Range Exploration of Phonation and Pitch in the First Six Months of Life

by

Lisa Danielle Bettany

B.A., University of Victoria, 2002

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF ARTS

in the Department of Linguistics

Supervisor: Dr. John H. Esling

ABSTRACT

In the first six months of life, infants systematically explore the laryngeal parameters of phonation and pitch. In existing research, laryngeal vocalizations, defined as "vegetative" or "reflexive", are characterized by the presence of "strained" and "rough" phonation with "high degrees of vocal tension" and dynamic pitch variations. Previous studies have focused exclusively on the development of linguistic precursors, including only "speech-like" sounds with "normal" or modal phonation. These studies have excluded laryngeal vocalizations (i.e. grunts, squeals and growls) from their experimental analyses and therefore have not provided an accurate description of early phonetic development.

This thesis attempts to fill the gap in the phonetic and articulatory description of the infant vocal capacity by investigating the exploration and development of the laryngeal mechanisms involved in the production of laryngeal phonation and laryngeal pitch. In order to account for the productive capability of infants, it is necessary to consider the vital role of the primary articulator in the adult and infant larynx, the aryepiglottic laryngeal sphincter. The mechanism of the laryngeal sphincter is actively engaged in early infancy to protect the tracheal airway from inundation.

In this study, two quantitative analyses of one English-speaking infant's vocalizations in the first six months of life were conducted. In analysis one, auditorily based analysis of 824 vocalizations was performed using the phonetic taxonomy of laryngeal modalities developed by Esling and colleagues (Esling, Benner & Bettany,

2004a; Esling, 2002). The incidence of five phonatory settings (i.e. harsh voice, creaky voice, whisper, modal voice and falsetto) and three pitch levels (low, mid and high) was reported. In analysis two, the laryngeal parameters involved in "range exploration", defined in this study as the instance of within-vocalization phonatory alternations, were quantified by means of acoustic analysis. 120 randomly selected vocalizations (20 from each of the six months) were used in this analysis component. The durations of the vocalizations and of individual phonatory settings within each vocalization were calculated using spectrographic analysis and compared statistically.

The present study was able to accurately identify the phonetic range and productive repertoire of infant vocalizations produced in the first six months of life. Four main findings were reported in this study: (1) the default setting in early infancy is laryngeally constricted and low-pitched, (2) the infant's phonetic repertoire of phonation and pitch expands at four months (3) the incidence of within-vocalization phonatory alternations increases at four months and, (4) the productive integration of phonation and pitch is acquired by the sixth month of life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

Thank you to all who helped on this challenging path in the adventurous journey of my life. Though many obstacles were presented during my time as a master's student, the support of those who continue to care, support and listen have helped me overcome adversities with their constant positive energy and unfailing compassion. It is to these beautiful people that I offer my deepest appreciation, for if it were not for you I would not have succeeded in the wondrous pursuit of knowledge.

I would like to thank my supervisor Dr. John H. Esling, who provided me with the seeds of a research dream, which has become the heart of this study. I appreciate the freedom I was given to cultivate my ideas and find my own path in the milieu of infant speech research and theoretical frameworks. Thank you for sharing your knowledge with me and providing me the opportunity to be a part of an inspirational research project. I hope that my findings will add to the infant speech project and inspire others to continue in this important area of research. I would also like to thank my committee members Dr. Joseph Kess and Dr. Emmanuel Hérique for their encouragement and time, which are the greatest gift. I appreciate your belief in my ability. I owe special thanks to Dr. Eric Vatikiotis-Bateson for your generous offer to be my external examiner. Your comments were instrumental in the final development of this piece of research.

Thank you to the all the faculty members of the Department of Linguistics. The support and understanding given throughout my undergraduate and graduate degrees by Drs. Ewa Czyakowska-Higgins, Leslie Saxon, Tadao Miyamoto and Su Urbanczyk will not be forgotten. Thank you to Gretchen Moyer and Maureen Kirby for their assistance throughout the years.

And now I must thank the inspirational support of my friends and family for listening to my heart and allowing me to forever dream.

Allison, I admire your strength, intelligence, knowledge and kindness. Your support has provided constant stability to my rollercoaster experience. I thank you and Anna for the motivation to finish this thesis. Your kind heart has kept my faith in this project alive. Aliki, you are a kindred spirit. Thank you for your positive energy and belief that one day the healing powers of the mind will set us both free. Ronan, you inspired me to begin this journey and follow my heart. I am eternal grateful for this and our intertwined path. Dad, thank you for saving me at the last minute with your understanding and generosity. I could not have finished without my little laptop.

The dedication I make is to my mother who has supported every dream and passion I have ever had. Thank you for listening to my endless ramblings day after day, and helping me discover my true passions in life.

DEDICATION

To my mother Jane,

your beauty as a mother and a person is inspiring

gentle, caring, intelligent,
strong, selfless and supportive.

thank you for your gift of unconditional love

i am eternally blessed.

