Dynamics of oral–respiratory coordination in full-term and preterm infants: II. Continuing effects at 3 months post term

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Abstract

Thirty-two infants participating in a longitudinal study of the effects of premature birth on sucking and breathing were tested at 3 months post term. They were assigned at a previous test to either a healthy full-term, healthy preterm, or high risk preterm group on the basis of birth weight, postconceptional age at birth, and perinatal medical status. Positive and negative sucking pressure as well as chest and abdominal breathing movements were recorded during nutritive sucking. The high risk preterms used a simpler and more stable pattern of coordination between sucking and breathing, were more likely to interrupt breathing at milk onset, and produced longer phase lags between positive and negative sucking pressure.

Within minutes after birth, infants will close the jaw, gums and lips on a nipple placed in the mouth. They are able to produce perfectly normal non-nutritive sucking patterns in the first hour after birth (Wolff, 1968 1991). However, it may take several hours or days before breast or bottle feeding becomes well established. What coordination demands make nutritive sucking so difficult? Classic radiographic (Ardran, Kemp & Lind, 1958) and more recent video-fiberscope and ultrasound studies of oral articulator movements (Selley, Ellis, Flack, Curtis & Callon, 1986; Bullock, Woolridge & Baum, 1990; Eishima, 1991; Iwayama & Eishima, 1997) reveal that nutritive sucking involves temporal sequencing of the articulators into a cycle of expression and suction. At the initiation of the cycle, jaw and lip closure compresses the nipple, expressing some fluid and creating a vacuum within the oral cavity. The anterior to posterior movement of the tongue is associated with increasing negative (suction) pressure, drawing milk into the concavity formed between the tongue and palate, prior to swallowing. The infant’s success in feeding, therefore, depends in part upon a particular sequencing of the articulators. Optimal timing of expression and suction allows a sufficient interval for the ‘pumping’ action of negative pressure to draw a volume of milk before the next cycle of lip and jaw compression begins. One goal of this study was to examine how the suction pattern becomes temporally sequenced with the opening and closing of the jaw.

Respiration must also accommodate to the expression–suction cycle in anticipation of swallowing. Taking a breath during the portion of the cycle when milk has collected in the back of the mouth could result in choking, and so inspiration must be timed to avoid coinciding with suction. When the infants in the present study were 38–40 weeks gestational age, Goldfield, Wolff & Schmidt (this issue) found that cycles of jaw compression on a pacifier (i.e. non-nutritive sucking) were timed so that sucking was coordinated with breathing, even though no milk was present. It is possible that these early coordination patterns of jaw compressions and breathing provide certain constraints around which the more complex coordination requirements of nutritive sucking are organized. Such constraints may greatly simplify the task of learning how to suck nutritively. If the acquisition of nutritive sucking is guided by the existing constraints of a cycle of jaw compression and breathing, then there should be some lawful relation between the timing of suction and...
the ongoing cycle of jaw opening and closing. A second goal of the study, therefore, was to examine the timing of the suction phase of nutritive sucking relative to the opening and closing of the jaw.

In experiments which regulated the flow of milk to a nipple during infant sucking, Wolff (1972) found that negative suction pressure dropped out when milk flow stopped, and that rate of sucking increased from 1 Hz to approximately 2 Hz. Subsequent studies have further examined the relative plasticity of the expression and suction components (Sameroff, 1972) as well as the effects of milk onset and offset on breathing (Selley, Ellis, Flack & Brooks, 1990). Selley et al. (1990) found that clamping the milk supply line for about 20 s resulted not only in increased frequency of infant jaw oscillation but also a change in the pattern of breathing. During nutritive sucking, there were ‘apneic’ periods when breathing was inhibited. The present study uses a similar experimental manipulation to further explore the effects of interrupting milk flow on the relation between the expression and suction phases, and on the patterning of inspiration and expiration.

