

## **Cry Threshold Predicts Regulatory Disorder in Newborn Infants<sup>1</sup>**

**Philip Sanford Zeskind<sup>2</sup>**

*Virginia Polytechnic Institute and State University*

**Timothy R. Marshall**

*Christopher Newport University*

**Dennis M. Goff**

*Randolph Macon Woman's College*

*Received December 19, 1995; accepted April 1, 1996*

---

*Studied the autonomic regulation of 37 infants with a typical cry threshold and 17 infants with a high cry threshold (typical of problems in nervous system function). Infants with a high cry threshold had a longer latency to cry, a shorter first cry sound, and a shorter overall bout of crying. Spectrum analysis of 2 hours of heart rate variability showed that a high cry threshold was predictive of fewer reliable rhythms and a lower power of the basic 40-min rhythm in heart rate. High cry threshold infants also showed fewer startles and changes in behavioral state. Results suggest a high cry threshold predicts disrupted autonomic regulation and poor coordination among rhythmic systems affecting cardiac activity.*

---

**KEY WORDS:** newborn infants; crying; heart rate; rhythms; assessment.

Analyses of the threshold and sound of crying in the newborn and young infant have long been shown to be sensitive to individual differences in the functional integrity of the infant's developing nervous system. A high threshold for eliciting a sustained cry and a distinctive high-pitched cry sound have differentiated

<sup>1</sup>Special thanks is offered to Lee Huntington and Julie Weiseman Baker for help in data collection.

<sup>2</sup>All correspondence should be addressed to Sandy Zeskind, Department of Pediatrics, Carolinas Medical Center, P. O. Box 32861, Charlotte, North Carolina 28232-2861

infants with conditions that range from obvious cases of brain damage to low birth weight and preterm birth to other biomedical circumstances that place infants at risk for nonoptimal development (Lester & Boukydis, 1985; Lester, Newman, & Pedersen, in press). The analysis of infant crying may be especially useful in the capacity to detect problems in nervous system function among infants who are seemingly normal and healthy. For example, full-term, full birth weight infants who show no abnormal signs on routine neurological and physical examinations but who are at risk due to pre- and perinatal conditions that adversely affect nervous system function have cries with a higher fundamental frequency (basic pitch), a higher cry threshold, a longer latency to cry from stimulation, a shorter initial cry segment and a shorter overall bout of crying than comparison infants (Zeskind & Lester, 1978, 1981). Recent work has shown these measures of crying also to be sensitive to the possible damaging effects of prenatal exposure to maternal use of cocaine (Lester et al., 1991) and alcohol, even in the absence of abnormal clinical signs (Zeskind, Platzman, Coles, & Schuetze, in press).

Generally, variations in the threshold and sound of crying in relatively healthy newborns have been conceived as reflecting a disrupted organization of behavior. While conceptual models have described the relations among infant crying, vagal tone, and autonomic nervous system activity (Lester, 1984), most empirical work has focused on the significance of differences in the *sound* of crying. For example, studies have shown that a higher fundamental frequency ( $F_0$ ) is related to cardiac measures of poor auditory orientation (Lester, 1975) and lower vagal tone (Porter, Porges, & Marshall, 1988). In one of the few studies to specifically examine relations between cry threshold and other behavioral systems, performance on the Neonatal Behavioral Assessment Scale (NBAS) was factor analyzed with several measures of the sound and threshold of crying (Zeskind, 1983). Unlike measures of the cry sound, higher thresholds and shorter durations of crying were related to poorer performance on the NBAS clusters of Autonomic Stability, Range of State, and Regulation of State. Low scores on these clusters resulted from high numbers of startles, tremors, and changes in skin color, and low or high numbers of state changes during the exam. In another study, the resting heart rates of infants with a high cry threshold were compared to those of infants with a typical cry threshold (Zeskind & Field, 1982). Whereas no difference was found in mean heart rate, groups differed in heart rate variability. Heart rate patterns of infants with a high cry threshold were described as more unpredictable and erratic than those of comparison infants. These studies suggest that a high cry threshold in seemingly healthy infants is related to a lesser, or disordered, capacity to regulate behavioral state and autonomic function.

Spectrum analysis of heart rate variability may be a useful method by which the autonomic regulation of newborns who vary in cry threshold can be further examined. Changes in heart rate reflect the summed effects of a wide range of

internally and externally derived sensory conditions including those that result from oscillations or changes in thermoregulation, blood pressure, respiration, vasomotor activity, and behavioral state (Porges, 1983). Spectrum analysis basically detects rhythmic patterns imbedded in the variability that results from the effects of oscillating systems which contribute to changes in heart rate. For example, rhythmic changes in heart rate at 0.35 Hz, 0.1 Hz, and 0.025 Hz reveal the effects on cardiac activity of oscillations in respiration, blood pressure, and thermoregulation, respectively (Sayers, 1973). Spectrum analysis of short-term (several minutes), beat-to-beat variability has been used in several studies to estimate vagal tone and patterns of autonomic reactivity (e.g., DiPietro, Larson, & Porges, 1987; Richards & Cameron, 1989). In contrast to the detection of specific neural processes, spectrum analyses of long-term variability has mostly been used to describe rhythmic activity underlying the infant's regulation of arousal. Analyses of 2 hours or more of heart rate have been used to detect cycles in fetal heart rate with periods of 2–3 and 3–4 hours (Hoppenbrouwers et al., 1981) and a 40-minute rhythm in the fetus (Hoppenbrouwers et al., 1981) and newborn (Zeskind, Goff, & Marshall, 1991). The 40-minute rhythm in heart rate has been observed in other behaviors as well and may reflect the effects on heart rate of the basic rest–activity cycle (BRAC) (Stratton, 1982).