Chapter One

INTRODUCTION

1.1 Purpose of the study

In the first year of life, infants systematically explore the productive capabilities of laryngeal mechanisms, practicing a dynamic range of phonation and pitch. Previous studies on infant vocalizations have reported that laryngeal vocalizations, which are described as "vegetative" or "reflexive", comprise a large percentage of vocal output in the first months of life. These laryngeal vocalizations are differentiated from "speech-like" vocalizations with "normal" phonation, by the presence of "strained" and "tense" sounding phonation (Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980, 2000; Stark, 1980; Wermke et al., 2002). The theoretical models presented in these studies only consider the horizontal plane of the glottis (e.g. voicing, breath and pitch), ignoring the vital role of the vertical plane above the glottis, including the ventricular folds, the aryepiglottic folds and the laryngeal aryepiglottic sphincter which is engaged in early infancy to protect the tracheal airway from inundation (Crelin, 1973; Esling, 2000). It is necessary to consider both horizontal and vertical planes of the larynx, in order to account for the prevalence of laryngeal vocalizations in early infancy.

I propose a bi-level auditory-phonetic model of the larynx in order to account for the exploration of constricted laryngeal phonation in the vocalizations of one English-speaking infant in the first six months of life. This auditorily based articulatory model developed by Esling and colleagues (Esling, 1996, 1999b, 2002; Esling, Benner & Bettany, 2004a; Esling & Edmondson, 2002; Esling & Harris, 2003) is based on laryngoscopic observations of the adult pharynx and larynx during the production of laryngeal place and manner articulations (i.e. pharyngeal stop, fricative, and approximant), in addition to constricted phonatory modalities (i.e. harsh voice, creaky voice and whisper). These observations of the pharynx and the larynx demonstrate that the laryngeal aryepiglottic sphincter is the principle contributing physiological maneuver in the production of constricted vocalizations (Esling, 1996, 1999b, 2002; Esling & Edmondson, 2002; Esling & Harris, 2003). During the engagement of the laryngeal constrictor, the aryepiglottic folds move forward and up under the epiglottis causing full closure of the aryepiglottic location across the top of the glottis (Esling, 2002). Additional physiological maneuvers, including tongue retraction toward the posterior wall of the pharynx, and larynx raising up and forward, occur concomitantly to sphincter engagement. The laryngeal mechanism is also related to the shortening of the length of the glottis, and therefore predisposes low pitch. The cumulative work of Esling et al., from a large representation of language families, including Nuuchahnulth (Wakashan), Nlaka'pamux (Salish), Tibetan (Tibeto-Burman), Bai (Sino-Tibetan), Cantonese (Sinitic), Thai (Tai), Korean (Altaic), Arabic (Semitic), Tigrinya (Semitic) and Somali (Cushitic), has provided accurate canonical profiles for adult laryngeal vocalizations (Esling, 1996; Esling & Harris, 2003).

In this thesis, I will apply the laryngeal parameters of these adult profiles to infant prelinguistic vocalizations, which demonstrate a dynamic range of laryngeally constricted phonatory settings (e.g. harsh voice, creaky voice and whisper) and glottal pitch (low, mid, and high) during exploratory play in the first six months of life.

The application of a parametrical model based on the laryngeal constrictor to infant prelinguistic vocalizations accommodates the progression of infant vocal tract development, as the configuration of the early infant larynx is postured in a raised and forward position predisposing constriction. Though the refined control of the independent structures required for fine oral articulations is lacking in early infancy, the efficient control of the primary laryngeal mechanism involved in phonation (i.e. the glottal source for voicing) and protection of the larynx (i.e. sphincter) is present at birth. It is in this constricted default setting that infants first begin to test out the productive capacity of their voices. Consequently, phonatory production in infancy begins with constricted modes of phonation, including harsh voice and creaky voice with the default pitch setting being low (Esling, Benner & Bettany, 2004a).

At around three months of life, the infant's phonatory and articulatory range dramatically expands as the larynx descends in the throat (Fitch & Giedd, 1999; Thelan, 1991; Wermke et al., 2002). During the months that follow the restructuring of the infant vocal tract, researchers have observed a stage of increased vocal activity defined as "vocal play" (Stark, 1980; Oller, 1980) or "exploratory play" (Oller, 2000) characterized by dynamic variations in duration, intensity (e.g. "whispering" and "yelling"), mode of phonation (e.g. falsetto and harshness), frequency (e.g. "squealing" and "growling") and periodic (e.g. modal voice) and aperiodic (e.g. "pharyngeal friction") sound sources.

(Buder, Oller & Magoon, 2003; Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980, 2000; Stark, 1980, 1986; Roug, Landberg & Lundberg, 1989). Findings from numerous studies suggest that infants gain increasing control over speech mechanisms during the systematic exploration of phonation and pitch as evidenced by greater duration and intensity (Lieberman, 1985; Papaeliou et al., 2002; Stark, 1986; Vihman, 1996), and more stable fundamental frequency and within utterance pitch contouring (Amano et al., 2003; Hsu et al., 2000; Kent & Murray, 1982; Oller, 2000; Wermke et al., 2002). These studies highlight but do not provide motivation or accurate phonetic descriptions of two crucial observations of early infant speech development: (1) infants explore vocalizations with varying degrees of laryngeal constriction and laryngeal pitch and, (2) infants gain control of laryngeal features during a period of increased vocal play.

This thesis will present acoustic and perceptual analyses of one English-speaking infant's prelinguistic vocalizations in the first six months of life, focusing on the exploration and development of the laryngeal mechanisms involved in the production of phonation and pitch. I will propose a new theoretical description of exploratory play, termed "range exploration" defined as within-utterance timing alternations between phonatory settings.

The examination of these features will consist of two main analyses. In analysis one, auditorily based techniques will be used to determine the phonatory setting and pitch of each vocalization. I will compare the occurrence of constricted phonatory settings (i.e. harsh voice, creaky voice and whisper) with unconstricted phonatory settings (i.e. modal voice, falsetto, breath and breathy voice). Analysis two will focus on quantifying the incidence of range exploration by means of acoustic and statistical measures. Finally, the instance of alternations within vocalizations and the duration of phonatory settings will be calculated.

