RIB CAGE AND ABDOMINAL MOVEMENT DURING UTTERANCE PRODUCTION IN INFANTS AROUND THE FIRST YEAR OF LIFE

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Arts with a major in Communication Sciences and Disorders.

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Douglas F. Parham, Committee Chair

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ABSTRACT

Introduction: The chest wall is composed of two primary components: the rib cage and the abdomen. In healthy adults, these two mechanisms are coupled during both breathing at rest and speech breathing. However, with regards to infants the coupling that is observed in adults is not yet present in infants. Little is known about when during human development the coupling of the two components occurs. This study explored the contribution to chest wall movement that each component plays during single-syllable utterances by infants around the first year of life.

Methods: Vocalizations and breathing kinematics were recorded from 10 infants between 9 and 16 months of age during vocal play with their mothers. The movement of both the rib cage and the abdomen were measured during production of single-syllable utterances. The relative contributions of the rib cage and abdomen were compared to see how they impacted chest wall movement during utterance production. Contributions were measured as a percentage of total chest wall movement.

Results: For the infants in the study, it was determined that the abdomen contributed to a greater degree than the rib cage during the total respiratory cycle and the inspiratory phase, and that both the rib cage and the abdomen contributed to differing degrees during the expiratory phase.

Discussion: The findings relate the role of the rib cage and abdomen to total chest wall movement during utterance production. This study adds information about how breath support for utterance production develops during infancy. By studying further this particular aspect of chest wall development, knowledge may be gained that could aid in the early identification of infants who might be developing atypically.

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CHAPTER 1

REVIEW OF THE LITERATURE

Introduction

Infant respiratory physiology and vocalization are two significant and distinct areas of scientific inquiry. A great deal of information is known about each as a separate area. Regarding to infant respiratory physiology, there is an extensive history of research examining respiratory development (e.g., Charnock & Doershuk, 1973; Gaultier, 1995; Hershenson, Colin, Wohl, & Stark, 1990). A key finding is that during tidal breathing in young age infants, the chest wall can be considered a single entity. Tracheal pressure is generated by infants through diaphragmatic contraction and subsequent abdominal displacement; the compliance of the rib cage impacts its expansion by limiting the mechanical advantage of inspiratory muscle action on the rib cage (Hershenson, 1992; Muller & Bryan, 1979; Openshaw, Edwards, & Helms, 1984). However, this research has focused primarily on infants who are asleep and/or not producing vocalizations or any acoustic output. Therefore, we know a great deal of information about infant respiratory physiology, most of what we know does not help us when it comes to understanding speech development. A primary area of research that would benefit the field is the integrated knowledge of how the infant uses the respiratory system to support sound production.

With regards to infant vocalization, the developmental sequence of sounds that infants produce during the first few years of life, is generally agreed upon by investigators. The order of distinct stages is well documented (Koopmans-van Beinum & van der Stelt, 1986; Nathani, Ertmer, & Stark, 2006; Oller, 1980, 2000; Scheiner, Hammerschmidt, Jürgens, & Zwirner, 2002; Stark, Bernstein, & Demorest, 1993). However, current literature concerning developmental trajectories of speech sound development says little regarding the critical role that the respiratory system plays in the aerodynamics, acoustics, and physiology of sound production.

Differences in speech breathing patterns demonstrate respiratory adaptation in adult speakers, resulting from varied requirements for particular speech tasks (Conrad & Schönle, 1979; Hoit & Hixon, 1986, 1987; McFarland, 2001; Smith & Denny, 1990; Stathopoulos, Hoit, Hixon, Watson, & Solomon, 1991). During the teenage years, advanced, variable control of breathing support for speech tends to establish itself, allowing for more variety in speech breathing (Boliek, Hixon, Watson, & Jones, 2009; Hoit, Hixon, Watson, & Morgan, 1990; Netsell, Lotz, Peters, & Schulte, 1994; Russell & Stathopoulos, 1988; Sapienza & Stathopoulos, 1994; Stathopoulos & Sapienza, 1997).

Infant Speech-Related Breathing

Boliek, Hixon, Watson, and Morgan (1996, 1997) examined the relationship between respiration and vocalizations in infants in their first three years of life. Respiration was measured in volumetric and kinematic units. Vocalizations were defined as cries, whimpers, grunts and syllable utterances (Boliek et al., 1996), or syllable utterances, word utterances and combined syllable and word utterances (Boliek et al., 1997). When examining the relationship between respiration and vocalization, the authors found that as age and body length increased, air volume measures increased as well. However, there was great variability among the vocalization types for all age groups.

Parham, Buder, Oller, and Boliek (2011) studied differences in tidal breathing and breathing during utterance production by infants in their second year of life. Both tidal breathing and breathing during utterance production were examined. The breathing that occurred during utterance production supported two types of single syllable utterances: articulated and unarticulated. In the conclusion of the study, it was found that tidal breathing cycles were considerably different from speech-related breathing cycles, or those that supported vocalizations. It remains unclear if speech-related breathing exists due to adaptations that are made to tidal breathing, or if speech breathing is a new form of breathing that emerges during vocal development.

As a division of respiratory patterning occurs, this division enables tidal breathing and speech-related breathing to clearly appear. This distinct division appears to be defined primarily in the second year of life; however, the division also can be observed during the second half of the first year of life (Boliek et al., 1996, 1997; Connaghan, Moore, & Higashakawa, 2004; Langlois, 1975; Moore, Caulfield, & Green, 2001; Parham et al., 2011; Reilly & Moore, 2009).

Infant Chest Wall Movement During Vocalization

Moore, Caulfield, and Green (2001) studied the chest wall movements of typically developing 15-month-old children. These investigators observed that there was an apparent difference in movements of the rib cage and abdomen during tidal breathing in comparison to speech breathing. Rest breathing was described by the rib cage and abdomen moving together or coupled; however, during speech breathing these two components did not move in a synchronized motion and coupling was not observed.

Connaghan, Moore, and Higashakawa (2004) looked at typically developing infants, ages 9 to 48 months. Their findings were similar to those of Moore, Caulfield, and Green (2001). They inferred that tidal breathing and speech-related breathing are two separate entities. With this being said, it is also important to note that the speech related breathing develops following tidal breathing. This is due to differences related to the chest wall including anatomical configuration and motor engagement.

Reilly and Moore (2009) examined the respiratory movements of healthy 7- and 11-month-old infants. They concluded that as the chest wall develops, it is increasingly controlled by neuromotor components. The addition of neuromotor components allows the chest wall to be more efficient, enabling infant utterances to be supported. Changes in anatomical components of the chest wall (e.g., the compliance of the rib cage decreases, making it stiffer and easier to move) and the body's ability to support utterance production are both key components in the respiratory changes observed.

The Difficulty with This Area of Research

Due to the complexity and variety of respiratory signals from infants, this specific area of research has been shown to be particularly difficult. Figure 1 shows strong coupling of the two chest wall components. This pattern of signal coupling typifies tidal breathing or "rest breathing." In this type of breathing, no vocalizations or vocal sounds are produced. Upward movement of a signal indicates inspiration, downward movement indicates expiration. The two signals differ in amplitude, but not direction. The signals presented in Figure 1 are not characteristic of infant chest wall movement during behaviors such as vocalizing, crying, and gross motor movement.

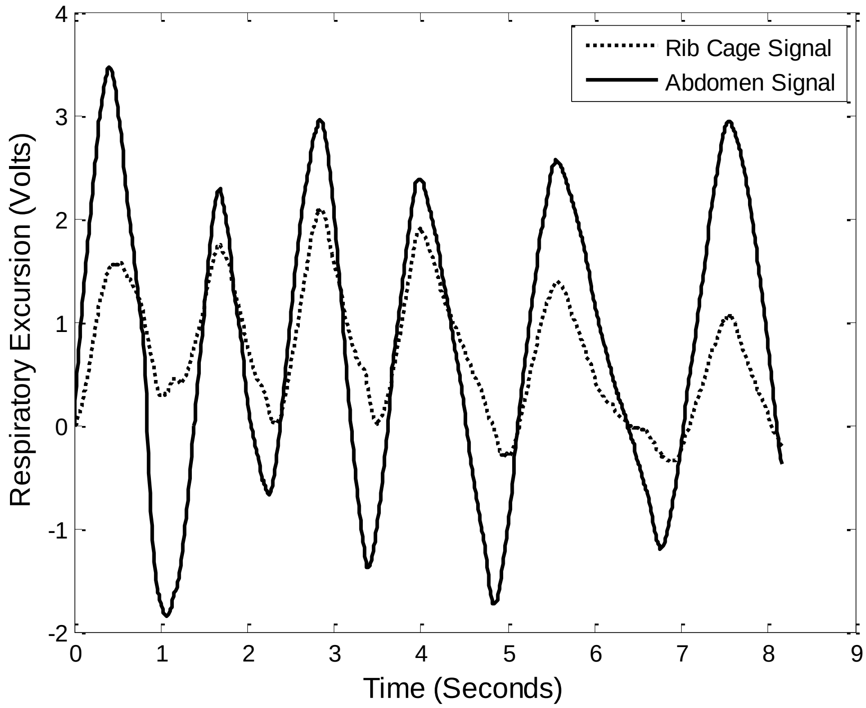

Figure 1. Example of coupled respiratory signals during non-verbal tidal breathing (rib cage, dotted line; abdomen, solid line).