Analytical tools motivated by a dynamical systems perspective on coordination (Wolff, 1987; Treffner & Turvey, 1993; Thelen & Smith, 1994; Goldfield, 1995) are used here to identify the dynamics of jaw oscillation during sucking. Dynamical systems approaches have in common an emphasis on the rhythmic character of motor behavior, because behavioral rhythms may be probed for their temporal organization and stability, hallmarks of coordination. For example, dynamical systems approaches afford the possibility of gaining insight into the functional components of a system by a description of behavior at a macroscopic level. Relative phase is such a macroscopic description of the timing of two or more component actions in a complex coordination pattern. For two time series, say A and B, that contain rhythms in a 1:1 frequency lock, a point estimate of relative phase measures the coincidence of the peaks at A with those at B. The mean and standard deviation of the phase angle between A and B is an indication of their relative coordination over the entire time series. We examined the relation between the expression and suction phases quantitatively by calculating a point estimate of the relative phase between peaks of positive and negative pressure. The phase angle provides a measure of the timing of suction relative to the opening and closing of the jaw.

Analysis of relative phase as well as frequency locking in a Farey tree structure are used here to compare at 12 weeks a group of healthy full-term infants with two groups of infants who were born prematurely. In the previous report of these infants at 38–40 weeks gestational age (Goldfield et al., this issue), the ratio between the frequencies of pacifier sucking and breathing was examined as a measure of coordination. So, for example, proceeding to the branch representing two sucks for each breath, 2/1, indicates one of the stable coordination patterns to which sucking and breathing tend to be attracted. An examination of the distribution of these patterns in the three groups of infants provides a way of comparing their coordination. Goldfield et al. (this issue) found that all of the 38- to 40-week-old infants produced patterns that were integer frequency ratios of sucking and breathing, either simple patterns of one or two sucks for each breath (1/1 or 2/1, respectively), or complex patterns of three sucks for every two breaths (3/2). The healthy full-term and healthy preterm infants were significantly more likely to produce a greater number of complex 3/2 patterns, while the lowest birth weight infants with respiratory problems were more likely to produce simpler patterns of 1/1 or 2/1. Thus, at term, sometimes as much as 12 weeks after birth, coordination of sucking and breathing distinguished preterm infants with respiratory and other medical problems from the other infants.

Many outcome studies have looked at the effects of early birth with medical complications on later motor, cognitive and linguistic development (e.g. Sostek, Smith, Katz & Grant, 1987; Gorga, Stern, Ross & Nagler, 1991; Landry, Fletcher, Denson & Chapieski, 1993). However, little is known about the continuing effects of prematurity in the first months of life on the underlying processes governing behavioral coordination, a fundamental process by which large numbers of motor components are assembled into functional units (Wolff, 1987; Thelen & Smith, 1994; Goldfield, 1995). Studies of the low birth weight infant make it possible to examine, not only how motor behaviors such as sucking and breathing recover from the effects of early birth, but also how changes in the intrinsic characteristics of sucking and breathing (e.g. their frequencies) influence the normal development of feeding.

The focus of this paper is on the period 12 weeks after term, thought to be a transitional period for the organization of oral–motor behaviors during feeding, and possibly a period of general neuromotor reorganization (Prechtl, 1984). Infants in one group were born full term, so that their second test occurred 12 weeks after birth. Infants in the other two groups, low risk preterms with no medical complications at birth or high risk preterms with intraventricular hemorrhage (IVH) and respiratory problems at birth, were tested 12 weeks after their expected birth date. These infants therefore had chronological ages between 5 and 6 months. By comparing these infants at their term equivalent ages...
corrected for the effects of prematurity, any observed group differences could be attributed to the persisting effects of perinatal complications (see for example Palisano, 1986; Allen & Alexander, 1990).

In summary, the study examines three sets of hypotheses concerning the coordination of sucking and breathing during nutritive sucking at 3 months post term: (1) healthy full-term and preterm infants will be significantly more likely than infants in the high risk preterm group to produce complex 3/2 frequency ratios of sucking and breathing during nutritive sucking, (2) infants in the high risk preterm group will produce negative pressure at a longer latency (i.e. at a greater relative phase angle) from expression and with greater variability between expression and suction (higher standard deviation of relative phase) during nutritive sucking than will the infants in the other two groups, and (3) the onset of milk flow will be significantly more likely to interrupt the breathing of the high risk preterm infants than the infants in the other two groups.