1.2 Research Questions

The goal of this study is to provide an accurate phonetic description of infant vocalizations demonstrating a dynamic range of phonation and pitch in the first six months of life. The research questions will focus on three main areas: (1) the developmental role of pitch and constriction and their interaction, (2) the dynamic process of phonatory exploration or "vocal play" and, (3) the phonetic description of infant vocalizations.

- How are the laryngeal mechanisms of pitch and constriction explored in the first six months of life?
- How does pitch interact with constriction in infant vocalizations? How does this interaction change over time?
- What is the default phonatory setting in early infancy and how does this change over time?
- What is the developmental pattern or process of phonatory "play" or "range exploration"?
- At what age in infancy does this exploratory vocal behaviour begin?
- What are the phonatory ranges or limits of pitch and constriction in exploratory play?

- How do the ranges of phonation and pitch change in the first six months of life?
- What phonatory settings are explored in the first six months of life?
- Is there a hierarchical development pattern of phonation types in the first six months of life?
- Is laryngeal control attained through exploratory play?

I will investigate the parameters of pitch and constriction in the first six months of life. In analysis one, I will determine the default voice setting of the laryngeal mechanism and the progression of the infant's phonatory development as the vocal tract develops and changes in months 3 to 6. In the second analysis, I will propose a systematic process entitled "range exploration" to account for the developing control of the laryngeal mechanism. Finally, I will provide acoustic and perceptual evidence to define the exploratory range continuum of pitch and constriction within the two developmental periods. Findings presented in this thesis will confirm that infants actively and systematically explore the full capacity of their vocal apparatus within a constricted setting to increase and develop control of phonetic parameters.

1.3 Limitations of the study

The findings from this study of one English-speaking infant provide an excellent foundation in the phonetic identification of phonatory exploration and development in the first six months of life. Though this study is a "small-n" study (n=1), the data set is extensive, consisting of 824 vocalizations collected from a body of 24 hours of raw data.

This large corpus was gathered from 12 sessions recorded bi-monthly during the first six months of life. Further empirical investigations and quantitative measurements involving a large systematic sampling of both longitudinal and cross-sectional infant data from a number of ambient languages is necessary to identify greater trends in infant vocal production in the first year of life. Presently, a collaborative project of this nature is in progress under the supervision of Dr. J. H. Esling in the Department of Linguistics at University of Victoria (Esling, Benner, Bettany & Zeroual, 2004). It is expected that the findings of this detailed analysis on infant prelinguistic vocalizations identified in this master's thesis will be confirmed by further studies.

Presently, the technical equipment necessary to provide instrumental support for the study of laryngeal constriction and its interaction with pitch in early infant vocalizations has not yet been developed. In this study, the primary analysis tool used in the identification of constriction and pitch in infant vocalizations was auditorily based coding used in conjunction with acoustic support (i.e. spectrograms). Auditorily based coding is an accurate method in identifying a finite set of phonetic modalities, including laryngeal articulations (i.e. place, manner and phonatory quality). Numerous researchers have shown greater success identifying developmental trends in early infant vocalizations using auditorily based coding methods, than traditional acoustic methods (Buder & Oller, 2003; Nathani & Oller, 2001; Stark, 1993).

1.4 Outline

This paper presents a study on the phonatory development and exploration of one English-speaking infant in the first six months of life. In Chapter 1, I outlined the purpose of my study, listed the relevant research questions, and addressed the methodological limitations. Chapter 2 will present a review of literature focusing on previous research of infant prelinguistic vocalizations in the first six months of life. This section will introduce the new theoretical model considering the role of the aryepiglottic laryngeal constrictor in the production of laryngeal vocalizations by both adults and infants. In Chapter 3, I will describe my methodology of two perceptual and acoustic analyses of a large data set of infant vocalizations. The results of analysis one and two will be presented in Chapter 4. Chapter 5 will discuss the main findings of this study and reinterpret previous phonetic descriptions of infant vocalizations. Chapter 6 will summarize the main findings and report the contributions of this study the understanding of early speech development.

Chapter Two

LITERATURE REVIEW

This section presents a review of literature focusing on four main areas pertinent to the study of infant vocal production in the first six months of life: (1) previous descriptions of infant prelinguistic vocalizations, (2) the application of a bi-level model of the larynx to infant vocalizations; (3) the development of laryngeal control and (4) the linguistic phenomenon of exploratory "vocal play" (Oller, 1980; Stark, 1980).

In the first year of life, infants systematically explore the productive capabilities of laryngeal mechanisms, practicing a dynamic range of phonation and pitch. Previous studies on infant prelinguistic vocalizations have identified the instance of "strained" and "tense" sounding laryngeal vocalizations in early vocal practice (Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980, 2000; Stark, 1980).

2.1 Infant prelinguistic vocalizations

In recent years, considerable research has focused on infant vocalizations in the first six months of life as precursors to communication and language development (Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980, 2000; Stark, 1980). The primary goal of previous research was to demonstrate the progression of vocalizations towards meaningful speech. These researchers have focused exclusively on "speech-like" sounds with "normal" or modal phonation, excluding laryngeally "strained" and "tense" sounding vocalizations from their analyses (Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980; 2000). These vocalizations deemed as "vegetative" or "reflexive" or described with colloquial terms such as "coughing", groaning", "moaning" or "croaking", which imply the engagement of the vertical laryngeal constrictor, represent a large percentage of vocalizations produced in early infancy (Esling, Benner & Bettany, 2004a; Oller, 1980; Stark et al., 1975). These impressionistic terms do not provide an accurate description of the productive capability of infants or the integral role of laryngeal constriction in the vocalizations of infants, and furthermore limit research from tracking infant speech development in a principled manner.