Recent work suggests that the power spectra of long-term heart rate variability may also reflect individual differences in behavioral organization and autonomic regulation in newborn infants. For example, the power spectra of long-term heart rate variability in infants with patterns of atypical fetal growth show (a) fewer reliable rhythms and (b) a lower power of the 40-minute basic rhythm than the power spectra of comparison infants (Zeskind et al., 1991). In other studies, infants with the same patterns of atypical fetal growth have been shown to have a higher cry threshold (Zeskind & Lester, 1981) and to exhibit less-well organized patterns of behavior and autonomic regulation, as measured by the NBAS (Zeskind, 1981). Similarly, in separate studies, bottle-fed newborns have shown both lower vagal tone and differential performance on the NBAS (DiPietro et al., 1987) and fewer reliable peaks in the power spectra of their long-term heart rate variability (Zeskind, Marshall, & Goff, 1992). These differences in power spectra have been conceptualized as reflecting poorer coordination among the systems contributing to heart rate variability and as evidence of the infant's altered behavioral organization. Other than this indirect evidence though, no known studies have examined the relation between any measures of crying and the heart rate power spectrum.

The purpose of the present study was to directly examine the power spectra of the long-term heart rate variability of infants who vary in cry threshold, independent of their demographic or medical history or risk status. Three hypotheses were generated based on the literature reviewed above. First, infants with a high cry threshold were hypothesized to also show differences in other measures

of cry reactivity—a longer latency from stimulation to the first cry sound, a shorter duration of the initial cry sound, and a shorter overall bout of crying. Second, to the extent that a higher cry threshold reflects processes associated with a disordered regulation of autonomic activity, the power spectra of high cry threshold infants were expected to show fewer reliable peaks and a lower amplitude in the basic 40-minute rhythm than infants with a typical cry threshold. Third, we hypothesized that infants with typical and high cry thresholds would differ in the number of spontaneous startles and changes in behavioral state emitted during observation, thereby providing convergent evidence of disrupted autonomic regulation.

## METHOD

### *Participants*

Measures of infant crying and autonomic regulation were obtained from a sample of 64 infants who resided in the normal newborn nursery of a small urban hospital. Subsets of this sample were examined in previous studies in which the heart rate paradigm used in the present study was developed (Zeskind et al., 1991, 1992). Examination of infants' and mothers' medical records showed no nervous system or physical anomalies in any subjects; all infants were regarded as normal and healthy by routine physical and neurological examinations. Infants were from low socioeconomic status (SES) families as defined by their mothers' participation in a prenatal care program for the indigent. Based on the standard cry-eliciting procedure used in previous studies and described below, 37 infants required a single stimulus to elicit a sustained cry, 10 required two stimuli, and 17 required from three to five stimuli. As in all previous studies, stimulation resulted from application of a standard rubber band snap (RBS) to the sole of the infant's foot. Whereas infants typically require a single RBS to elicit a sustained cry, brain-damaged (Karelitz & Fischelli, 1962) and high-risk infants (Zeskind & Lester, 1978, 1981) usually require an average of three or more RBS. For the present study, high-threshold infants were defined as those requiring three or more RBS to elicit a sustained cry (multiple-RBS infants). Infants with a typical cry threshold were defined as those requiring a single RBS (single-RBS infants). Because they may constitute an heterogeneous group that may add unnecessary error variance to group analyses, it was decided a priori that the small number of subjects who required two RBS to elicit a sustained cry were not included in subsequent group comparisons.

Table I shows the means, standard deviations, and results of *t* tests comparing single-RBS and multiple-RBS infant groups on several standard demographic and obstetric measures. Single-RBS and multiple-RBS infants did not reliably

Table I. Birth Characteristics of Single-RBS and Multiple-RBS Infants

Variables	Group				<i>t</i> (52)	<i>p</i> <
	Single-RBS ( <i>n</i> = 37)		Multiple-RBS ( <i>n</i> = 17)			
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
Birth weight (g)	3,250	370	3,341	419	.81	.42
Gestation age (weeks)	39	1.7	39	1.7	.19	.85
OCS	95	18.8	100.9	25	.96	.34
Apgar (1 min)	7.6	1.8	7.9	2.1	.66	.51
Apgar (5 min)	9.0	0.62	8.8	1.3	.67	.51
Maternal age (years)	20.7	3.8	21.8	6.1	.51	.44
Maternal weight gain (lbs.)	29.5	7.9	24.6	20.7	.36	.36
Maternal education (years)	10.7	1.7	10.8	1.9	.82	.82
Distributions for chi-square analyses						
	Single-RBS		Multiple-RBS		$\chi^2$	<i>p</i> <
Male/female	18/19		7/10		0.26	.61
African-/Anglo-American	21/16		9/8		0.07	.79
C-Section (no/yes)	25/12		11/6		0.84	.84
Breastfed (no/yes)	26/11		14/3		0.54	.54
Circumcision (no/yes)	33/4		16/1		0.05	.94
Atypical ponderal index (yes/no)	10/27		7/10		1.08	.30

differ in birth weight, gestational age, Apgar scores at both 1 and 5 minutes, Obstetric Complications Scale (OCS) score, maternal weight gain, maternal age, or maternal education. Chi-square analyses further showed that the two groups did not reliably differ in the distributions of sex, ethnicity, method of delivery, method of feeding, circumcision, or pattern of fetal growth, as determined by the ponderal index (PI), a weight-length ratio used to show atypical fetal growth (see Zeskind & Lester, 1981). These data suggest that the two groups were remarkably similar on a host of standard demographic and pediatric measures.