Figure 2 shows an example of rib cage and abdominal movements during vocalization by an infant. Here, the opposing directional movements of the two components suggest a strong degree of decoupling.

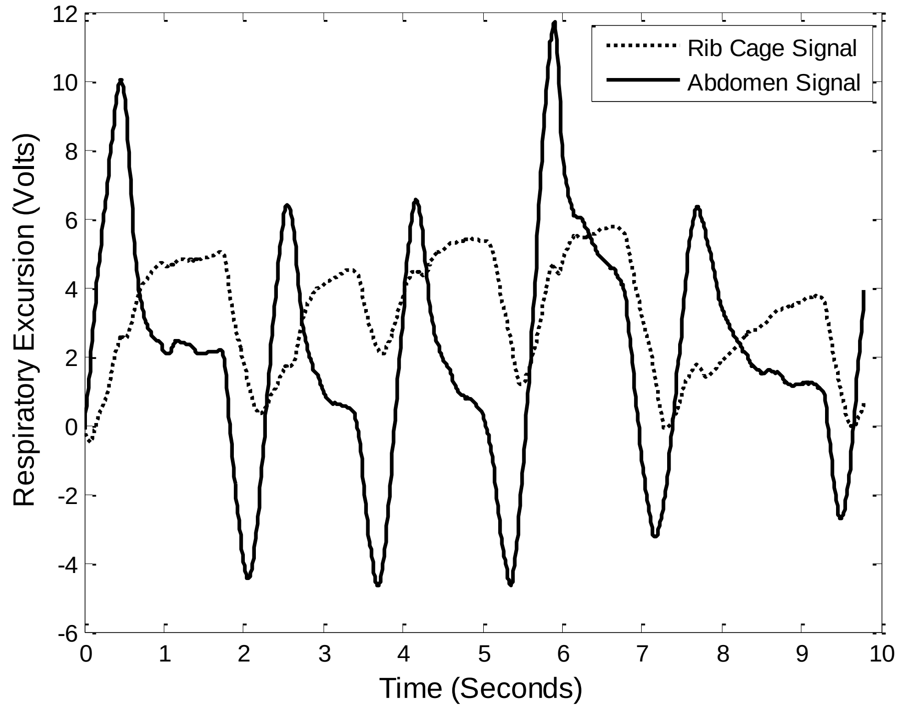

Figure 2. Example of decoupled respiratory signals (rib cage, dotted line; abdomen, solid line).

Results of Pilot Data from Adolescents

Pilot data from a recent study (Sticken, Patton, & Parham, 2012) explored the effects of position on the respiratory support of speech breathing in adolescent children. It was hypothesized that (a) when children were seated, speech would be supported mainly by rib cage movement (expansion of the thoracic cage) with limited abdominal movement, and (b) both rib cage and abdomen would contribute equally when children were standing. Rib cage and abdominal kinematics (i.e., movements) of six healthy children ages 8 to 13 were measured during both conversational speech and reading aloud in both standing and sitting positions. The large age range of the children was due to the exploratory focus of the study. The respiratory signals were compared to determine the relative contributions of the rib cage and abdomen during the speech tasks. Figure 3 shows a comparative example of rib cage and abdominal signals from that study (Sticken, Patton, & Parham, 2012).

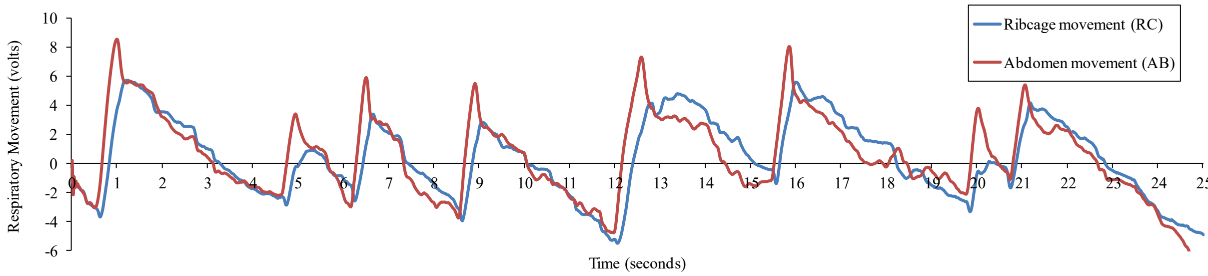

Figure 3. Comparative example of rib cage and abdominal signals used for analysis.

The study's hypotheses were not supported by the data. For only two of the children, both reading and speaking in the seated position were supported mainly by rib cage movement with limited abdominal movement. In the standing position, both rib cage and abdomen contributed equally in only two children's speaking and reading. Variation in the rib cage and abdominal contributions was apparent across tasks and within individuals. Such findings might help to identify and categorize respiratory behaviors for speech in adolescence. They serve as a guide for speculating about infant speech-related breathing.

CHAPTER 2

MOTIVATION FOR THE STUDY

Motivation

Little information is known about how the respiratory system supports utterance production in infancy, defined as the first two years of life. Movement of the chest wall, also known as respiratory kinematics, can be analyzed by measuring the movement the rib cage and abdomen, which are the two chest wall components. When these two measurements are compared, they provide valuable information regarding how breathing supports speech production. One remaining question is how breath support for utterance production develops during infancy. Normative results are needed to understand how respiratory development relates to speech development. Knowledge regarding typical chest wall movement during single syllable utterances could be gained which has the potential to aid in the early identification of infants who might be developing atypically.

Variables of Interest

This study measured (a) rib cage movement and (b) abdominal movement during single-syllable utterance production. Both variables were measured and coded during inspiration and expiration, and then compared for differences in relative contribution to the total chest wall movement. Specifically, what percent of chest wall movement during inspiration was due to rib cage movement compared to the percent of chest wall movement during expiration due to abdominal movement.

Infants ranging from 9 months to 16 months were included because that developmental time frame is when infants in this age range generally produce a sufficient number of single-syllable utterances for analysis. Single-syllable vocalizations were chosen as the type of utterance because they are produced at a higher frequency than multi-syllabic utterances by infants in this age range.

Research Question and Predictions

This study attempted to answer the following question related to the relationship between rib cage and abdominal movement during single-syllable utterances by infants around the first year of life: *Are there general patterns in the relative contributions of rib cage and abdomen to chest wall movement in infants during early speech development demonstrated during single syllable utterances?*

Based on previous evidence, it was predicted that there would be more abdominal contribution to total chest wall movement in these infants. Infants in this age range are still developing the ability to use the respiratory system to support speech-like utterances. At the same time, it was expected that there would be large variation in chest wall movement among the infants, given the variability of infant motor behaviors reported in the literature. Infants in this age range are learning to coordinate increased postural control and movement, and—at the same time—expand their ability to communicate with increasingly syllabic utterances.

CHAPTER 3

METHODS

IRB Approval

This study was approved by the Institutional Review Board at Wichita State University (IRB No. 1425; Project Title: "Vocalization and Speech Breathing in Infants and Adults"). A member of the research team explained the informed consent form to each parent. Each parent signed the informed consent form. The families (all from the greater Wichita area) that participated in the study received monetary compensation of $20.00 for each recording session.

Study Population

Ten infants (9 to 16 months old) were included in this study. By parents' reports, all of the infants were healthy and born at full term. None of the infants had any identified hearing pathology, allergies, pulmonary disease or neuromuscular disease. No infant had a cochlear implant. Gender was not a variable of interest in this study because no difference in respiratory performance has been reported in the literature between female and male infants in this age range (Boliek et al., 1996, 1997). Unpublished existing data were used to increase the number of infant subjects to 10 for this study. The infants' ages, in weeks, were as follows: 37.5, 39, 42, 45, and 49 (forming a younger group); 61, 64, 64, 65, and 66 (forming an older group).

Setting

The recordings took place at an urban university laboratory setting. The first room was a playroom designed to resemble a family-friendly living room. The second room contained all of the instrumentation and recording equipment (see "Instrumentation" section below) and was equipped with a large one-way mirror for observation.

Instrumentation

Respiratory movements were measured using a respiratory inductive plethysmograph (RIP), namely Inductotrace®, Model 10.9000 (Ambulatory Monitoring, Inc., Ardsley, NY). RIP is the standard way to measure breathing in infants; it is also non-invasive (Adams, Zabaleta, Stroh, Johnson, & Sackner, 1993; Boliek et al., 1996, 1997; Parham et al., 2001).