**Method**

**Participants**

Thirty-two infants participated in the study. Eight additional infants in the original sample were not tested, because of equipment failure, refusal to accept the nipple used in the experiment or failure to appear for the test. Participants were previously assigned to one of three groups, based upon their gestational age at birth, birth weight, and number of medical complications at birth (see Table 1). Sixteen of the infants, who had gestational ages between 37 and 38 weeks, birth weights greater than 2500 g, and no medical complications at birth, were assigned to the healthy full-term group. Sixteen infants with gestational ages between 26 and 37 weeks were assigned to one of two preterm groups. Eight infants with birth weights between 1070 and 2450 g and no medical complications at birth were assigned to the healthy preterm group. The remaining eight infants, with birth weights between 450 and 2000 g, exhibited respiratory distress at birth or developed broncho-pulmonary dysplasia, and were assigned to the high risk preterm group.

**Design and procedure**

The 32 infants were re-examined 3 months after their first test at term (between 37 and 40 weeks gestational age). All of the infants were tested in a quiet room in the Infancy Laboratory of the Department of Psychiatry at Children's Hospital, Boston. Parents signed an informed consent in the hospital at the inception of the study, and received 15 dollars at each laboratory visit for travel and parking expenses.

Sucking and breathing

The coordination of sucking and breathing was recorded while the infant was wearing a diaper and cotton shirt and either lying supine on a changing table or held in a semi-supine position by the mother. A Ross red nipple without holes was modified to record positive and negative sucking pressure. The type of nipple used at 38 weeks was again used here to control for possible effects of nipple size and shape on sucking. Three small holes were drilled at the base of the nipple, and two in the tip, to allow insertion of pressure lines for recording positive pressure, negative pressure and milk delivery, respectively. After steam sterilization, the nipple was assembled in a sterile field by inserting the pressure lines and securing them in place with Silastic silicone medical adhesive. The base of the nipple was sealed with a disc of Stomahesive wafer. The two lines used to record positive and negative pressure, respectively, were each connected to a pressure transducer (Argon Medical, Lakewood, CO) via a CDX pressure transducer cable and then to separate channels of a custom built portable amplifier/calibrator. Pressure was calibrated so that a reading of 5 V was equivalent to 100 mmHg. Milk was supplied by gravity feed to the milk line by a 60 cc syringe (Becton-Dickinson 309663) and three-way stopcock (Baxter 2C6206). Milk flow was calibrated by a drip method at a rate of 4 cc of milk per minute. A roller clamp placed 5 cm from the base of the nipple was used to turn the milk supply on or off. To record sucking, the nipple was placed in the infant’s mouth and held there by the

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Post-conceptional age at birth (days)</th>
<th>Birth weight (g)</th>
<th>NAPI score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>285.81 (7.64)</td>
<td>3509.06 (433.96)</td>
<td>465.56 (44)</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>237.25 (25.64)</td>
<td>2109.63 (490.16)</td>
<td>361.38 (78.35)</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>197.25 (19.71)</td>
<td>1099.63 (475.93)</td>
<td>346.38 (76.31)</td>
</tr>
</tbody>
</table>

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mother via an attached ring. Infants were tested while lying supine on the changing table or while held supine in the mother’s lap. Breathing was recorded as described in Goldfield et al. (this issue).

Experimental interruption and resumption of milk flow
At the beginning of each trial, the mother placed the nipple in the infant’s mouth while it delivered milk. After 20 s, the flow of milk was experimentally stopped by a roller clamp on the plastic tubing. After another 10 s, the milk supply was resumed by releasing the roller clamp. This procedure was continued for ten periods each of milk flow on or off. All infants completed at least eight trials during which milk flow was interrupted and then restarted.