The phonetic framework provided in this thesis, which emphasizes the role of laryngeal constriction, gives us a descriptive and analytical tool to account for the productive capability of the infant in the first six months of life.

2.1.1 Bi-level model of the larynx

The proposed bi-level auditory-phonetic model of the larynx developed by Esling and the phonetic team at the University of Victoria (Esling, 1996, 1999a; Esling, Benner & Bettany, 2004a; Esling & Edmondson, 2002; Esling & Gao, 2003; Esling & Harris, 2003; Teshigawara, 2003) is based on laryngoscopic observations of the adult pharynx and larynx during the production of laryngeal place and manner articulations (i.e. pharyngeal stop, fricative, and approximant), in addition to constricted phonatory modalities (i.e. harsh voice, creaky voice, whisper and whispery voice). These observations demonstrate that there are two levels of laryngeal control: (1) a vertical level located above the glottis and (2) a horizontal level located at the glottis.

2.1.1.1 Vertical level: Aryepiglottic laryngeal sphincter

Laryngoscopic observations by Esling et al. inquiring from a vertical plane above the larynx have demonstrated that the aryepiglottic laryngeal sphincter is a primary articulator in the production of the sound category "pharyngeal" and a number of phonatory settings (e.g. harsh voice, creaky voice, whisper and whispery voice). The action of the physiological features involved in laryngeal sphinctering causes a narrowing of the epilaryngeal tube, creating the potential for a secondary, and possibly aperiodic, source. In addition, sources generating friction within the vocal tract may increase, and resonant formant frequencies become more characteristic of a small pharyngeal cavity when the laryngeal constrictor is engaged. The acoustic quality of vocalizations produced while the laryngeal constrictor is engaged, may be aperiodic, noisy, and pharyngealized (high f1, low f2).

The three major physiological components involved in laryngeal sphinctering are: (1) sphinctering of the aryepiglottic folds, (2) tongue retraction and, (3) larynx raising. During the engagement of the laryngeal constrictor, the aryepiglottic folds move forward and up under the body of the epiglottis causing approximation or full closure of the aryepiglottic location across the top of the glottis (Esling, 2002). Concomitant physiological maneuvers, including tongue retraction toward the posterior wall of the pharynx, and larynx raising up and forward, are also important in the laryngeal sphincter mechanism.

The laryngeal mechanism is also related to the shortening of the length of the glottis and, therefore, predisposes low pitch as in creaky voice. Conclusions regarding the interdependency between laryngeal constriction and pitch have been drawn from laryngoscopic observations of the pharynx and larynx during pharyngeal articulations with varied larynx heights Esling (1999a). These observations suggest that when constriction is present the larynx can be lower, raised or held in neutral position; however, the tendency is towards larynx raising. The effects of this tendency in the acoustic correlate of pitch have not been systematically examined.

According to this research, the vertical laryngeal sphincter is the primary articulator involved in the production of constricted phonatory settings, including harsh voice (high, mid and low), creaky voice and whisper.

2.1.1.1.1 Constricted phonatory settings

Descriptions of phonatory settings involving the vertical laryngeal constrictor, including harsh voice, creaky voice, whisper and whispery voice, are drawn from observations of the larynx and pharynx (Esling & Edmondson, 2002; Esling & Harris, 2002). Table 2-1 presents the physiological features and acoustic characteristics of constricted phonatory settings. The numbers 1 and 2 in the physiological features column represent the horizontal level (1) and vertical level (2) of the larynx.

Table 2-1. Physiological features and acoustic characteristics of constricted phonatory settings.

Phonatory setting	Physiological features	Acoustic characteristics
Harsh voice	1. vocal fold adduction 2. extreme engagement of constrictor	1. presence of voicing 2. aperiodic irregularities
Creaky voice	1. vocal fold adduction and shortening 2. moderate engagement of constrictor	voicing pulse striations, low pitch (<100 Hz)
Whispery voice	1. closure of vocal folds in "Y" shape with no vibration 2. slight engagement of constrictor	1. presence of voicing 2. aperiodic turbulent noise
Whisper	1. closure of vocal folds in "Y" shape with no vibration 2. slight engagement of constrictor	1. absence of voicing 2. aperiodic turbulent noise

The mechanisms of the laryngeal constrictor produce a range of sphincteric activities in the form of degrees of constriction (i.e. extreme, moderate, slight) and levels of pitch (low, mid and high).

Harsh voice, creaky voice and whispery voice involve glottal voicing (i.e. vocal fold adduction). The lack of voicing with laryngeal constriction defines the state whisper. The glottal feature of voice contrasts whisper and its related state whispery voice. Whisper and whispery voice involve similar physiological mechanisms which create a "hushing" or turbulent, noisy airflow (Esling & Harris, 2002).

2.1.1.2 Horizontal plane: Glottis

Inquiring from a horizontal plane, researchers have shown that the glottis (i.e. vocal folds) is the primary sound source (i.e. phonation) in the vocal tract (Catford, 1977).