The infants' vocalizations were captured using a Sennheiser Evolution G2 100 Series wireless microphone system (Sennheiser Electronic Corporation, Old Lyme, CT). A lapel microphone was attached to each infant's shirt. A high-quality digital audio recorder was used to capture an additional audio signal (at 48,000 or 96,000 samples per second). These audio recordings were used to locate the infants' utterance productions relevant to their breathing cycles.

Signals were captured using USB-based data acquisition modules (Data Translation, Inc., Marlboro, MA), digitally recorded, and saved for analysis using the TF32 software program (Lab Automation Level) (Milenkovic, 2001).

Study Protocol

Each infant was placed in a high chair in the observational playroom with the parent seated in a comfortable chair facing the infant. It was important to control the infants' movement without constricting them (as would be the case if they were strapped within an infant car seat). Following a standard procedure (Boliek et al., 1996), two RIP bands were placed around each infant—at the rib cage and at the abdomen—to track all chest wall movements during breathing. If an infant was wearing layered clothing, all but the shirt or material closest to the skin was removed to allow for the proper placement of the RIP bands.

The best way to determine the relative contributions of the chest wall components is for a participant to hold his or her breath and then, in an alternating fashion, protrude the abdominal wall and compress it. This shifting of the volume of air from the upper rib cage to the lower rib cage and abdomen is called an "isovolume maneuver," and it can be used to determine the contributions of the different chest wall components. Infants cannot perform this maneuver voluntarily, but, when tickled, they can move reflexively in a way that mirrors the isovolume maneuver (Boliek et al., 1996; Parham et al., 2011). The respiratory signals were calibrated using this procedure.

After the microphones and RIP bands were placed on the infant, speech output and respiratory movements were collected during face-to-face interaction and free play with the parent. Parents were instructed to play and verbalize with their infants as if they were interacting naturally at home. The recordings lasted between approximately 15 minutes for single sessions and 3 hours across multiple sessions (see Table 1 below for recording times).

Data Analysis

The Inductotrace® system produced three signals for each respiratory recording: a signal representing rib cage movement, another representing abdominal movement, and a third that was the arithmetic sum of the first two and represented total chest wall movement. Each infant's respiratory signals were examined to determine whether both the rib cage and abdominal signals were analyzable. Figure 4 shows an example of the audio signal (top row) and the three respiratory signals (bottom three rows).

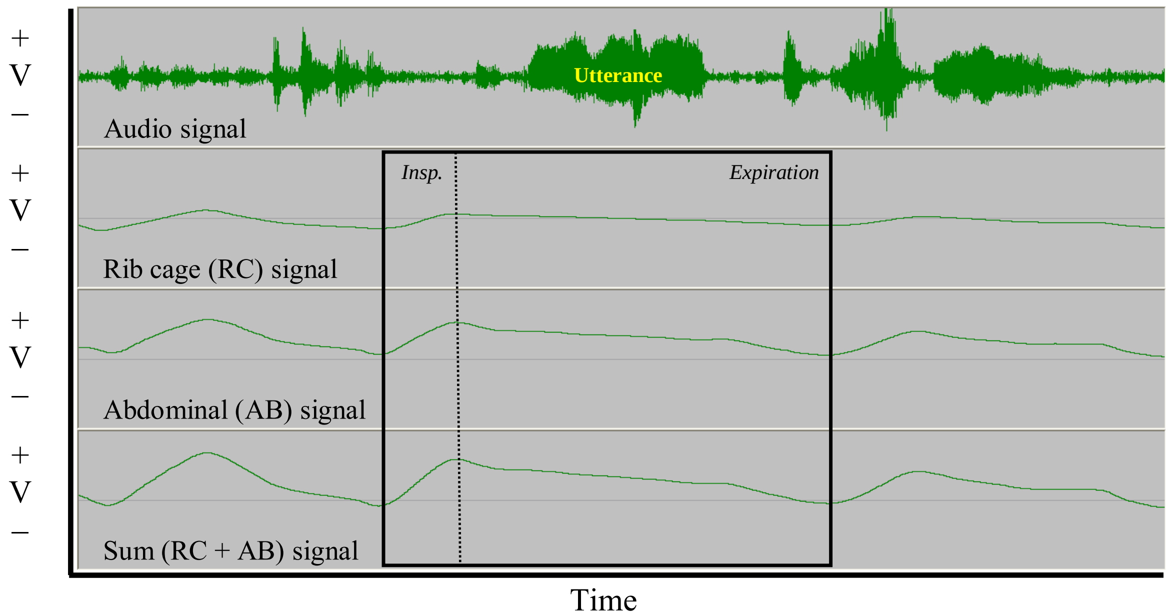

Figure 4. Example of a breath cycle and utterance in a 7.3 second recording (V = volts).

Two independent coders identified breath cycles (inspiration and expiration) underlying single-syllable utterances. The coders disagreed on breath cycle identification on less than 5% of the data. Breath cycles were identified as unanalyzable if either the rib cage signal or the abdomen signal was affected by motion artifact, as is shown in Figure 5.

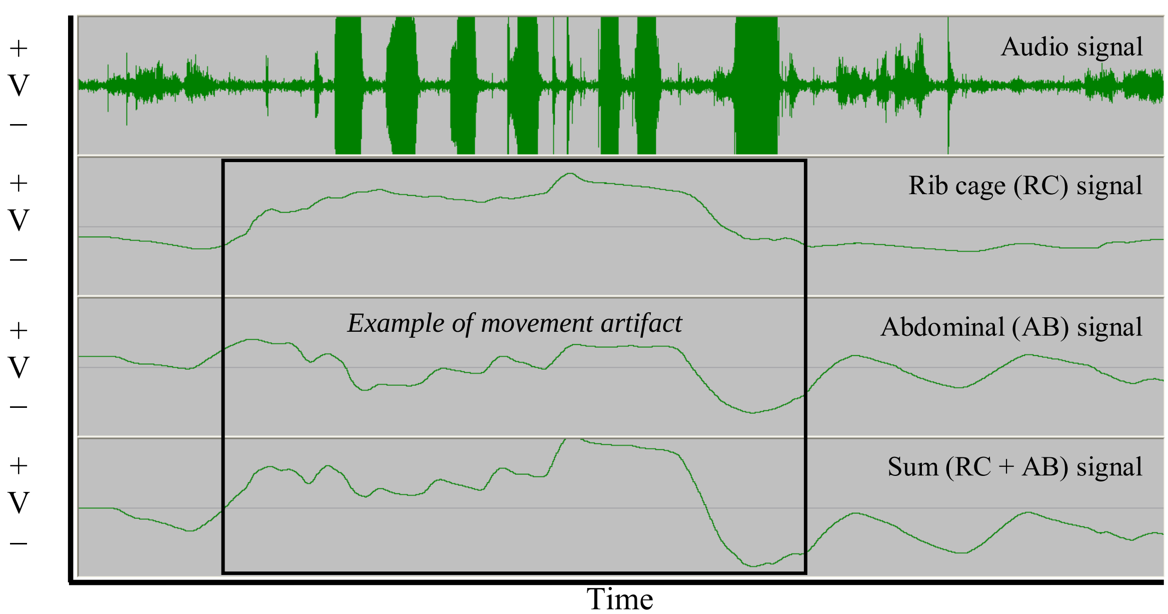

Figure 5. Example of movement artifact in the respiratory signals.

Table 1 shows the number of vocalizations that each infant produced across his or her respective recordings, as well as the number of analyzable respiratory cycle and single-syllable utterance signal pairs produced by each infant.

TABLE 1

NUMBER OF ANALYZABLE RESPIRATORY AND SINGLE-SYLLABLE UTTERANCE SIGNAL PAIRS PRODUCED BY EACH INFANT

Infant	Recording time (hours, minutes)	Total vocalizations	Number of analyzable respiratory cycle and utterance signal pairs
		Younger group	
A	1h, 7m	552	23
B	0h, 37m	234	16
C	0h, 41m	162	11
D	0h, 29m	209	20
E	1h, 23m	159	47
		Older group	
F	0h, 39m	156	6
G	0h, 13m	55	9
H	2h, 46m	864	40
I	0h, 41m	235	32
J	0h, 52m	273	43

Despite the large number of total single-syllable vocalizations across all recordings, a small number of each infant's utterances were associated with analyzable respiratory signals. This low ratio of analyzable signals has been reported in the literature (Boliek et al., 1996, 1997; Parham et al., 2011).