Data reduction
The waveforms for each channel (see Figure 1) (chest, abdomen, sucking positive pressure, sucking negative pressure) were reduced for analysis with software algorithms (Dataq Calc) which automatically marked the peaks and valleys, indicated by the vertical marks. Reading down from the top of the figure, the first channel was used to mark the onset and offset of milk flow, the second and third channels recorded chest and abdominal movements, respectively, with inspirations as upward displacements, the fourth channel recorded positive (intra-nipple) pressure, and the fifth channel recorded negative (intra-oral) pressure. Mean frequency (Hz) was defined as the reciprocal of the peak to peak intervals of each waveform. Amplitude (V) was defined as the difference between a peak and its preceding valley. Bidirectional weighted coherence was calculated as described in Goldfield et al. (this issue).

Calculation of relative phase
The relative phase (in degrees) describing the relation between positive and negative sucking pressure was based upon point estimates at each peak and valley. The positive pressure signal was arbitrarily chosen as a reference, and the abdominal signal as a target. Phase angle was calculated by (1) determining the difference between the temporal lag (in seconds) between each peak of positive pressure (maximum compression of the nipple) and the corresponding peak of negative pressure (maximum intra-oral suction pressure), (2) dividing that difference by the period of negative pressure, and (3) multiplying the quotient by 360.

Farey tree diagrams were used to organize the data on the relation between sucking and respiratory frequencies. The Farey tree is a graphic representation and computational tool for examining the relationship between stable patterns of frequency ratios for two oscillatory behaviors, in this case sucking and breathing (see Beek, 1989).

Results

Frequency of positive pressure during non-nutritive and nutritive sucking
Positive sucking pressure was analyzed during each non-nutritive and nutritive sucking burst for each of the infants in the three groups. Table 2 presents the means and standard deviations of frequency (number of sucks per second) for both types of sucking burst as a function of group membership. A Kruskal–Wallis analysis of variance (ANOVA) was used to examine group differences in sucking frequency. There was a significant difference between the groups in non-nutritive sucking frequency, \( H(2, N = 32) = 8.84, p = 0.012 \). Mann–Whitney tests with \( \alpha \) adjusted for the number of two-way tests was used for post hoc comparisons. The healthy full-term infants sucked at a significantly slower rate than the healthy preterm infants, \( U = 5.00, p = 0.005 \), or the high risk preterms, \( U = 31.5, p = 0.04 \). There was also a significant difference between the groups in frequency of nutritive sucking, \( H(2, N = 32) = 12.27, p = 0.002 \). The high risk preterms sucked at a higher rate than the full-term infants, \( U = 14.5, p = 0.002 \), and the healthy preterms, \( U = 2.00, p = 0.002 \). Thus, the high risk preterm infants sucked at a higher frequency than the other infants during both types of sucking.

Figure 1 An example of the waveforms of sucking and breathing produced by each infant (see text for details).
During nutritive sucking, the groups again differed in the distribution of sucking and breathing. All of the non-nutritive and nutritive sucking bursts were classified as either of the other groups, 02(2) patterns, 02(6) or 3/2 patterns, 02(2) = 53.13, p = 0.001. The infants in the two healthy groups (1 and 2) were significantly more likely to exhibit 3/2 sucking and breathing frequency ratios than the high risk preterm group, 02(2) = 18.40, p = 0.001, and infants in group 3 were significantly more likely to suck twice for each breath than infants in either of the other groups, 02(2) = 26.76, p = 0.001.

The Farey tree also provides a means of testing predictions about the effects of milk flow onset on the frequency ratios of sucking and breathing. Neighboring values on lower branches indicate ratios that are more stable. Infants unable to sustain coordination at higher ratios, such as 3/2 or 2/1, would be expected to switch to a more stable coordination pattern, such as 1/1. Table 4 presents the distribution of infants who maintained the same coordination pattern between sucking and breathing or who switched to a more stable pattern when milk was turned on. χ² analysis indicated that most of the healthy full-term infants sustained the 3/2 pattern when milk was turned on, and that the preterm infants either stayed in the relatively stable 2/1 pattern for both types of sucking or switched to the 1/1 pattern when milk was turned on. Thus, during both pacifier and nutritive sucking, the coordination of sucking and breathing distinguishes infants in the high risk group from the other infants.