### Procedure

Following informed consent, infants were observed for 2 continuous hours midway between scheduled feedings while the infants rested quietly in a sound-attenuated and temperature-controlled (32 °C) isolette. Electrodes from a Corometrics 515a Neo-trak cardiorespiratory monitor were securely attached to the infant's pectoral and abdominal regions. The monitor provided a digital display of the infant's heart rate per minute, averaged with a moving window of approximately 10 seconds in duration. Measurement of heart rate and the observations

of behavior began 10 minutes after electrode placement by three research assistants who were unaware of the hypotheses of the study and salient information about the infant. Heart rate was determined from visual inspection of the digital display of the monitor every 30 seconds during the 2-hour observation period by one researcher who used a stopwatch to indicate when each 30-second point had been reached. The 240 measures of heart rate for each infant were recorded manually during the behavioral observation and later served as time-series data for spectrum analysis.

Concurrent with measurements of heart rate, infants' behavioral state and the number of "spontaneous" behavioral startles that occurred during the 30-second epoch were recorded at each 30-second point. Behavioral startles were defined as full body jerks that consisted of a momentary abduction of the shoulders with extension of the arms, elbows, wrists, and fingers, followed by a brief disturbance in respiration (Wolff, 1966). The infant's behavioral state during the final 10-second window of the 30-second epoch was determined by consensus of the three research assistants. Measures of behavioral state used in this study were based on commonly used definitions (see Brazelton, Nugent, & Lester, 1987) and included (a) quiet sleep, (b) active sleep, (c) drowse, (d) alert, (e) active alert, and (f) crying. As would be expected, infants were observed while they were in either the Sleep or Drowse states during 88% of the 30-second epochs. Interobserver agreement on 10 infants interspersed throughout the study was 98% for quiet sleep, 97% for active sleep, 95% for drowse, 98% for alert, 96% for active alert, and 95% for crying. The number of changes in behavioral state was subsequently determined by counting the number of times an infant was observed in a different state after being in a previous state for at least two consecutive 30-second epochs.

### *Measures of Cry Threshold*

Following the 2-hour behavioral observations, infant cry reactivity was assessed via the same standard procedure used in previously reviewed studies of low- and high-risk infants (Zeskind, 1983; Zeskind & Lester, 1978, 1981) and of infants who show differential heart rate variability (Zeskind & Field, 1982). The procedure was conducted by the senior author who was blind to the data obtained during the observations of heart rate and behavior. While the infant was in a supine position and in an awake, nonfussy state, an Arco #64 rubber band was extended 15 cm along a straight-edged instrument and snapped on the sole of the infant's foot. A crying bout was no longer fully sustained when the infant first paused for breath and showed two contiguous inspirations with no expiratory sound. A stopwatch was used by a research assistant to determine the duration of the crying bout when the experimenter indicated the crying bout was no longer

sustained. If a cry of at least 10-second duration was not elicited, the infant's foot was snapped again, up to a maximum of five snaps. At the conclusion of the cry elicitation procedure, the infant was soothed, placed in its bassinet, and returned to the nursery. The entire procedure was recorded on a Marantz model PMD 221 tape recorder with an electret directional microphone held 20 cm midline from the infant's mouth.

The tape-recorded snaps and cry were subsequently converted from an analog-to-digital signal at 10,000 samples per second and analyzed via the Micro Speech Lab (MSL) sound analysis computer program. Measures of infant crying included the Latency, durations of the First Cry Sound, and Overall Crying Bout and the pitch of the Peak Fundamental Frequency. Latency and First Cry Sound were determined by moving the cursor across a graphical oscilloscopic display which produced a picture of the RBS and entire initial cry sound. The display produced a digital output of the elapsed time between points marked by the cursor with a resolution of measurement of 0.0037 seconds. Latency was measured as the duration of time (in milliseconds) between the onset of the first RBS to the onset of the first sound emitted by the infant. Duration of the First Cry Sound was determined as the amount of time (in seconds) from the onset to the end of the expiratory component of the first cry sound emitted by the infant. Duration of the Crying Bout was the total amount of time (in seconds) of the infant's first sustained crying bout (>10 seconds). The Peak Fundamental Frequency (Hz) of the cry sound was derived from a Fast Fourier Transform of the 25-millisecond block at which the fundamental frequency showed its highest point in a sonographic display of the harmonic structure. This measure was chosen so that the presence of the high-pitched, hyperphonated acoustic structure ( $F_0 > 1000$  Hz), characteristic of cries of high-risk infants, could be detected.

### *Spectrum Analysis of Heart Rate*

Heart rate data were analyzed according to the procedures detailed by Gottman (1981) and used in other studies of long-term heart rate variability (for a more complete description, see Zeskind et al., 1991, 1992). Linear trends in the data were removed before the heart rate spectra were computed in order to improve the stationarity of the time series. The residual variance of each time series was then spectrum analyzed using a Blackman-Tukey window. A Kolmogorov-Smirnov test was calculated for each power spectrum to determine the signal to noise ratio and significance of spectral peaks ( $p < .05$ ). This analysis allowed for the detection of rhythms ranging from 1 to 60 cycles per hour (cph) with a resolution of 0.5 cph. Results showed that the cumulative variance distribution of heart rate departed from that of white noise for 50 of the 54 infants (all  $ps < .01$ ); the heart rates of two infants in each group were not described by any

