
Expressions												
Positive	0.42_{a}	0.83	$1.05_{\rm b}$	0.13	$0.82_{ m c}^{\ddagger}$	0.13	$0.94_{\rm ad}$	0.17	0.32_{ae}	0.07	$0.28_{\rm ae}^{\dot{\tau}}$	0.07
Negative	$0.07_{\rm a}$	0.29	$0.26_{\rm a}$	0.08	$0.30_{ m a}^{\dagger}\dot{ au}$	0.08	$1.04_{\rm b}$	0.18	$1.77_{\rm c}$	0.26	$2.27_{\rm d}^{\dagger}$	0.28

ontrasts. HR = heart rate; RSA(VNA) = amplitude of respiratory sinus arrhythmia.

 $\dot{\tau}$ Significant linear increase over minutes.

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 \sharp Significant quadratic trend over minutes.

 $^{+}_{p < .10.}$

TABLE 2

Correlations Between Heart Rate, Vagal Tone, and Arm Response Over Time in 56 Infants

	Base	eline			Lea	rning			Exti	nction
	1	2	3	4	5	6	7	8	9	10
Arm										
HR	09	03	06	16	04	04	.02	03	01	13
V_{NA}	.16	.15	17	.07	12	10	.03	.08	.01	08
HR^{a}										
V_{NA}	25 ⁺	31*	19	36**	37**	36**	43**	44 **	12	21+

Note. HR = heart rate; V_{NA} = vagal tone via the nucleus ambiguous.

^aControlling for arm did not affect the relations between the cardiac measures.

+			
n	<	.10.	

* *p* < .05.

** p < .01.

TABLE 3

Correlations Between Cardiac and Expression Measures Over Minutes During Learning and Extinction

	Bc	ISE			Learn	ing			Extine	tion
	I	7	Ι	7	з	4	5	9	I	7
Positive and negative expressions	14	14	38**	33 *	34 **	35 **	33*	23+	23+	18
Positive expressions and cardiac measur	se									
Positive expression and HR	13	04	11	.01	11	03	.01	14	.01	12
Positive expression and $RSA(V_{NA})$	09	08	60'-	0 05	08	16	05	03	03	.01
Negative expressions and cardiac measu	Ires									
Negative expression and HR	14	.37**	.19	.38**	.34**	.37**	.38**	.17	.28*	.27*
Negative expression and $RSA(V_{NA})$	00.	09	.10	14	.04	80.	.14	.10	.32*	60.

Note. Partial correlations controlling for arm rate did not differ from the tabled correlations. Transition minutes are shown in boldface. N = 56. HR = heart rate; RSA(VNA) = amplitude of respiratory sinus arrhythmia.

 $^{+}_{p < .10.}$

p < .05.p < .01.p < .01.