There are three main physiological maneuvers of the glottis: (1) adduction of the vocal folds which produces voicing, (2) abduction of the vocal folds which produces a larger glottal opening during forceful breathing and (3) longitudinal stretching of the vocal folds which produces higher pitch. The features of the glottis involved in the production of unconstricted phonation have been studied at length by numerous researchers (Catford, 1977; Laver, 1980). In the production of voicing, the glottis is closed at its posterior end by the adduction of the arytenoid cartilages, which brings the vocal folds together at the midline (Esling, 2002). Several horizontal mechanisms of the larynx, including the forward tilting of the thyroid cartilage, the movement of the arytenoid cartilages and the tensing of the glottis stretch the vocal folds longitudinally in the production of high pitch.

2.1.1.2.1 Unconstricted phonatory settings

The four main unconstricted phonatory settings are modal voice, falsetto, breath and breathy voice. The physiological features and perceptual characteristics of unconstricted phonatory settings are provided below in Table 2-2. In the production of unconstricted settings the mechanisms of the horizontal plane of the larynx may be engaged to produce voicing (adduction) or high pitch (adduction and stretching), however, the vertical plane of the aryepiglottic sphincter remains open and unengaged. It is important to differentiate the state of breath (i.e. 'audible breathing') and "nil phonation" (i.e. 'silent breathing') which involve vocal fold abduction. The audibility of breath is caused by the turbulence of the airflow through the open glottis. In the production of breathy voice (i.e. voiced breath), the glottis is "not narrowed enough to produce whisper" (Catford, 1977, p. 101). According to Esling and Harris (2002), breath (voiceless) and its related state breathy voice (voiced) are distinguished from whisper (voiceless) and whispery voice (voiced) by the lack of sphincteric activity. Due to the presence of audible turbulence in both settings, the distinction between these states of the glottis has not been examined in infant vocalizations. Researchers Oller (2000) and Stark et al. (1975) use the terms "breathiness" and "whisperiness" or whisper interchangeably to mean voiceless turbulence. It can be assumed that the setting observed by Oller and Stark et al. is voiceless constriction or whisper.

Table 2-2. Physiological features and perceptual characteristics of unconstricted phonatory settings.

Phonatory setting	Physiological features	Perceptual characteristics
Modal voice	vocal fold adduction for voicing	normal phonation (Oller, 1980) mid pitch
Falsetto	vocal fold adduction for voicing and longitudinal stretching	"head voice" (Laver, 1980) high pitch
Breath	vocal fold abduction widely opened glottis	audible breathing (Catford, 1977) voiceless turbulence
Breathy voice	vocal fold adduction slightly open glottis	"sigh-like" (Catford, 1977) voiced turbulence

The direct observation of the larynx and pharynx of infants is limited, but the canonical profiles of a bi-level model of the larynx considering the vertical plane may provides an accurate description of how infant vocalizations are produced. The application of a parametrical model based on the laryngeal constrictor to infant prelinguistic vocalizations accommodates the inherent anatomy and posturing of infant vocal tract, which predisposes constriction.

2.1.2 Posture of the infant vocal tract

Based on phonetic knowledge of the larynx provided in the previous sections, it is clear that adults make use of the structures involved in laryngeal constriction. In the next section I will discuss the posturing of the infant vocal tract, which predicts that infants will also make use of this primary laryngeal articulator.

According to medical research, the anatomical features of the infant vocal tract apparatus include: (1) the gradual arching slope of the oro-pharyngeal channel; (2) the retracted positioning of a large tongue in relation to a small oral cavity and short pharyngeal cavity; (3) the short, underdeveloped vocal folds; (4) the less retracted and, therefore, more raised and constricted positioning of the larynx which protects the airway by preventing the passage of substances into the lungs; (5) the superior positioning of the epiglottis against the soft palate (velum) which maintains a respiratory passageway from the larynx to the posterior nares (Crelin, 1973; Eckel et al., 1999; Fitch & Giedd, 1999; Kent & Bauer, 1987; Lieberman et al., 2001; Sasaki et al., 1977; Vorperian et al., 1999).

These studies present a view of infant speech development that highlights the limited vocal capacity of the infant in the first months of life, but do not recognize the pharyngeal articulatory capacity that infants display. The configuration of the newborn infant vocal tract is specifically designed to protect the airway, allowing the infant to swallow and breath simultaneously without the risk of inundation (Crelin, 1973; Kent, 1981). A number of researchers describe the infant vocal tract as "underdeveloped" or "primitive", stating that the refinement of respiratory, laryngeal and oral articulatory mechanisms which allow the adult human to produce complex articulatory movements required for vocal production is not present in early infancy (Fitch & Giedd, 1999; Kent, 1984; Thelan, 1991). This interpretation of anatomical findings to speech development emphasizes the anatomical differences of the adult and infant vocal tract and does not consider the significant role that the aryepiglottic sphincter plays in laryngeal articulations produced by both adults and infants.

The refined control of the independent structures required for fine oral articulations may be underdeveloped in early infancy, but the efficient control of the primary laryngeal mechanism involved in phonation (i.e. the glottal source for voicing) and protection of the larynx (i.e. sphincter) is present at birth. It is with these efficiently coordinated mechanisms that infants first begin to test out the productive capacity of their voices.