Tolerance bands and coherence

To examine deviations around the rational numbers indicating frequency locking at 3 months so as to be comparable with the 38 week data, 0.05 tolerance bands were calculated for the non-nutritive sucking data (see Goldfield et al., this issue, for justification). For each of the five trials of non-nutritive sucking and breathing of

### Table 2 Non-nutritive and nutritive suck frequency (based on eight bursts and pauses for each of the 32 infants)

<table>
<thead>
<tr>
<th>Group</th>
<th>Non-nutritive suck frequency</th>
<th>Nutritive suck frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>1</td>
<td>2.06</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>1.89</td>
<td>0.23</td>
</tr>
<tr>
<td>3</td>
<td>1.98</td>
<td>0.27</td>
</tr>
</tbody>
</table>

### Table 3 Respiratory frequency and amplitude during non-nutritive and nutritive suck bursts (based on eight bursts and pauses for each of the 32 infants)

<table>
<thead>
<tr>
<th>Group</th>
<th>Non-nutritive suck burst</th>
<th>Nutritive suck burst</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burst</td>
<td>Pause</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>1</td>
<td>1.08</td>
<td>0.26</td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>1.14</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Respiratory frequency during non-nutritive and nutritive sucking

The frequency of abdominal breathing movements was calculated during all sucking bursts and non-nutritive sucking pauses (Table 3). Group differences in respiratory frequency were examined by Kruskal–Wallis ANOVA. There was a significant group difference in respiratory frequency during nutritive sucking bursts, H(2, N = 32) = 6.11, p = 0.04, due to the difference between the healthy full-term and high risk preterm infants, U = 20.5, p = 0.007, but no overall difference during pauses. There was also a significant group difference in respiratory frequency during nutritive sucking bursts, H(2, N = 32) = 7.37, p = 0.02. Mann–Whitney tests indicated that high risk preterm infants breathed faster than the healthy preterm infants, U = 24, p = 0.01. There were too few pauses during nutritive sucking to examine any group differences. Thus, while breathing slows during the transition from pacifier to nutritive sucking, it still remains relatively higher overall in the high risk infants.

Ratio of sucking frequency to respiratory frequency

The mean sucking and respiratory frequencies were additionally used for an analysis of the frequency ratio of sucking and breathing. All of the non-nutritive and nutritive sucking bursts were classified as n sucks to m breaths, where n/m equaled 1/1, 2/1, 3/1 or 3/2. Figures 2 and 3 present the distribution of these ratios by group and type of sucking according to a Farey tree diagram. The distribution of patterns generated by Farey trees was tested by χ² tests. During non-nutritive sucking, the groups differed significantly overall in the distribution of sucking/respiration frequency ratios, 02(6) = 63.41, p = 0.0001. Groups 1 and 2 were significantly more likely than group 3 to exhibit 3/2 ratios of sucking and breathing, 02(2) = 11.09, p = 0.004. Group 2 was significantly more likely to exhibit 2/1 rates than either of the other groups, 02(2) = 17.21, p = 0.0001. During nutritive sucking, the groups again differed significantly overall in the distribution of 1/1, 2/1, 3/1 or 3/2 patterns, 02(6) = 53.13, p = 0.001. The infants in the two healthy groups (1 and 2) were significantly more likely to exhibit 3/2 sucking and breathing frequency ratios than the high risk preterm group, 02(2) = 18.40, p = 0.001, and infants in group 3 were significantly more likely to suck twice for each breath than infants in either of the other groups, 02(2) = 26.76, p = 0.001.
each infant (a total of 160; see Table 5 for means and standard deviations), every predicted rational number fell within a 0.05 tolerance band around the observed ratio of sucking and breathing frequencies. ANOVA on the arc sine transformed ratios 1/1, 2/1 and 3/2 (excluding the six trials of 3/1) indicated that the width of the tolerance bands was significantly different as a function of the nature of the frequency lock, $F(2, 152) = 3.07$, $p = 0.05$, and of group membership, $F(2, 152) = 3.66$, $p = 0.03$. Tukey HSD post hoc tests indicated that the width of the 1/1 frequency lock was significantly greater than for the other two, and that the high risk preterm infants differed significantly from the other two groups. ANOVA on arc sine transformed values of bidirectional weighted coherence for the same trials (see Table 6 for means and standard deviations) found a significant difference as a function of the nature of the frequency lock, $F(2, 152) = 16.19$, $p = 0.0001$, but no differences between the three groups. Tukey HSD post hoc tests indicated that the weighted coherence of the 1/1 frequency lock was significantly greater than for the other two.