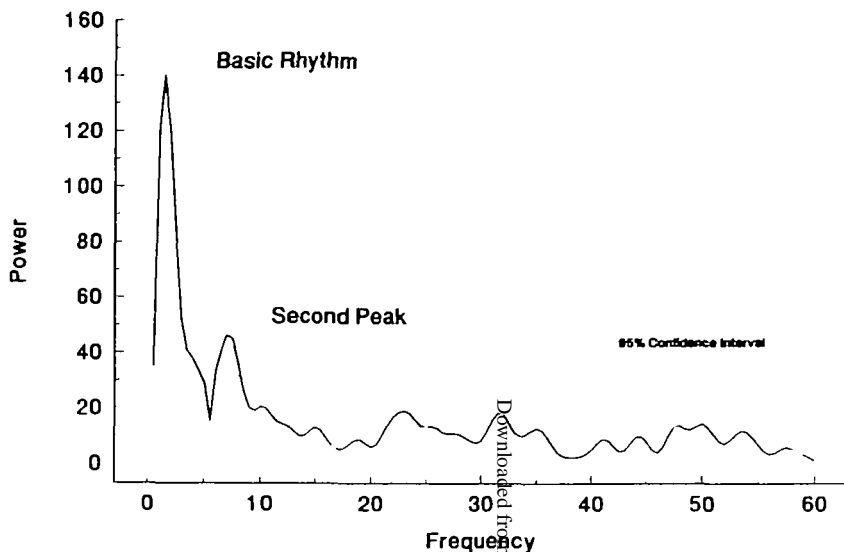


Fig. 1. The power spectrum of heart rate and Kolmogorov-Smirnov test for one infant.

reliable rhythms. The first peak in the power spectrum was evident at  $1.5 \pm 0.5$  cph (1 cycle approximately every 40 minutes) for all 50 infants. Thirty-two infants showed additional nonharmonic peaks at a wide range of higher frequencies.<sup>3</sup> Figure 1 shows an example of a power spectrum of heart rate for one infant. The peaks of the basic 40-minute rhythm and a second reliable cycle are seen above the line of statistical significance as determined by the Kolmogorov-Smirnov test.

## RESULTS

The means and standard deviations of the measures of crying, heart rate, and autonomic behaviors are shown in Table II. The 10 dependent variables were

<sup>3</sup>The linear trends accounted for a mean of 9% of the variance ( $SD = 0.13$ ) and were reliable for 35 infants (at  $p < .05$ ). The Blackman-Tukey window had a truncation point of 40 (which gives a bandwidth of 0.21) in the Fourier transform of the autocovariance function. We then used the Kolmogorov-Smirnov test to compare the maximum absolute difference of the standardized partial sums of the spectrogram and the cumulative distribution function of a uniform random distribution (white noise). The Kolmogorov-Smirnov test was calculated separately for each power spectrum to determine the signal to noise ratio and significance of spectral peaks. This procedure determined whether the detrended heart rate time series departed from that expected if it was white noise (at  $p < .05$ .) A 95% confidence interval was then constructed around the theoretical spectral densities for white noise (see Gottman, 1981, p. 223). If the peak in the power spectrum was above the line denoting the 95% confidence interval, the peak was judged to be significant.



**Table II.** Means and Standard Deviations of Measures of Crying, Heart Rate, State Changes and Startles of Single-RBS and Multiple-RBS Infants

Variables	Group				<i>t</i> (52)	<i>p</i> <
	Single-RBS ( <i>n</i> = 37)		Multiple-RBS ( <i>n</i> = 17)			
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
<b>Measures of crying</b>						
Latency (msec)	571	389	859	425	2.45	.02
First cry sound (sec)	5.95	2.42	3.27	1.38	4.25	.001
Crying bout (sec)	24.8	13.9	11.6	5.6	4.96	.001
Peak $F_0$ (Hz)	1139.5	652.6	992.8	490.1	0.82	.41
<b>Measures of heart rate</b>						
Mean (bpm)	128.2	11.9	126.5	7.8	0.54	.59
Variance ( $\log_{10}$ )	2.06	0.42	1.76	0.37	2.48	.02
Variance of the time series ( $\log_{10}$ )	2.01	0.43	1.71	0.38	2.47	.02
Number of reliable rhythms	2.11	1.2	1.35	0.79	2.37	.02
Power of basic rhythm ( $\log_{10}$ )	2.03	0.516	1.73	0.519	2.01	.05
<b>Behavioral state and startles</b>						
No. of state changes	50.3	28	38.3	16.7	1.98 <sup>a</sup>	.05
No. of behavioral startles	43.9	27.4	30	16.2	2.34 <sup>a</sup>	.02

<sup>a</sup>Forty-eight degrees of freedom were used in this analysis based on the use of separate variance estimates

analyzed in three separate Hotellings  $T^2$  multivariate tests, representing each of the three hypotheses. The first analysis showed a significant multivariate effect for the four measures of infant crying,  $F(4, 49) = 8.08, p < .001$ . Examination of the univariate  $t$  tests showed that multiple-RBS infants had a longer Latency to the sound of crying, a shorter Crying Bout, and a shorter First Cry Sound than single-RBS infants. No differences between single-RBS and multiple-RBS groups were found in the mean Peak Fundamental Frequency (Hz) of the cry sound. Seven of the 17 multiple-RBS infants showed evidence of hyperphonation (Peak  $F_0 > 1000$  Hz); 19 of the 37 single-RBS infants showed this distinctive acoustic structure. Chi-square analyses determined that the distribution of hyperphonation in the two groups of infants did not depart from that expected by chance,  $\chi^2(1) = 0.356, p < .558$ .