2.1.2.1 Restructuring of the vocal tract

In the third month of life, dramatic growth of the infant vocal tract begins to expand the infant's productive capabilities. The growth and reconfiguring of the infant vocal tract include: (1) the (anterior and caudal) descent of the larynx, the epiglottis, the hyoid bone and the tongue, (2) the disengagement of the velum and palate and, (3) the lengthening of the vocal tract with a decrease in the oro-laryngo-pharyngeal angle (Eckel et al., 1999; Goldfield, 2000; Lieberman et al., 2001; Sasaki, et al., 1977; Vorperian, et al., 1999).

After the third month, researchers have observed an expansion in the infant's phonatory repertoire, including numerous dimensions of phonation such as voice, intensity, pitch, pitch contouring, degree of constriction and degree of openness. The productive speech phenomenon of "vocal play" in addition to a new proposed definition entitled "range exploration" will be presented in the next section.

2.1.2.2 Vocal play

"Exploratory play" (Oller, 2000) or "vocal play" (Oller, 1980; Stark, 1980) has been described as a stage in infant speech development where a wide variety of new sounds and phonation types begin to occur between three to seven months of age. In an interpretive sense, vocal exploration can be described as vocal exercise – the way infants use their vocal apparatus to practice or play with contrastive features such as constricted and unconstricted settings, high and low pitch, voiced and unvoiced segments. The practice of opposing settings can occur rapidly within one utterance or over several utterances in a sequence (Oller, 2000). Researchers have related this increased vocal activity observed in these months to the anatomical growth of the vocal tract (Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980; Roug et al., 1989; Thelan, 1991). During the months of increased vocal activity, researchers note two important findings: (1) that infants expand their repertoire of phonation and pitch and (2) that infants seem to gain control of laryngeal mechanisms.

The occurrence of "vocal play" in the vocalizations of infants is mentioned in a number of studies. Roug et al. (1989) Stark (1980) and Oller (1980) note the exploration of laryngeal mechanisms, including features of the glottis such as voice and pitch, and features of the aryepiglottic constrictor (e.g. creak, "glottal pulse", and harshness).

These features are reported to occur from the fourth to the eighth month. The sound quality of growling is described as involving very low pitch or creaky with high degrees of tension (Oller, 1980). Nathani and Oller (2001) also note "aberrant phonation, breaks in voicing, rapid pitch variation" as being present in infant vocalizations produced in the first six months of life (2001, p. 4). Koopmans-van Beinum and van der Stelt (1986) mention the manipulation of friction noises, low-pitched and high-pitched trilling in months 3 to 7.

These existing acoustic and phonetic descriptions are scattered and do not provide a cohesive description of this dynamic developmental process. Furthermore, these stage-like descriptive terms only provide a partial view of the productive exploration of the full range continuum of pitch and laryngeal constriction. In order to analyze these features quantitatively in this study, a new definition will be proposed entitled "range exploration" described as the alternation of phonatory settings within vocalizations over time. I posit that through "range exploration", infants gain laryngeal control of their laryngeal mechanisms.

The literature reviewed above relates anatomical and vocal development in order to better understand the vocalizations produced in infancy. The studies presented in section 2.1.2 highlight the constraints of the infant vocal tract apparatus, which differs in size, as well as configuration, from that of the adult vocal tract. The view of the researchers is that the productive capability of the infant speech mechanism is primitive and limited. This infant speech development emphasizes the differences in the adult and infant vocalizations. Using this approach, researchers have been unable to account for infant vocalizations with existing "glottal" models (Bauer & Kent, 1982; Lieberman et al., 1971; Oller, 1980; Papaeliou et al., 2002; Robb et al., 1989). A number of accurate phonetic observations regarding the laryngeal quality of vocalizations such as "strained" sounds with dramatic pitch fluctuations have been provided. The next section investigates the development of laryngeal features in infant vocalizations occurring in the first six months of life.

2.2 Development of laryngeal features

I will provide a survey of current literature on infant prelinguistic vocalizations, focusing on three main areas: (1) the methods and tools of analysis (phonetic, acoustic or auditory), (2) the types of vocalizations and phonation types considered in this research and (3) the data and/or findings demonstrating that infants explore phonatory ranges, including pitch (at the glottis) and laryngeal constriction (above glottis)?

First, I will look at research focusing on the development of laryngeal control in the first year of life. The authors discussed in this section present "glottal" models of infant vocalization development, as their research designs only include and examine phonatory and articulatory features occurring on the horizontal plane of the glottis without identifying the effects of the vertical level of aryepiglottic laryngeal constriction above the glottis (Amano et al., 2003; Kent & Murray, 1982; Lieberman, 1985; McCune et al., 1996; Wermke et al., 2002.) The following laryngeal features of the glottis are examined: the development of subglottal pressure (intensity and duration) reported in Lieberman (1985), vocal fold tension (fundamental frequency) reported in Kent and Murray (1982), Amano et al. (2003) and Wermke et al. (2002), and the simple closure mechanism of the vocal folds during glottal stop as discussed in McCune et al. (1996).

The laryngeal voicing source (i.e. phonation) is the primary sound producing mechanism (Oller, 1980). The basic components in the production of phonation and their correlating acoustic variables are as follows: subglottal pressure (intensity, amplitude, and duration) and vocal fold tension/the rate of glottal vibration (fundamental frequency) (Lieberman, 1985). Since the late 1960s, researchers have noted that these glottal aspects of speech development are the first aspects of speech production to be explored and controlled in early infancy (Fry, 1966). More recent studies have focused on identifying the process and order of glottal phonatory control in infancy.