Table 4  Effect of milk flow onset on frequency ratios of sucking and breathing (number of subjects)

<table>
<thead>
<tr>
<th>Group</th>
<th>Stay</th>
<th>Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3/2</td>
<td>2/1</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2  Farey tree representations of the distribution of frequency ratios of pacifier sucking (positive pressure) and breathing for (from top to bottom) (a) healthy full-term, (b) healthy preterm and (c) high risk preterm infants. The numbers next to each ratio represent the number of suck bursts during which the ratio was apparent.

Figure 3  Farey tree representation of the distribution of frequency ratios of nutritive sucking and breathing, based on positive pressure for this analysis, for (from top to bottom) (a) healthy full-term, (b) healthy preterm and (c) high risk preterm infants.
During nutritive sucking, a point estimate of relative phase (based upon the peaks and valleys of the two waveforms) was used to calculate the phase angle between positive pressure of the lips and jaw on the nipple and negative (intra-oral suction) pressure for each burst. Kruskal–Wallis ANOVAs were used to examine group differences in mean relative phase during (a) a steady state period with milk off, (b) a transition period at milk onset, and (c) a steady state during which milk flow was uninterrupted (see Figure 4). For this reason, it was not possible to compare the timing of positive and negative pressure during the initial steady state. There were no group differences in either the mean or the standard deviation of relative phase during this period: all coordination patterns clustered around a mean relative phase between $0^\circ$ and $45^\circ$. Initial inspection of the transition period data indicated that mean relative phase angle clustered around one of three values: $45^\circ$ or less, $46^\circ$–$135^\circ$, or $136^\circ$–$225^\circ$. Since inclusion of bursts in all three categories of relative phase changed the means and standard deviations of relative phase across groups, separate analyses were conducted. There was a significant difference between the groups in relative phase during the transition period (i.e. at the onset of milk), both when all categories of relative phase were included, $H(2, N = 32) = 7.55, p = 0.023$, and when only relative phase angles less than $135^\circ$ were included, $H(2, N = 32) = 7.02, p = 0.03$. In both types of trials, the high risk preterm infants sucked with higher relative phase between expression and suction than the healthy full-term infants, $U = 24.5, p = 0.01$. Thus, the coordination of expression and suction seems to be organized around values of $0^\circ$, $90^\circ$ and $180^\circ$ relative to the opening and closing of the jaw, and relative phase of the high risk preterms was more likely to be attracted to $90^\circ$ or $180^\circ$.

### Table 5 Tolerance bands around the hypothesized frequency locks of sucking and breathing (arc sine of mean, SD)

<table>
<thead>
<tr>
<th>Group</th>
<th>1.1</th>
<th>2.1</th>
<th>3.2</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.518 (0.04)</td>
<td>0.396 (0.20)</td>
<td>0.305 (0.18)</td>
<td>0.406 (0.11)</td>
</tr>
<tr>
<td>2</td>
<td>0.365 (0.15)</td>
<td>0.353 (0.23)</td>
<td>0.314 (0.11)</td>
<td>0.344 (0.03)</td>
</tr>
<tr>
<td>3</td>
<td>0.651 (0.19)</td>
<td>0.559 (0.41)</td>
<td>0.393 (0.35)</td>
<td>0.534 (0.13)</td>
</tr>
<tr>
<td>All</td>
<td>0.511 (0.14)</td>
<td>0.436 (0.11)</td>
<td>0.337 (0.05)</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6 Weighted coherence of sucking and breathing frequencies (arc sine of mean, SD)