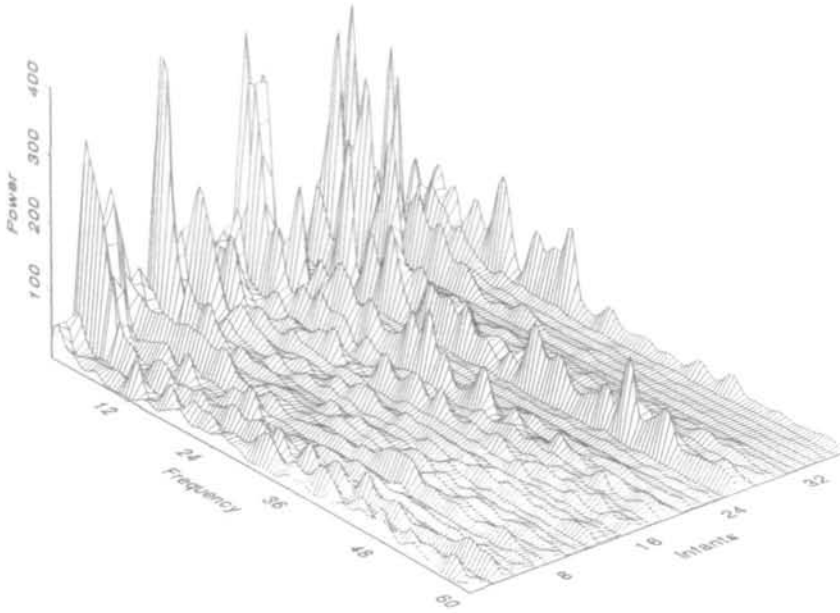
The second multivariate test was conducted on the measures of neonatal heart rate. Heart Rate Variance was a measure of the overall statistical variance of the 240 observations of heart rate. Heart Rate Variance of the Time Series was the residual variance accounted for following removal of the linear trends and was the data on which the time-series was conducted.  $\log_{10}$  transformations of these measure of heart rate variability, as well as the power of the basic peak, were performed to normalize their distributions (Porges, Arnold, & Forbes,

1973). The Hotelling's  $T^2$  showed a significant multivariate effect for the four measures of heart rate activity,  $F(4, 49) = 2.88, p < .032$ . Examination of the univariate  $t$  tests first showed that multiple-RBS infants exhibited reliably less statistical variance in the 240 measurements of heart rates during the 2-hour observation period, less variance on which the time series was conducted, fewer reliable numbers of peaks in their power spectra, and a lower mean Power of the Basic Rhythm than single-RBS infants. As found in previous work, groups did not differ in the *mean* of the 240 observations of heart rate. These results indicate that multiple-RBS infants showed less complexity in the rhythmicity of their heart rate and less power in the basic rhythm.

The third Hotelling's  $T^2$  showed a significant multivariate effect for the numbers of state changes and behavioral startles,  $F(2, 51) = 3.31, p < .044$ . While the multivariate test shows the robustness of effects, separate variance estimates were used for the univariate comparisons because Bartlett-Box tests of homogeneity of variance showed reliable differences in the groups' variances. Results showed that multiple-RBS infants exhibited reliably fewer numbers of State Changes and Behavioral Startles than single-RBS infants. These results indicate that multiple-RBS infants also differed in other behaviors previously used to describe autonomic regulatory activity.

Although the average number of episodes for both groups was small, single-RBS infants ( $M = 9.4; SD = 22.4$ ) were observed in the Crying state more often than multiple-RBS infants ( $M = 1.3; SD = 3.3$ ),  $t(39) = 2.14, p < .039$  (39 *df* resulting from separate variance estimates). To examine whether the greater number of peaks in the power spectrum of single-RBS infants was an artifact of more often being in the Crying state, a separate analysis was conducted on a subsample of single-RBS ( $n = 23$ ) and multiple-RBS ( $n = 14$ ) infants who showed no 30-second observations in the state of Crying. Results showed that multiple-RBS ( $M = 1.35, SD = 0.63$ ) infants continued to show fewer numbers of reliable peaks in the power spectra than single-RBS ( $M = 2.0, SD = 1.04$ ) infants,  $t(35) = 2.33, p < .026$ . Reducing the range of heart rates resulted, however, in eliminating the group differences in the  $\log_{10}$  variance of the time series (single-RBS:  $M = 1.77, SD = 0.314$ ; multiple-RBS:  $M = 1.62, SD = 0.337, t(35) = 1.37, p < .18$ ). As would be expected, eliminating the difference in heart rate variability also eliminated the difference in the power of the basic frequency between single-RBS ( $M = 74.5; SD = 48.8$ ) and multiple-RBS ( $M = 74.7; SD = 100.9$ ) infants,  $t(35) = 1.00, p < .32$ . No differences in mean heart rate still characterized single-RBS ( $M = 125.5; SD = 10.9$ ) and multiple-RBS ( $M = 126.4; SD = 7.12$ ) infants,  $t(35) = 0.28, p < .78$ .

Figures 2 and 3 show a three-dimensional landscape of the power spectrum of heart rate for each infant in the single-RBS and multiple-RBS groups. The individual spectra are aligned on the Z axes with the frequencies and powers at which peaks occur on the X and Y axes, respectively. Clearly evident in the

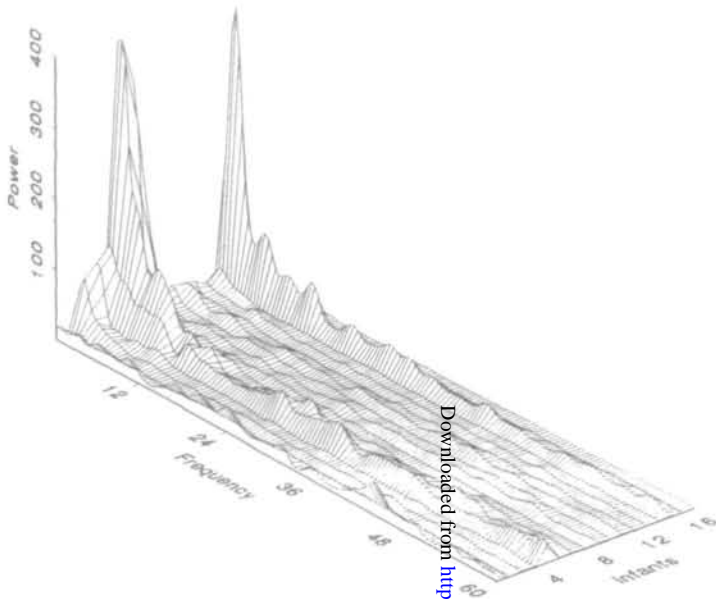


**Fig. 2.** A three-dimensional landscape of the power spectra of single-RBS infants. The spectrum for each infant is aligned on the Z axis with the frequencies and powers at which peaks occur on the X and Y axes, respectively.