Because the ribcage and abdomen signals were set to display equal deflection for equal input voltages, their respective sizes could be compared directly. A mathematical software program, MATLAB (The MathWorks, Natick, MA), was used to compare the two signals to determine if one signal was larger than the other (i.e., contributing more to chest wall movement). MATLAB was also used to calculate the means, standard deviations, and medians of the (a) respiratory durations, and (b) the relative contributions of the rib cage and abdomen components (rib cage signal and abdomen signal, respectively) in relation to the total chest wall movement. Each component's contribution was expressed as a percentage of total chest wall movement (e.g., the abdomen contributed to 51% of total chest wall movement). Rib cage and abdomen contributions were selected by MATLAB for total respiratory cycles (Figure 6), the inspiratory phases (Figure 7), and the expiratory phases (Figure 8).

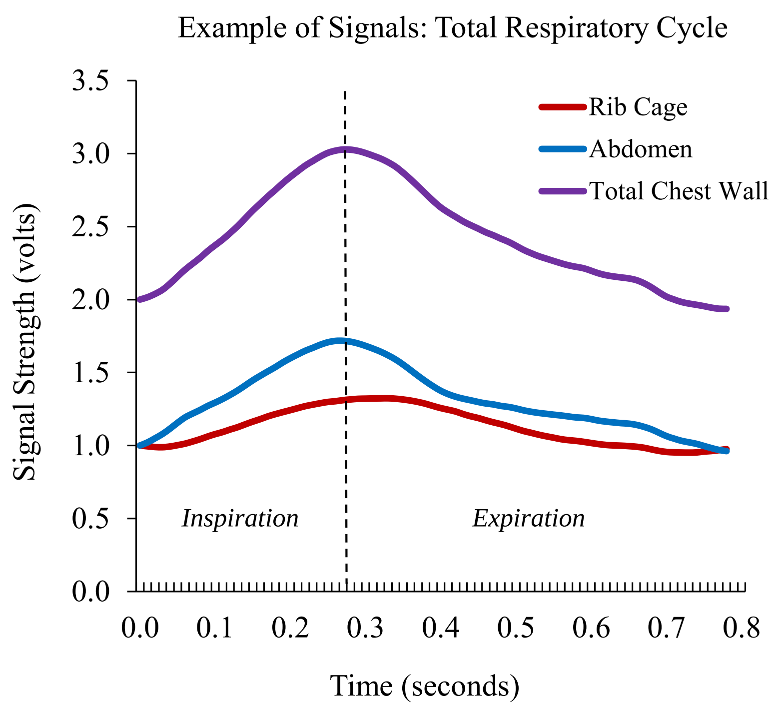

Figure 6. Example of signals: Total respiratory cycle.

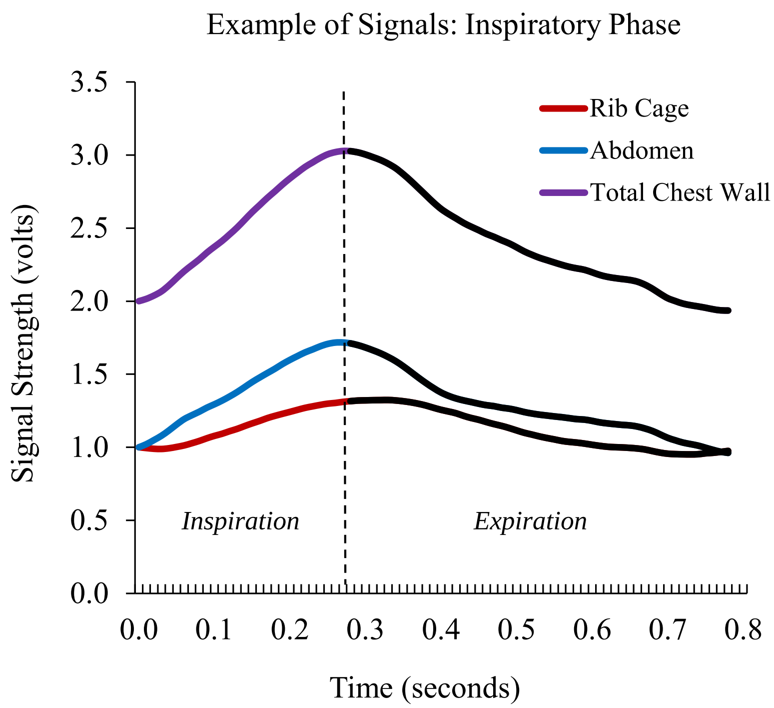

Figure 7. Example of signals: Inspiratory phase.

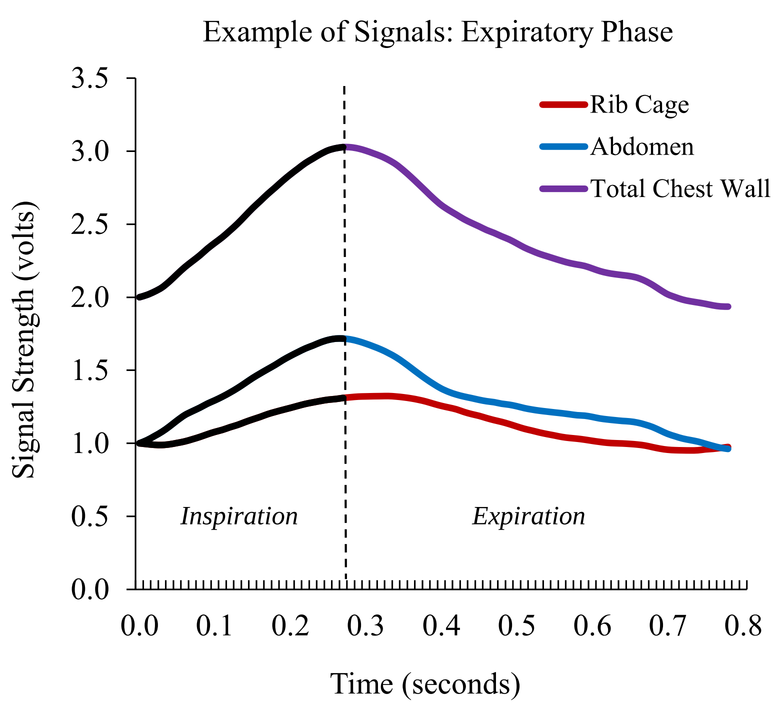

Figure 8. Example of signals: Expiratory phase.

Data Visualization

In order to answer the research question, the collected data were graphed on pie charts to allow for direct visualization of differences between the contributions of the rib cage and the abdomen for each infant and within the two age groups (younger vs. older).

CHAPTER 4

RESULTS

Results of Descriptive Statistics: Durations

The means, standard deviations, medians, minima, and maxima for the durations of the total respiratory cycles, inspiratory phases, and expiratory phases are presented in Table 2.

TABLE 2

DESCRIPTIVE STATISTICS FOR TOTAL RESPIRATORY CYCLE, INSPIRATORY PHASE, AND EXPIRATORY PHASE DURATIONS

	Descriptive statistic					
Infant	*N*	Mean	*SD*	Median	Minimum	Maximum
Total respiratory cycle duration (milliseconds)						
A	23	1253.9	589.6	960	510	2320
B	16	1687.5	564.7	1580	900	3060
C	11	1900.0	903.4	1380	1190	3900
D	20	1092.5	457.3	870	520	1990
E	47	2394.3	407.7	2400	1530	3550
Younger group	117	1804.4	754.3	1900	510	3900
F	6	1356.7	501.7	1405	660	1920
G	9	1826.7	655.7	1640	1100	2950
H	40	1571.3	359.4	1555	1020	2480
I	32	1672.5	508.8	1715	880	2850
J	43	1776.5	444.3	1680	940	3080
Older group	130	1671.8	463.7	1640	660	3080
All infants	247	1734.7	620.8	1700	510	3900
Inspiratory phase duration (milliseconds)						
A	23	388.3	143.0	350	200	640
B	16	463.1	154.5	425	290	910

(Table 2 continues)

TABLE 2 (continued)

Infant	*N*	Mean	*SD*	Median	Minimum	Maximum
	Descriptive statistic					
Inspiratory phase duration (milliseconds)						
C	11	471.8	109.3	470	330	700
D	20	331.0	109.0	310	200	580
E	47	687.2	156.9	660	420	1140
Younger group	117	516.7	203.2	490	200	1140
F	6	476.7	93.1	490	310	590
G	9	505.6	164.5	430	360	770
H	40	561.8	141.2	550	210	860
I	32	579.4	179.2	575	260	980
J	43	489.8	125.2	460	320	900
Older group	130	534.5	149.9	510	210	980
All infants	247	526.0	177.0	500	200	1140
Expiratory phase duration (milliseconds)						
A	23	865.7	511.9	640	240	1840
B	16	1224.4	535.7	1155	600	2690
C	11	1428.2	849.1	920	700	3200
D	20	761.5	414.0	595	310	1680
E	47	1707.0	388.9	1670	900	2650
Younger group	117	1287.8	627.5	1330	240	3200
F	6	880.0	445.1	910	350	1330
G	9	1321.1	602.5	1210	700	2250
H	40	1009.5	302.1	930	560	2050
I	32	1093.1	388.6	1065	530	1980
J	43	1286.7	374.7	1270	600	2620
Older group	130	1137.4	397.7	1095	350	2620
All infants	247	1208.6	523.7	1150	240	3200

The standard deviations for all three duration measures were high across the infants; however, this variability has been reported in the literature (Parham et al., 2011).