<table>
<thead>
<tr>
<th>Group</th>
<th>1.1</th>
<th>2.1</th>
<th>3.2</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.547 (0.02)</td>
<td>0.444 (0.16)</td>
<td>0.363 (0.13)</td>
<td>0.404 (0.06)</td>
</tr>
<tr>
<td>2</td>
<td>0.704 (0.31)</td>
<td>0.467 (0.13)</td>
<td>0.315 (0.15)</td>
<td>0.391 (0.11)</td>
</tr>
<tr>
<td>3</td>
<td>0.838 (0.23)</td>
<td>0.471 (0.20)</td>
<td>0.477 (0.20)</td>
<td>0.474 (0.01)</td>
</tr>
<tr>
<td>All</td>
<td>0.696 (0.15)</td>
<td>0.460 (0.01)</td>
<td>0.385 (0.08)</td>
<td></td>
</tr>
</tbody>
</table>

### The adaptation of breathing to milk presentation: analyses at the transition boundary

Milk presentation had a variety of effects on breathing (see Figure 4). For this reason, it was not possible to examine the relative phase of chest and abdomen at the transition boundary, as we did for positive and negative sucking pressure. Instead, as milk was turned on at each transition boundary, as we did for positive and negative sucking pressure, the high risk preterm infants responded to milk onset by a transient shift in relative phase between chest and abdomen, (b) rapid shift in relative phase from $0^\circ$ to $180^\circ$ and then back to $0^\circ$, (c) pause in breathing for less than $3$ s, (d) pause in breathing for $3$ s or more, or (e) brief sigh inspiration. Table 8 presents the frequencies of these different types of respiratory response by the infants in the three groups according to these categories. While more than $80\%$ of the healthy full-term infants responded to milk onset by a transient shift in relative phase between chest and abdomen (the first two categories), this was not the case for the infants in the two preterm groups. These infants were significantly more likely to sigh or take long pauses in breathing (the last three categories). A $\chi^2$ test computed on the first two categories (referred to as phase shift) and the last three categories (referred to as interruption) revealed a
significant difference between the infants in the three groups, $\chi^2(2) = 12.10, p = 0.0002$.

Discussion

At 3 months after term, the infants in the high risk preterm group breathed at a significantly higher rate than infants in the other two groups. The increased respiratory rate contributed to observed differences in the coordination of breathing and sucking, both in pacifier and nutritive sucking conditions. Infants in both healthy groups were more likely to produce three sucks for every two breaths (a 3/2 pattern), even when sucking procured milk. Among the high risk preterm infants, the 3/2 pattern was evident during more than one-quarter of the non-nutritive sucking bursts. However, during nutritive sucking, the 3/2 pattern dropped to only 6%.

The predominant pattern of coordination between nutritive sucking and breathing was two sucks to one breath, which occurred more than 80% of the time during nutritive sucking. However, respiratory rate is not the only contributing factor in this pattern. While the rate of sucking slowed significantly in the two healthy groups when feeding, it remained almost the same in both pacifier and nutritive sucking in the high risk preterm infants. The intrinsically higher rates of both sucking and breathing make it more likely that a simpler pattern of coordination emerges in these infants.

The faster rates of pacifier sucking and breathing among the preterm infants were also apparent in our earlier 38–40 week test (Goldfield et al., this issue). These infants also exhibited weaker coordination between sucking and breathing and fewer 3/2 frequency ratios of sucking and breathing than the infants in the healthy full-term group. The small number of 3/2 ratios of sucking and respiratory frequencies in the high risk preterm infants in both tests is consistent with an interpretation of their continued reliance on more stable patterns of coordination. The Farey tree is a mathematical tool in which successive branches correspond to smaller stable regions of frequency coupling. The coordination of sucking and breathing of these infants tends to occur at levels of the Farey tree which correspond to greater stability, even under conditions of minimal load on the oral articulators (i.e. with low suction during absence of milk). This distribution of frequency ratios at less stable regions of frequency coupling may indicate that these infants have greater difficulty performing motor activities that coordinate systems with different intrinsic frequencies. To determine whether such difficulty may be restricted to the oral–respiratory system or may be a more general
characteristic of the premature nervous system will require studies of how these infants coordinate other activities with different intrinsic frequencies (e.g. limb oscillations and breathing).