power spectra of the 37 single-RBS infants are the high power of the initial peaks at  $1.5 \pm 0.5$  cph ( $40 \pm 15$  minutes) and the rugged terrain denoting peaks in the spectrum at a wide range of frequencies. The character of this landscape is in stark contrast to that of the 17 multiple-RBS infants where there are generally lower initial peaks (except for 2 or 3 infants), and a smooth terrain indicating low power at frequencies throughout the power spectrum. Pearson product-moment correlations showed that the number of reliable peaks seen in this landscape was poorly related to the other measures of heart rate, including mean and variability (all  $ps > .40$ ).

## DISCUSSION

Results of the present study provide some of the first direct evidence that infants who have a high cry threshold show a wide range of biobehavioral measures previously described as reflecting the homeostatic properties and regulation of the infant's autonomic nervous system. First, infants who varied in cry threshold differed in other measures of infant cry reactivity. As found in previous



**Fig. 3.** A three-dimensional landscape of the power spectra of multiple-RBS infants. The spectrum for each infant is aligned on the Z axis with the frequencies and powers at which peaks occur on the X and Y axes, respectively.

studies, multiple-RBS infants had a longer latency from the first stimulus to the first cry sound, a shorter initial cry sound, and a shorter overall bout of crying than single-RBS infants (Zeskind & Lester, 1978, 1981). No difference was found in the peak fundamental frequency of the first cry sound. Although several studies have shown that *groups* of infants often vary in both the threshold and sound of crying, empirical work shows that these two dimensions of crying may reflect the activity of different biobehavioral systems and may not be related in a one-to-one basis in individual infants (Zeskind, 1983). In fact, Lester (1984) suggested that, whereas the sound of crying may reflect the effects of parasympathetic nervous system activity on vagal regulation of the laryngeal muscles that control  $F_0$ , the threshold of crying, and other measures of cry reactivity, may reflect the effects of sympathetic nervous system activity on the ability of the infant to be aroused. The higher threshold, longer latency, and shorter durations of crying suggest that the multiple-RBS infants were more difficult to bring to a higher state of arousal than single-RBS infants.

Second, results of this study show that infants with a high threshold for crying had fewer reliable peaks in the power spectrum of their long-term heart rate variability and a lower power of the 40-minute rhythm approximating the frequency of the BRAC. Possible statistical bases for these differences have been

discussed elsewhere (Zeskind et al., 1991), but it is interesting to note that the mean and *amount* of variability in heart rate were not related to the number of reliable peaks in the power spectrum. As suggested by Porges and Byrne (1992), the mean and variability in heart rate are not sensitive to individual differences in rhythmicity. Rhythmicity is determined by the way in which that variability is shaped. More reliable peaks in the power spectra essentially indicate that a higher number of sinusoidal waves, at increasingly higher frequencies, accounted for significant portions of the variance. That is, the changes in heart rate in infants with a typical cry threshold showed a more predictable and rhythmic rise and fall over time. Not surprisingly, infants who required more stimulation to elicit a sustained cry were observed in the state of crying less often than single-RBS infants. Because the power of a peak in the power spectrum is often directly related to the amount of variability in the signal (see Porges & Bohrer, 1990), the higher power of the 40-minute cycle in single-RBS infants was lessened when the range of naturally occurring states was limited to only the noncry states. Even with this reduced range and variability, though, infants with a high cry threshold still showed a less complex rhythmic structure in the power spectrum.

The complexity of the rhythmic structure depicted in the power spectrum provides important information about the infant's behavioral organization and developmental status. Development results from increasing *complexity* in behavioral organization as multiple systems become increasingly coordinated with one another (Thelen, 1989). As a collective variable, heart rate is particularly sensitive measure of this process because it becomes more variable and complex as multiple aspects of central and autonomic nervous system activities become increasingly coordinated with cardiac activity (see Berg & Berg, 1987). Less complexity in the heart rate power spectrum may result from less coordination among the oscillating systems that affect the regulation of heart rate and be evidence of a less well-organized behavioral system. Several studies show that infants who demonstrate poor behavioral organization on the NBAS and in vagal tone also show less complex patterns of behavioral rhythmicity (Zeskind et al., 1991, 1992). Similarly, fetuses of diabetic mothers have disrupted patterns of behavioral organization (Yogman, Cole, Als, & Lester, 1982) and fewer reliable cycles and less relative power in the rhythms underlying their behavioral motility than comparison infants (Robertson & Dierker, 1986). Based on the perspective that development is characterized by the increased complexity of behavior, less complexity in the power spectrum of heart rate is evidence of a less mature developmental state.