Results of Descriptive Statistics: Component Contributions

Tables 3, 4, and 5 contain the descriptive statistics for both the ratio of the rib cage contribution to the total chest wall, and the ratio of the abdominal contribution to the total chest wall for three comparisons: (a) total respiratory cycle: inspiration and expiration (Table 3); (b) inspiratory phase only (Table 4), and (c) expiratory phase only (Table 5). With the exception of the number of data points for each infant (i.e., *N*), the unit of measurement for all of these tables is a percentage of 100. For example, in Table 3, Infant A's mean rib cage-to-total chest wall ratio was 50.3, indicating that the rib cage movement contributed 50.3% of the overall chest wall movement; consequently, the abdomen contributed 49.7%.

TABLE 3

DESCRIPTIVE STATISTICS (IN PERCENTS) FOR COMPONENT RATIOS FOR TOTAL RESPIRATORY CYCLE

	Descriptive statistic					
Infant	*N*	Mean	*SD*	Median	Minimum	Maximum
Rib cage-to-chest wall ratio: inspiration and expiration						
A	23	50.3	2.4	49.5	46.5	57.0
B	16	49.9	0.8	49.8	48.7	51.2
C	11	48.9	3.0	49.4	44.1	54.7
D	20	48.5	5.0	47.7	41.1	59.9
E	47	49.5	1.7	50.0	45.5	53.6
Younger group	117	49.5	2.7	49.7	41.1	59.9
F	6	49.9	1.6	49.8	47.7	52.2
G	9	49.8	4.0	50.3	44.0	56.3
H	40	48.7	1.7	48.7	45.1	52.4
I	32	50.9	1.9	51.0	47.1	54.9

(Table 3 continues)

TABLE 3 (continued)

Infant	Descriptive statistic					
	N	Mean	*SD*	Median	Minimum	Maximum
	Rib cage-to-chest wall ratio: inspiration and expiration					
J	43	49.6	1.5	49.6	46.9	53.9
Older group	130	49.6	2.1	49.5	44.0	56.3
All infants	247	49.6	2.4	49.5	41.1	59.9
	Abdomen-to-chest wall ratio: inspiration and expiration					
A	23	49.7	2.4	50.5	43.0	53.5
B	16	50.1	0.8	50.2	48.8	51.3
C	11	51.1	3.0	50.6	45.3	55.9
D	20	51.5	5.0	52.3	40.1	58.9
E	47	50.5	1.7	50.0	46.4	54.5
Younger group	117	50.5	2.7	50.3	40.1	58.9
F	6	50.1	1.6	50.2	47.8	52.3
G	9	50.2	4.0	49.7	43.7	56.0
H	40	51.3	1.7	51.3	47.6	54.9
I	32	49.1	1.9	49.0	45.1	52.9
J	43	50.4	1.5	50.4	46.1	53.1
Older group	130	50.3	2.1	50.5	43.7	56.0
All infants	247	50.4	2.4	50.4	40.1	58.9

TABLE 4

DESCRIPTIVE STATISTICS (IN PERCENTS) FOR COMPONENT RATIOS FOR INSPIRATORY PHASE

Infant	Descriptive statistic					
	N	Mean	*SD*	Median	Minimum	Maximum
	Rib cage-to-chest wall ratio: inspiration					
A	23	48.5	1.2	48.6	45.2	51.2
B	16	49.4	0.5	49.3	48.5	50.4

(Table 4 continues)

TABLE 4 (continued)

Infant	Descriptive statistic					
	N	Mean	*SD*	Median	Minimum	Maximum
	Rib cage-to-chest wall ratio: inspiration					
C	11	48.6	2.1	48.4	45.8	52.6
D	20	45.4	2.3	45.6	39.9	49.2
E	47	48.7	1.2	48.6	46.9	52.9
Younger group	117	48.2	1.9	48.4	39.9	52.9
F	6	48.2	1.4	48.5	46.4	50.3
G	9	48.3	1.5	48.5	46.0	50.1
H	40	48.4	1.2	48.3	45.6	52.4
I	32	48.9	1.1	49.0	45.1	50.7
J	43	49.3	0.7	49.5	47.0	50.5
Older group	130	48.8	1.1	48.9	45.1	52.4
All infants	247	48.5	1.6	48.7	39.9	52.9
	Abdomen-to-chest wall ratio: inspiration					
A	23	51.5	1.2	51.4	48.8	54.8
B	16	50.6	0.5	50.7	49.6	51.5
C	11	51.4	2.1	51.6	47.4	54.2
D	20	54.6	2.3	54.4	50.8	60.1
E	47	51.3	1.2	51.4	47.1	53.1
Younger group	117	51.8	1.9	51.6	47.1	60.1
F	6	51.8	1.4	51.5	49.7	53.6
G	9	51.7	1.5	51.5	49.9	54.0
H	40	51.6	1.2	51.7	47.6	54.4
I	32	51.1	1.1	51.0	49.3	54.9
J	43	50.7	0.7	50.5	49.5	53.0
Older group	130	51.2	1.1	51.1	47.6	54.9
All infants	247	51.5	1.6	51.3	47.1	60.1

TABLE 5

DESCRIPTIVE STATISTICS (IN PERCENTS) FOR COMPONENT RATIOS FOR EXPIRATORY PHASE

Infant	Descriptive statistic					
	N	Mean	*SD*	Median	Minimum	Maximum
Rib cage-to-chest wall ratio: expiration						
A	23	51.0	3.1	49.9	44.6	59.5
B	16	50.1	1.0	49.9	48.6	51.7
C	11	49.3	3.7	49.9	42.7	55.1
D	20	49.9	6.6	48.7	41.8	65.2
E	47	49.9	2.0	50.3	45.1	54.3
Younger group	117	50.1	3.5	49.9	41.8	65.2
F	6	50.8	2.4	50.2	48.0	54.3
G	9	50.2	5.3	51.5	41.8	57.7
H	40	48.8	2.4	48.9	44.3	55.4
I	32	52.1	2.9	51.8	47.2	58.4
J	43	49.6	1.9	49.5	46.2	55.5
Older group	130	50.1	2.9	49.5	41.8	58.4
All infants	247	50.1	3.2	49.8	41.8	65.2
Abdomen-to-chest wall ratio: expiration						
A	23	49.0	3.1	50.1	40.5	55.4
B	16	49.9	1.0	50.1	48.3	51.4
C	11	50.7	3.7	50.1	44.9	57.3
D	20	50.1	6.6	51.3	34.8	58.2
E	47	50.1	2.0	49.7	45.7	54.9
Younger group	117	49.9	3.5	50.1	34.8	58.2
F	6	49.2	2.4	49.8	45.7	52.0
G	9	49.8	5.3	48.5	42.3	58.2
H	40	51.2	2.4	51.1	44.6	55.7

(Table 5 continues)

TABLE 5 (continued)

Infant	Descriptive statistic					
	N	Mean	*SD*	Median	Minimum	Maximum
			Abdomen-to-chest wall ratio: expiration			
I	32	47.8	2.9	48.2	41.6	52.8
J	43	50.4	1.9	50.5	44.5	53.8
Older group	130	49.9	2.9	50.5	41.6	58.2
All infants	247	49.9	3.2	50.2	34.8	58.2

Visualization of Descriptive Statistics: Component Contributions

Figures 5, 6, and 7 present infant-specific and group pie charts showing the relative ratios of the rib cage contribution to the total chest wall, and the ratio of the abdominal contribution to the total chest wall for three comparisons: (a) total respiratory cycle: inspiration and expiration (Figure 5), (b) inspiratory phase only (Figure 6), and (c) expiratory phase only (Figure 7). For all of the graphs, the rib cage contribution to chest wall movement is represented in red and the abdominal contribution is in blue. The numbers in each graph are the percentages of total chest wall contribution of each component.