Continuing problems in coordination are also apparent in the influences on breathing of experimentally turning milk on or off. The five types of response to the milk perturbations clearly distinguish the full-term infant from the preterm infant. In the healthy full-term infants milk onset most often resulted in a transient increase in phase lag or a shift in chest–abdomen phase, but most of the preterm infants exhibited some kind of interruption of breathing at milk onset. These findings on infant respiration suggest that the intrinsic temporal organization of inspiration and expiration as well as the vegetative demands on breathing result in a limited set of patterns to be used for ingesting fluids. The oral anatomy additionally imposes its own constraints on the formation of dynamic patterns for infant feeding. The human mandible oscillates about a hinged joint due to the balance of opposing muscle groups (Flanagan, Ostry & Feldman, 1990), and the lips must maintain a seal around the nipple as the jaw moves (Bosma, 1986).

The findings may also shed light on more general questions about infant motor development, including the relationship between neonatal and later motor patterns, and the nature of the process by which higher order synergies develop. Our previous report of pacifier sucking at 38 weeks gestational age (Goldfield et al., this issue) found that pacifier sucking exhibited the properties of a motor synergy: it is organized as a stable alternation pattern of bursts and pauses, has a mean frequency of 2 Hz, and establishes integer frequency locks with respiration. The experimental procedure of turning milk on and off when these infants reached 3 months of age indicated that the nutritive and non-nutritive modes of sucking may represent the same synergy under the changing task requirements of feeding. The concomitant slowing of sucking and breathing when milk is turned on allows the articulators to maintain the same relative coordination, so that mode locking of sucking and breathing frequencies either remains the same or switches to a more stable pattern (e.g. from 3/2 to 2/1). Infants also maintain coordination between the expression and suction cycles when milk is turned on, albeit with an increased phase lag, and the respiratory pattern is more likely to accommodate milk flow than be interrupted by it. Non-nutritive sucking and its coordination with breathing, therefore, may constitute an ontogenetic adaptation (Oppenheim, 1981), a behavioral pattern which prepares and supports the development of new functions. The mode locking of non-nutritive sucking and breathing both maintains the coordination pattern evident from birth and allows for the incorporation of the suction component within the opening and closing cycle of the jaw.

This balance between the conservative maintenance tendency of an existing coordination pattern and the possibility of creating new functions from it is a hallmark of complex adaptive systems. In the frequency domain, innovations may be made possible by the coupling of oscillations with different preferred frequencies, a process called symmetry breaking (see, for example, Carson, 1993; Kelso, 1995). In the formative periods of the organization of new patterns and in the maintenance of patterns that serve life supporting functions, nature appears to favor symmetry. So, for example, in newborn infants, the movements of the muscles of the chest wall exhibit 1/1 phase locking with the abdomen (Goldman et al., 1993). In the transition from active to quiet sleep, the relative phase of chest and abdomen switches abruptly from 180° to 0° but maintains the 1/1 phase locking. This ensures that the vital function of breathing is not interrupted by the inherent fluctuations of neural activity in transitions from sleep to wakefulness. Premature infants have more variable cardiovascular functioning (Eiselt et al., 1993) and this persists for several months after birth (Henslee, Schechtman, Lee & Harper, 1997). The consequence of the symmetry breaking of coupled sucking and respiratory rhythms in the high risk preterm infants may be to drive frequency synchronization into phase locks that have higher stability but are less complex.

Switching into the nutritive mode of sucking at the onset of milk flow implies that the perceptual systems may be continually exploring the ongoing dynamics of the oral articulators for the presence of sweet-tasting fluids, such as milk (Smith & Blass, 1996). The tongue, a muscular hydrostat (Smith & Kier, 1989), is an exquisite haptic tool; its differentiated musculature and receptor surfaces make it an exploratory organ capable of such discriminations (Gibson, 1967; Crook, 1979). In the nutritive mode, the infant uses the tongue to explore for milk, to pump milk into the mouth and to trigger swallowing (Selley et al., 1990). Further work is needed on the relation between the changing haptic perceptual capabilities of the tongue as they relate to the coordinated use of the tongue during nutritive sucking.

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