In his acoustic study of cry vocalizations from 15 infants, Lieberman (1985) investigates the development of subglottal control in the first three months of life. Lieberman notes that due to underdeveloped rib structure at birth, newborns do not control the inspiratory gesture of the intercostal muscles which regulate subglottal pressure. According to Lieberman, the inability to control subglottal pressure limits the duration of infant vocalizations for at least three months. Lieberman suggests that during the first three months of life, critical physiological development occurs allowing the infant to sustain phonation for a greater duration. During this time, the infant rib cage develops into an adult-like configuration and neuromuscular control of the intercostal and diaphragm muscles emerges. A dramatic increase in the mean length of vocalization from 200–600 ms at one month to 1500 ms at six months has been noted in numerous studies (Delack & Fowlow, 1978; Kent & Murray, 1982; Oller, 2000; Stark, 1993; Vihman, 1996).

As noted above, at three months, the ability to control subglottal pressure stabilizes, allowing infants to produce vocalizations with greater lengths. However, according to Kent and Murray (1982), the ability to combine the subglottal mechanisms that regulate air pressure control and the laryngeal mechanisms that regulate pitch control is not present until the sixth to eighth month of life.

Kent and Murray (1982) attempt to document the emergence of pitch control in the "non-distressed" vocalizations from a large group of infants (n=21) at three, six and nine months of age. In this study, a non-distressed vocalization is described as vocalic with a duration of 400 ms and a fundamental frequency range of 350–500 Hz. The results showed an insignificant decrease in fundamental frequency, which averaged 445 Hz at three months, 450 Hz at six months and 415 Hz at nine months.

The main developmental changes observed in this study involved the within-utterance fundamental frequency range and stabilization of laryngeal source excitation. In their analysis of melodic contours of 100 speech-like vocalizations for each age group, the researchers found a predominance of falling contours at three months and rising contours at six and nine months. Kent and Murray relate the tendency towards a falling contour to the lack of subglottal and glottal control in the first months of life. By nine months, control of both laryngeal functions were seen, as evidenced by the infant's ability to increase subglottal pressure over the duration of utterance and increase vocal fold length and tension at the end of the vocalization to produce a rising contour.

Additional acoustic examination of vocalizations at three months revealed an aperiodic turbulence in the spectrum described as "vocal tremor" or "vibrato" with abrupt changes in harmonic structure, "noise components, irregular vocal fold vibrations" (p. 360). The mean frequency of "vocal tremor", as reported in a later article by Kent and Bauer (1987), is approximately 15 Hz with a frequency range of 9–25 Hz similar to creak or "glottal pulse" reported in Buder, Oller and Magoon (2003). The observation of "squeals" produced with high pitch and high degrees of vocal tension has been cited in a number of studies (Stark, 1980; Oller, 1980, 2000). These descriptions suggest that phonatory settings involving constriction and interacting pitch levels are being produced in the first nine months of life. Furthermore, the presence of prelinguistic vocalizations with low pitch has not been accounted for.

A further discussion of the variable pitch and phonatory characteristics of fundamental frequency in infant vocalizations is found in a recent study by Wermke, Mende, Mangredi and Bruscaglioni (2002). This study acoustically analyzes the cry melodies of three pairs of identical twins from two to nine months, focusing on the development of melodic complexity and pitch stability, in addition to the relationship between pitch and intensity. Similar to previously mentioned studies, Wermke et al. (2002) found a high variability of pitch and quality in vocalizations produced in the early months.

The authors characterize the developmental changes of the melodic pattern as a maturation process with stepwise increases of complexity over time. In the first step, single building blocks (e.g. a simple rising pitch contour) are developed, differentiated and stabilized. The complexity increases in step two, when one process (e.g. pitch contour) is combined with another (e.g. intensity). The third step involves differentiation of the two processes as separate entities that can occur with disharmony.

The results of this study show the prevalence of simple rise-falling melody patterns in the first month of life. Pitch and intensity are coupled at this point. From month 3 to 6, the complexity gradually increases as an infant is able to vocalize the first melodic pattern, the rise-fall, twice in a row, then several times in a row with varied intensity and pitch. At the beginning of the ninth week, all pitch contours were produced independently from intensity contours. The authors suggest that this finding reinforces the assumption that pitch and intensity are "controlled by separate neuro-physiological mechanisms already in early infancy" (Wermke, et al., 2002, p. 512). Findings presented in this study support the hypothesis that the infant's control of mechanisms underlying laryngeal sound production increases in the first six months of life.

Over the last 30 years, a number of studies have focused on the developmental changes of fundamental frequency (f0) in infancy (Amano et al., 2003; Delack & Fowlow, 1978; Kent & Bauer, 1987; Sheppard & Lane, 1968; Wermke et al., 2002). The purpose of these studies was to provide findings that show a significant change in average f0 that coincides with the dramatic anatomical changes occurring in the first year of life, such as the descent of the larynx and the restructuring of the oro-pharyngeal channel (Crelin, 1973; Fitch & Giedd, 1999; Lieberman et al., 2001; Sasaki et al., 1977; Vorperian et al., 1999).

In a recent paper by Amano, Nakatani and Kondo (2003), the research team from NTT Communication Science Laboratories in Japan, presented a longitudinal acoustic study on the fundamental frequency changes in the vocalizations of two Japanese infants recorded for one hour per month from birth until five years of age. The average f0 was calculated for every voiced utterance and then the mean of the average f0 and its standard deviation were obtained for each month. Vocalizations with large shifts in pitch or noisy turbulence were excluded from the analysis. The authors predicted that as the infant's speech organ grows and reconfigures with age the average f0 should start to decrease over the observed period of 60 months.