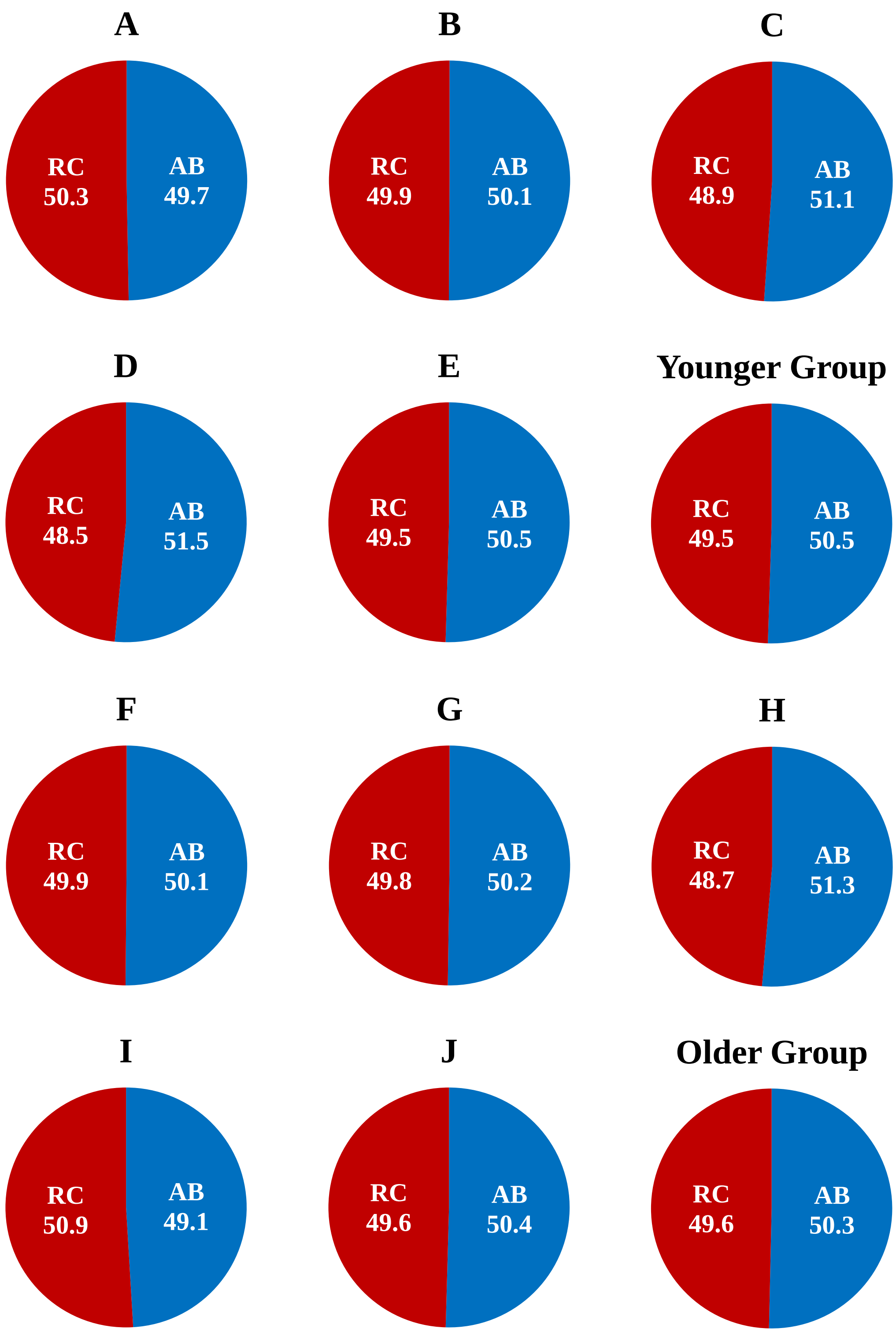

Figure 9. Comparison of rib cage (RC, red) and abdomen (AB, blue) contributions to chest wall movement for total respiratory cycle (numbers are percent contribution).

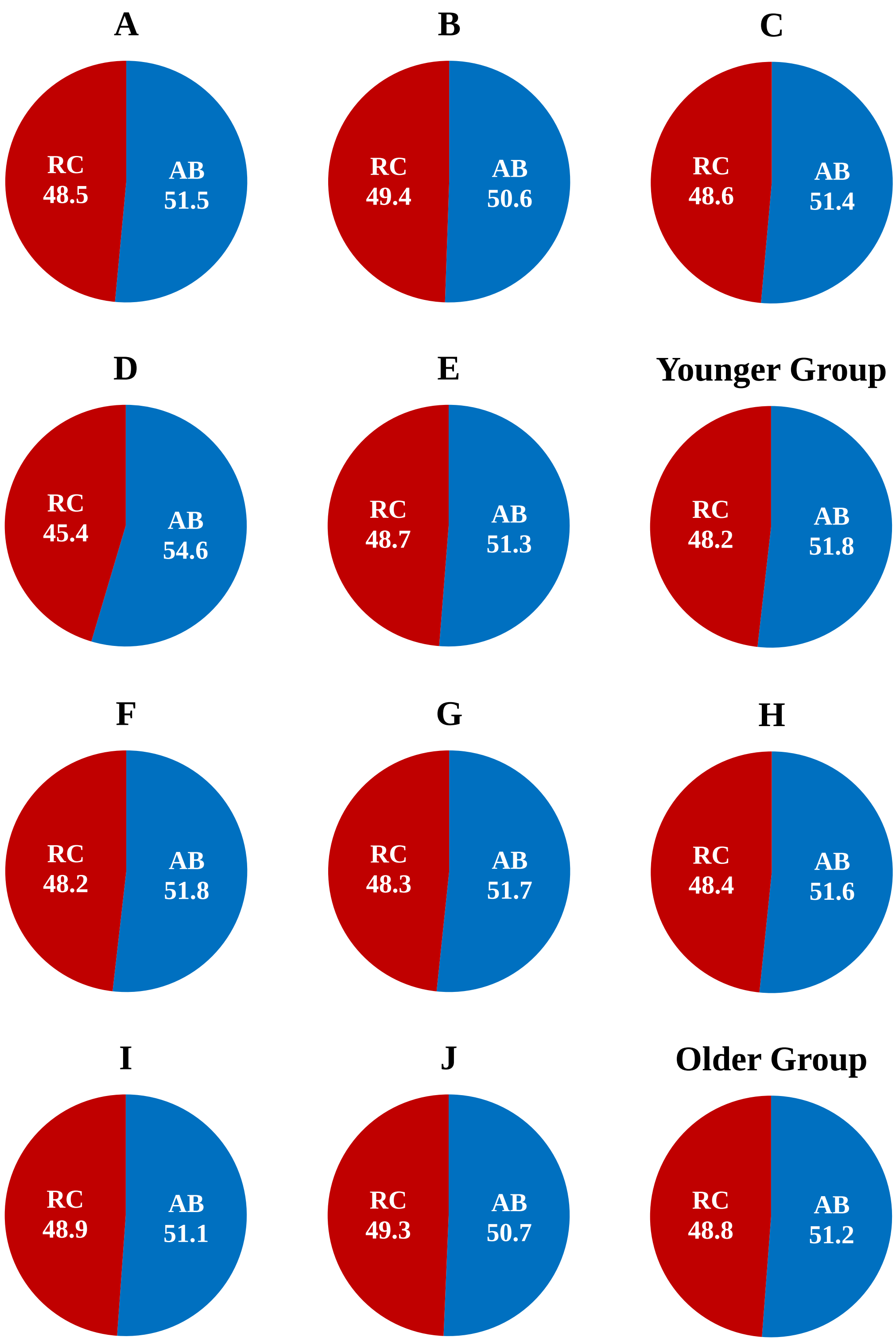

Figure 10. Comparison of rib cage (RC, red) and abdomen (AB, blue) contributions to chest wall movement for inspiratory phase (numbers are percent contribution).