The lower power of the basic peak of infants with a high cry threshold also provides support for a picture of a less well-coordinated system of autonomic regulation and behavioral organization. A wide range of literature indicates that a reduction in the power of cyclic activity often results from poor coordination among oscillating subsystems. For example, lower vagal tone reflects less coher-

ence between oscillations in cardiac and respiratory systems (Porges, 1986) and studies of physiological and behavioral arrhythmias indicate that dissociations among secondary oscillators may reduce the power of the primary rhythm (Moore-Ede, Sulzman, & Fuller, 1982). That is, when the many rhythmic systems contributing to the rhythmic activity of a common system are less well coordinated, such as being out of phase, the power of the rhythm of that commonly influenced system is lessened. Other work similarly suggests that a collective rhythm, like the 40-minute basic rhythm underlying changes in heart rate, has a power related to the coordination of the timing mechanisms influencing the rhythm or biological clock (Winfree, 1987). Further, Porges and Byrne (1992) have argued that, within normal parameters, less amplitude in the oscillation in physiological systems is associated with overall poorer health. This literature suggests that the lower power found in the 40-minute heart rate rhythm, which was predicted by the threshold of crying, reflects an overall poorly coordinated rhythmic system and poorer infant health.

The number of spontaneous startles and times an infant changed its state of arousal provided still further convergent evidence that cry threshold was associated with disrupted autonomic function. Poor autonomic regulation has been shown to be evidenced in either unusually high or low numbers of changes in behavioral state (Brazelton et al., 1987). High threshold infants showed reliably fewer changes in behavioral state than those who required a typical amount of stimulation to elicit a sustained cry. These infants also showed approximately 50% fewer behavioral startles during the 2-hour observation period. Whereas a *higher* number of startles has often been used as evidence of poor behavioral organization and excessive autonomic lability in newborn infants (Brazelton et al., 1987), infants who show less mature central nervous system development may emit *fewer* behavioral startles than comparison infants (Emory & Mapp, 1988). Finding fewer behavioral startles supports the view that the high cry threshold may be less developmentally advanced or "mature." Showing low numbers of startles is also particularly interesting because some suggest that startles aid the regulation of arousal by releasing energy when the infant is overaroused or producing energy when underaroused (e.g., Korner, 1969; Wolff, 1966). We add the anecdotal observation that the high-threshold infants often startled only when their respiratory and heart rates dropped to dangerously low levels and sometimes only during a brief apneic episode. Because the failure to startle during an apneic episode may be associated with the occurrence of Sudden Infant Death Syndrome, the results of this study has implications for understanding why cry analysis may be predictive of cases of this problem in autonomic regulation (Corwin et al., in press).

In conclusion, the threshold for crying appears to assess the newborn infant's capacity for behavioral rhythmicity and regulation of arousal. As described elsewhere (Zeskind & Marshall, 1991), behavioral rhythms may play a major



role in providing important autonomic stability, especially during the infant's transition from the relatively predictable sensory environment of the womb to the rapidly changing sensory environment of the postnatal context. Infants who have a high cry threshold may not have the same capacity to integrate sensory experiences as infants with a typical cry threshold. The findings of this study may also have implications for understanding processes underlying other important behavioral constructs. For example, differences in behavioral reactivity have long been discussed in terms of reflecting the underlying temperament of the newborn and young infant (Birns, 1965). A difficult temperament has long been defined not only by less behavioral rhythmicity (Thomas, Chess, & Birch, 1968) but also by variations in self-regulation, the threshold, latency, and duration of infant reactivity (Rothbart & Derryberry, 1981) and heart rate variability (Stifter & Fox, 1990)—all behaviors which differentiated infants in the present study. Future work that examines the stability and change of the infant's cry threshold and how it is related to the stability and change of these measures of the infant's behavioral constitution may provide an interesting window into the processes underlying the development of temperament and other behavioral dimensions.

## REFERENCES

- Berg, W. K., & Berg, K. M. (1987). Psychophysiological development in infancy: State, startle, and attention. In J. Osofsky (Ed.), *Handbook of infant development* (2nd ed., pp 238-317). New York: Wiley.
- Birns, B. (1965). Individual differences in human neonates' responses to stimulation. *Child Development*, *36*, 249-256.
- Brazelton, T. B., Nugent, K., & Lester, B. M. (1987). Neonatal Behavioral Assessment Scale. In J. Osofsky (Ed.), *Handbook of infant development* (2nd ed., pp. 780-817). New York: Wiley.
- Corwin, M. J., Lester, B. M., Sepkoski, C., Peucker, M., Kayne, H., & Golub, H. (in press). Newborn acoustical cry characteristics of infants subsequently dying of SIDS. *Pediatrics*.
- DiPietro, J. A., Larson, S. K., & Porges, S. W. (1987). Behavioral and heart rate pattern differences between breast-fed and bottle-fed neonates. *Developmental Psychology*, *23*, 467-474.
- Emory, E. K., & Mapp, J. R. (1988). Effects of respiratory distress and prematurity on spontaneous startle activity in neonates. *Infant Behavior and Development*, *11*, 71-81.
- Gottman, J. M. (1981). *Time-series analysis: A comprehensive introduction for social scientists*. New York: Cambridge University Press.
- Hoppenbrouwers, T., Combs, D., Ugartechea, J. C., Hodgman, J., Sterman, M. B., & Harper, R. M. (1981). Fetal heart rates during maternal wakefulness and sleep. *Obstetrics and Gynecology*, *57*, 301-309.
- Karelitz, S., & Fischelli, V. (1962). The cry thresholds of normal infants and those with brain damage. *Journal of Pediatrics*, *61*, 679-685.
- Korner, A. (1969). Neonatal startles, smiles, erections and reflex sucks as related to state, sex and individuality. *Child Development*, *40*, 1040-1052.
- Lester, B. M. (1975). Cardiac habituation of the orienting response in infants of varying nutrition status. *Developmental Psychology*, *11*, 432-442.
- Lester, B. M. (1984). A biosocial model of infant crying. In L. Lipsitt (Ed.), *Advances in infant behavior and development*. Norwood, NJ: Ablex.
- Lester, B. M., & Boukydis, C. F. Z. (Eds.). (1985). *Infant crying: Theoretical and research perspectives*. New York: Plenum Press.