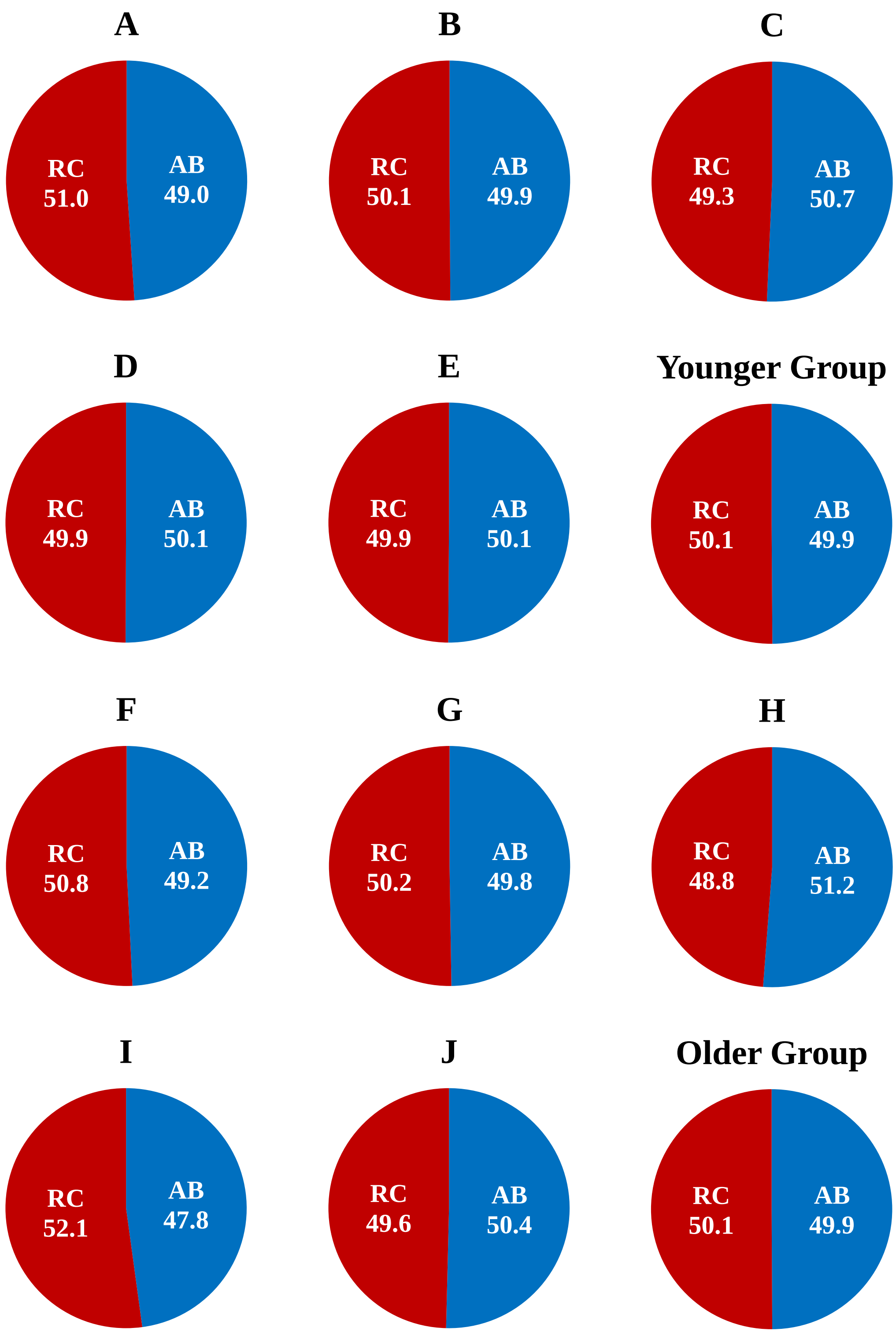

Figure 11. Comparison of rib cage (RC, red) and abdomen (AB, blue) contributions to chest wall movement for expiratory phase (numbers are percent contribution).

Additionally, the mean maximum height of the rib cage component and the abdomen component were graphed together for each infant. This is presented in Figure 7.

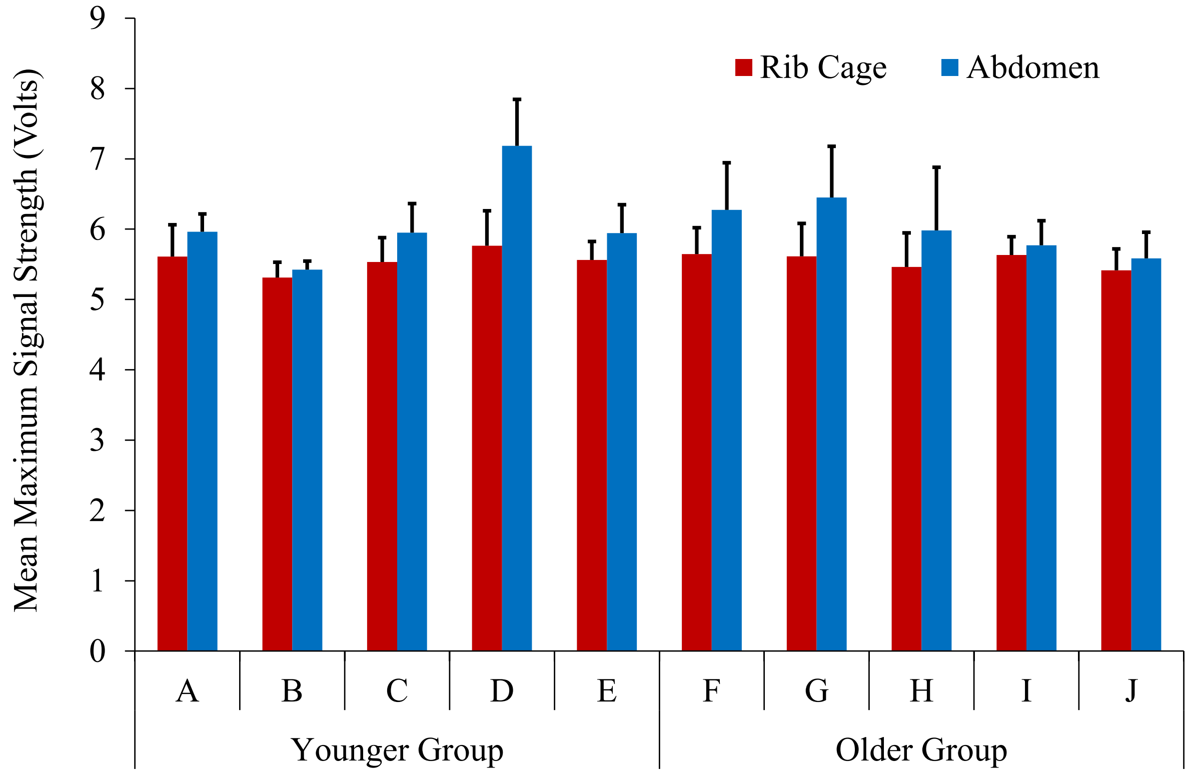

Figure 12. Mean maximum height of rib cage (RC, red) and abdomen (AB, blue) contributions to chest wall movement for the entire respiratory cycle.

CHAPTER 5

DISCUSSION

This study attempted to answer the following question related to the relationship between rib cage and abdominal movement during single-syllable utterances by infants around the first year of life: *Are there general patterns in the relative contributions of rib cage and abdomen to chest wall movement in infants during early speech development demonstrated during single syllable utterances?*

When examining the total respiratory cycle, it was found that for all infants, the abdomen had the largest mean signal strength compared to the rib cage. However, the mean contribution of the rib cage and abdomen components varied depending on the phase being analyzed and the infant. During the inspiratory phase, the abdomen was used consistently to a greater degree than the rib cage among all subjects. During the expiratory phase, both the rib cage and the abdomen contributed to chest wall movement to differing degrees. Approximately half of the individuals demonstrated greater contribution from the rib cage, and the other half showed greater contribution from the abdomen. Among all three measurements (total respiratory cycle, inspiratory phase, and expiratory phase), the degree of contribution of individual components differed within subjects. However, age did not appear to influence the pattern of contribution for the chest wall, as the younger infants and older infants did not differ from one another as a group.

The Findings and Infant Development

As an infant's chest wall develops, there are many anatomical and developmental changes that occur within the body (Hershenson, 1992; Muller & Bryan, 1979; Openshaw, Edwards, & Helms, 1984). During the late first year of life, infants are able to sit independently, pull to stand, cruise, and often walk without support because of increased postural control. At this age, the compliance of the rib cage decreases and the chest wall becomes stiffer. This leads to an increase in the infant's ability to move the chest wall and support longer and more complex utterance production (Boliek et al., 1996, 1997). Thus, infants within the 9-12 month age range are learning to use the respiratory system to produce new sounds, but at this age, there is large variability in chest wall movements when the contributions of rib cage and abdomen are compared. Infants in the 14-16 month age range appear to be learning to use chest wall movements to support speech-related utterances in a more purposeful way, as documented by the decreased variability in movements of the rib cage and abdomen. The infants in this older group have stiffer and stronger rib cages that have a lesser degree of compliance than those of the younger infants (Boliek et al., 1996, 1997; Connaghan, Moore, & Higashakawa, 2004; Langlois, 1975; Moore, Caulfield, & Green, 2001; Parham et al., 2011; Reilly & Moore, 2009). This implies that older infants can manipulate the respiratory system in better ways to support speech production. Despite these noted developmental changes related to maturation of the respiratory system, age did not appear to play a role in differences in the contribution of the abdomen and rib cage during chest wall movement in the infants in this study.

The results indicate that during the total respiratory cycle, the majority chest wall movement produced by infants in both age groups can be accounted for primarily by the abdomen in comparison to the rib cage (see Figure 5). This greater degree of contribution from the abdomen is true for both the younger (37–49 weeks) and older (61–66 weeks) groups of infants. This being said, the rib cage also is playing a key role in total chest wall movement during the total respiratory cycle; however, overall the abdomen is playing a greater role.