- Lester, B. M., Corwin, M. J., Sepkoski, C., Seifer, R., Peucker, M., McLaughlin, S., & Golub, H. L. (1991). Neurobehavioral syndromes in cocaine exposed newborn infants. *Child Development, 62*, 513-547.
- Lester, B. M., Newman, J. D., & Pedersen, F. (Eds.). (in press). *The social and biological aspects of infant crying*. New York: Plenum Press.
- Moore-Ede, M. C., Sulzman, F. M., & Fuller, C. A. (1982). *The clocks that time us*. Cambridge, MA: Harvard University Press.
- Porges, S. W. (1983). Heart rate patterns in neonates: A potential diagnostic window to the brain. In T. Field & A. Sostek (Eds.), *Infants born at risk* (pp. 3-22). New York: Grune & Stratton.
- Porges, S. W. (1986). Respiratory sinus arrhythmia: Physiological basis, quantitative methods, and clinical implications. In P. Grossman, K. Janssen, & D. Vaitl (Eds.), *Cardiorespiratory and cardiosomatic psychophysiology* (pp. 101-115). New York: Plenum Press.
- Porges, S. W., Arnold, W. R., & Forbes, E. J. (1973). Heart rate variability: An index of attentional responsiveness in human newborns. *Developmental Psychology, 8*, 85-92.
- Porges, S. W., & Bohrer, R. E. (1990). The analysis of periodic processes in psychophysiological research. In J. T. Cacioppo & L. G. Tassinari (Eds.), *Principles of psychophysiology: Physical, social, and inferential elements* (pp. 708-753). New York: Cambridge University Press.
- Porges, S. W., & Byrne, E. A. (1992). Research methods for measurement of heart rate and respiration. *Biological Psychology, 34*, 93-130.
- Porter, F. L., Porges, S. W., & Marshall, R. E. (1988). Newborn pain cries and vagal tone: Parallel changes in response to circumcision. *Child Development, 59*, 495-505.
- Richards, J. E., & Cameron, D. (1989). Infant heart-rate variability and behavioral developmental status. *Infant Behavior and Development, 12*, 45-58.
- Robertson, S. S., & Dierker, L. J. (1986). The development of cyclic motility in fetuses of diabetic mothers. *Developmental Psychobiology, 19*, 223-234.
- Rothbart, M. K., & Derryberry, D. (1981). Development of individual differences in temperament. In M. E. Lamb & A. L. Brown (Eds.), *Advances in developmental psychology* (Vol. 1, pp. 37-86). Hillsdale, NJ: Erlbaum.
- Sayers, B. M. (1973). Analysis of heart rate variability. *Ergonomics, 16*, 17-32.
- Stifter, C. A., & Fox, N. A. (1990). Infant reactivity: Physiological correlates of newborn and 5-month temperament. *Developmental Psychology, 26*, 582-588.
- Stratton, P. (1982). Rhythmic functions in the newborn. In P. Stratton (Ed.), *Psychobiology of the human newborn* (pp. 119-145). New York: Wiley.
- Thelen, E. (1989). Self-organization in developmental processes: Can systems approaches work. In M. Gunnar & E. Thelen (Eds.), *Systems and development: The Minnesota Symposia on Child Psychology* (Vol. 22, pp. 77-117). Hillsdale, NJ: Erlbaum.
- Thomas, A., Chess, S., & Birch, H. G. (1968). *Temperament and behavioral disorders in children*. New York: New York University Press.
- Winfrey, A. T. (1987). *The timing of biological clocks*. New York: Freeman.
- Wolff, P. H. (1966). The causes, controls, and organization of behavior. *Psychological Issues, 5*(1, Serial No. 17).
- Yogman, M., Cole, P., Als, H., & Lester, B. M. (1982). Behavior of newborns of diabetic mothers. *Infant Behavior and Development, 5*, 331-340.
- Zeskind, P. S. (1981). Behavioral dimensions and cry sounds of infants of differential fetal growth. *Infant Behavior and Development, 4*, 321-330.
- Zeskind, P. S. (1983). Production and spectral analysis of neonatal crying and its relation to other biobehavioral systems in the infant at risk. In T. Field & A. Sostek (Eds.), *Infants born at risk: Physiological, perceptual and cognitive processes* (pp. 21-43). New York: Grune & Stratton.
- Zeskind, P. S., & Field, T. (1982). Neonatal cry threshold and heart rate variability. In L. Lipsitt & T. Field (Eds.), *Infant behavior and development: Perinatal risk and newborn behavior* (pp. 51-60). Norwood, NJ: Ablex.
- Zeskind, P. S., Goff, D. M., & Marshall, T. R. (1991). Rhythmic organization of neonatal heart rate and its relation to atypical fetal growth. *Developmental Psychobiology, 24*, 413-429.
- Zeskind, P. S., & Lester, B. M. (1978). Acoustic features and auditory perceptions of the cries of newborns with prenatal and perinatal complications. *Child Development, 49*, 580-589.



- Zeskind, P. S., & Lester, B. M. (1981). Analysis of cry features in newborns with differential fetal growth. *Child Development, 52*, 207-212.
- Zeskind, P. S., & Marshall, T. R. (1991). Temporal organization in neonatal arousal: Systems, oscillations, and development. In M. Weiss & P. Zelazo (Eds.), *Newborn attention: Biological constraints and influence of experience*. Norwood, NJ: Ablex.
- Zeskind, P. S., Marshall, T. R., & Goff, D. M. (1992). Temporal organization of arousal in breast-fed and bottle-fed newborn infants. *Early Development and Parenting, 1*, 79-87
- Zeskind, P. S., Platzman, K., Coles, C. D., & Schuetze, P. (in press). Cry analysis detects subclinical effects of prenatal alcohol exposure. *Infant Behavior and Development*.