Further, during the inspiratory phase, a common pattern emerged among all subjects. The abdomen was shown to be used consistently to a greater degree (see Figure 6). When the data were collapsed into the two groups, the infants used their rib cage less than their abdomen when contributing to total chest wall movement. The degree of contribution of individual components differed within subjects; however, all infants demonstrated a greater degree of contribution from the abdomen during the inspiratory phase.

When examining the expiratory phase, there was not a consistent pattern established. Half of the individuals used their rib cage to a greater degree during the expiratory phase, and the other half used the abdomen more (see Figure 7). The age of the infants did not appear to play a role in this distinct division. In general, the rib cage and abdomen appeared to contribute equally to the expiratory phase among infants as a whole, regardless of age.

Across all infants, the abdomen always had the largest mean signal strength for the total respiratory cycle (see Figure 8), but the mean contribution of the rib cage and abdomen components varied depending on the phase being analyzed and the infant. For the infants in this study, the abdomen contributed to a greater degree than the rib cage during the inspiratory phase, and both the rib cage and the abdomen contribute to differing degrees during the total respiratory cycle and the expiratory phase.

Study Limitations

There are two limitations associated with this study. First, not every infant produced an equal amount of analyzable data regardless of whether the infants were in the younger or the older age group. Second, the Inductotrace® bands were negatively affected by movement, and all infants moved in the high chair to some degree, resulting in loss of potential data. As a result, the ratio of analyzable data to total data was low, as has been reported in the literature (Boliek et al., 1996, 1997; Parham et al., 2011). It could be that breath support for utterance production during gross motor movement is different than was observed in the data obtained in this study.

Conclusion

This study explored the roles and functions that both the rib cage and the abdomen assume during utterance production in infants around the first year of life. Little is known about how the respiratory system supports utterance production in infancy. Respiratory kinematics (i.e., movement of the chest wall) can be analyzed by measuring the movement of two chest wall components: the rib cage and the abdomen. Information related to how breathing supports speech production is provided when these two components are combined. Little has been documented about how breath support for utterance production develops during infancy. In order to understand the relationship between respiratory development and speech development, normative results are needed. In this study, the abdomen played a larger role than the rib cage in chest wall movement during inspiration for all infants regardless of age, but results for the total respiratory cycle and the expiratory cycle were not conclusive. By studying further this particular aspect of chest wall development, knowledge may be gained that will aid in the early identification of infants who might be developing atypically. Such knowledge could be used to improve speech outcomes in infancy and early childhood.

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APPENDICES

APPENDIX A

INSTITUTIONAL REVIEW BOARD (IRB) APPROVAL LETTER

WICHITA STATE UNIVERSITY
RESEARCH ADMINISTRATION

Date: September 21st, 2012

Principal Investigator: Douglas Parham

Co-Principal Investigator: n/a

Department: CSD, Box 75

IRB Number: 1425

The University Institutional Review Board (IRB) has reviewed your research project application entitled:

"Vocalization and Speech Breathing in Infants and Adults"
Application Renewal

and approved the project according to the Federal Policy for the Protection of Human Subjects. As described, the project also complies with all the requirements and policies established by the University for protection of human subjects in research. Unless renewed, approval lapses one year after approval date.

Please keep in mind the following:

1. Any significant change in the experimental procedure as described should be reviewed by the IRB prior to altering the project.
2. When signed consent documents are required, the principal investigator must retain the signed consent documents for at least three years past completion of the research activity.
3. At the completion of the project, the principal investigator is expected to submit a ***final report***; the form is attached.

Thank you for your cooperation. If you have any questions, please contact me at ext. 6945.

Sincerely,

Michael Rogers, Ph.D.
Chairperson, IRB

Wichita State University, Wichita, Kansas 67260-0007 Telephone: (316) 978-3285 Fax: (316) 978-3750

APPENDIX B

IRB APPROVED CONSENT FORM

WICHITA STATE UNIVERSITY
COLLEGE OF HEALTH PROFESSIONS
Department of Communication Sciences and Disorders

Consent Form for Adult Participants and Their Infants

Purpose: You and your infant are invited to participate in a study of speaking and breathing. The purpose of this research is to explore how speaking and breathing develop across different stages of the human life span.

Participant Selection: You and your infant are eligible to participate in this study because it focuses on how infants learn to speak. Your infant's speech can be compared with those of other infants and persons across the human life span. It is anticipated that between 40 and 50 infants and their families will participate in this study.

Explanation of Procedures:

- This study will take place in the Speech Development and Communication Lab at the Eugene M. Hughes Metropolitan Complex, located at Oliver and 29th Street.
- If you decide to participate, you will be asked to provide basic information related to your infant's health, such as the history of ear infections and/or complications during or after birth.
- Your role will be to encourage your infant to produce speech sounds.
- Your infant will be seated in a high chair or an alternative (for example, a Bumbo baby seat). You will be seated in a chair facing your infant. If your infant is too young or too small to fit in the seating devices, you will hold your infant.
- You and your infant will each wear a microphone, respiratory bands (around the rib cage and abdomen), and body movement sensors. You yourself can opt not to wear the equipment.
- To measure breath volume, you will be asked to blow air into a tube for several minutes and your infant will breathe into a small face mask for several seconds.
- You and your infant's speech, respiration, and body movements will be recorded. A video recording will also be made of the interaction.
- During the recording session, your infant will also interact with a graduate student from the Department of Communication Sciences and Disorders who is associated with the study. The role of the graduate student is to encourage your infant to produce speech sounds.
- Each recording session will last between one and two hours, but will be stopped if your infant becomes upset or distressed.
- You and your infant may be eligible to participate in future recording sessions while this research project is in progress.
- You will also be given the options of having your infant's hearing and/or overall development screened. If you are interested in one or both of these screenings, they will be scheduled either as part of the initial recording session or for a separate visit at another time.
- It is possible that the video recording will be used in the future in educational and/or academic settings. Your permission for the educational use of the video recording is an entirely separate issue than your participating in the study. You and your infant may agree to be in the study without agreeing to the educational use of the video recording.

Discomfort/Risks: There are no known physical risks to the infants or adults participating in this study. The instrumentation systems and the data collection methods are non-invasive and do not pose any direct physical risk to you or your infant. Regarding potential emotional risks, your infant might express some discomfort being in an unfamiliar setting, interacting with an unfamiliar adult, or wearing a face mask during the first part of the recording session. Your infant will not be out of your physical or visual contact, and you may stop the recording session at any time. Although no other risks are anticipated with this study, there is always a small chance of unforeseen risk.

Benefits: By participating in this research, you can be expected to benefit from knowledge gained about human development. The findings of this research will fill in the gaps of the current scientific knowledge of speech development.

Compensation:

- For you and your infant's combined participation in each recording session, you will receive a one-time monetary compensation of $20.00.
- Wichita State University does not provide medical treatment or other forms of reimbursement to persons injured as a result of or in connection with participation in research activities conducted by Wichita State University or its faculty, staff, or students. If you believe that you have been injured as a result of participating in the research covered by this consent form, you can contact the Office of Research Administration, Wichita State University, Wichita, KS 67260-0007, telephone (316) 978-3285.

Confidentiality:

- Any information obtained in this study in which you can be identified will remain confidential to the extent permitted by law and will be disclosed only with your permission.
- The data from you and your infant will be associated with unique codes known only to the study's research team and will be referenced only by those codes.
- Study-related files will be kept locked away when not in use by the research team.
- Federal agencies such as the Food and Drug Administration (FDA) and the Office for Human Research Protections (OHRP) may review study data as allowed by law.
- You will have the right to decide about the special use of the video recording for educational purposes (see separate form).
- You also reserve the right to have part or all of the recordings of you and your infant permanently erased at any time during or after the study.

Refusal/Withdrawal/Termination: Participation in this study is entirely voluntary for you and your infant. Your decision to participate or not will not affect your future relations with Wichita State University. If you agree to participate in this study, you are free to withdraw from the study at any time without penalty. If the Principal Investigator determines that your participation or your infant's participation in the study is causing undue discomfort or distress to you or your infant, the recording session will be terminated.

Contact: If you have any questions about this research, you can contact Douglas Parham, PhD, Principal Investigator, at the Department of Communication Sciences and Disorders at Wichita

State University, Wichita, KS 67260-0075 (Telephone: 316-978-5634; E-mail: douglas.parham@wichita.edu). If you have questions pertaining to your rights as a research subject, or about research-related injury, you can contact the Office of Research Administration at Wichita State University, Wichita, KS 67260-0007 (Telephone: 316-978-3285).

You are under no obligation to participate in this study. You may stop your participation and the participation of your infant at any time. Your signature indicates that you have read the information provided above and have voluntarily decided to participate. You will be given a copy of this consent form to keep.

______________________________ Signature of Parent/Legal Guardian as Participant	______________ Date
______________________________ Signature of Parent/Legal Guardian to Give Permission For the Infant to Be a Participant	______________ Date
______________________________ Signature of Person Conducting Informed Consent Discussion	______________ Date