A significant monthly decline in fundamental frequency could not be drawn from this study as only Infant B showed a statistically significant decrease in f0 over the period studied (500 Hz–400 Hz). The f0 of Infant C showed an insignificant decrease from 350

Hz–300 Hz. Infant A was excluded from the study. No reasons were provided for this exclusion. Previous acoustic studies reported similar findings, stating that the average f0 range is from 335 Hz–550 Hz and shows little to no change in mean value over the first year of life (Delack & Fowlow, 1978; Kent & Bauer, 1987; Sheppard & Lane, 1968; Wermke et al., 2002).

This area of research has not provided any conclusive findings demonstrating a relationship between a change in the average f0 of "non-distressed" vocalizations and the change in size and configuration of the infant vocal tract. The authors note that because f0 has a wide range in value (200–2000 Hz) and is "unstable", discontinuously changing to double or half its value, f0 is often difficult to extract from acoustic analysis. In order to identify infant vocalizations with varied pitch and constriction, auditorily based coding for prelinguistic vocalizations has been developed by Esling, Benner and Bettany (2004a, 2004b) to corroborate acoustic findings. It is the opinion of this researcher that auditory perception is a better indicator of laryngeal constriction as well as of the interaction of constriction and pitch. The auditorily based techniques used in this study will be discuss\ed in greater detail in section 3.3.2 in the methodology section of this paper.

Vocalizations involving the laryngeal constrictor (e.g. "grunts", "fusses", "cries", "squeals" and "growls") are usually excluded from analysis, as these sounds are considered "vegetative" or "reflexive" rather than "linguistic" (Koopmans-van Beinum & van der Stelt, 1986; Oller, 2000). As one of the primary goals of this study is to observe and account for all vocalizations, it is worth mentioning one of the few studies to systematically observe and acoustically analyze "reflexive" grunt vocalizations by McCune, Vihman, Roug-Hellichius, Bordeneave and Gogate (1996).

This study by McCune et al. (1996) examines the physiological and psychological basis for laryngeally produced grunt vocalizations of five infants from eight to 16 months of age. Acoustic and phonetic evidence provided in this study on the developmental progression of grunts at the transition to speech at approximately eight months, show that laryngeal function is practiced then used communicatively in infancy.

The researchers separate grunts into three categories due to the physiological basis for the production of grunts and the developmental pattern found in their results, (1) effort grunts, (2) attention grunts and, (3) communicative grunts.

Grunts first occur as a sound, related to the adjustment of the vocal tract for protective closure and food ingestion (Oller, 2000; Roug, Landberg, & Lundberg, 1989; Stark, 1986). Studies have noted an increased frequency of grunts at about three months of age in association with the effort of upright face-to-face communication (Oller, 2000; Stark, 1993). According to Stark (1993), effort grunts begin to accompany active movement and early object manipulation at five months. The effort of these movements activates the respiratory muscles and constricts the glottis. After movement, the breath that has been held in is released, producing an effort grunt. Also emerging at this time are attention grunts. These occur when the infant is engaged in visual (and often tactile) focal attention, which may be attributed to lung expansion, which stabilizes the thorax and maintains the trunk upright, facilitating fine object manipulations (Ruff, 1986).

The results of this study show that grunt vocalizations were first observed under conditions of effort and were most frequent in months 8 to 10, decreasing in month 12. Grunts used in an expressive manner, with the goal of communication, did not emerge until month 11, increasing in frequency over the next five months. To summarize, grunts seem to first occur under consistent autonomic conditions (effort or attention), but through systematic practice soon begin to be expressed as intention movements having a functional representation within the infant's communication system.

The authors phonetically define a grunt as a vocalization that results when a brief glottal closure is followed by an abrupt vowel-like release (e.g. a brief egressive voiced breath) occurring with open or closed lips but no other supraglottal constriction. Here, the authors' describe a plosive with no oral closure, which could be either glottal or pharyngeal. According to Esling, Benner and Bettany (2004a; 2004b) grunt-like vocalizations in early infancy usually involve some degree of laryngeal constriction above the glottis, either maximal constriction as in an epiglottal (pharyngeal) stop, or moderate constriction as in a forced glottal stop. The phonetic description of grunts and other "vegetative" vocalizations will be discussed in detail in the next section.

2.3 Previous phonetic descriptions

Numerous studies on early infant speech production and communication have attempted to provide categorical, colloquial and phonetic descriptions of infant vocalizations in the first six months of life. Table 2-3 (see p. 28) displays a comprehensive survey of existing terms and descriptions used in current research.

The extensive colloquial terms used above for the wide variety of vocal behaviours produced in infancy suggest that phonetic descriptions of vocalizations must be complex. A number of researchers, most notably Oller and colleagues (Buder, Oller & Magoon, Nathani & Oller, 2001, Oller, 1980) have highlighted various coding strategies administered to deal with the complexity of infant vocalizations. The "infraphonological" theoretical construct utilized by Oller et al. is based on adult phonological systems, "the basic building blocks of mature speech" (Nathani & Oller, 2001, p. 2). As the goal of Oller et al. is to monitor the progress of speech-like vocalizations toward language in early infancy, Oller et al. exclude laryngeally constricted vocalizations (e.g. "grunts", "fusses", "cries", "squeals" and "growls") from analysis, as these sounds are considered "vegetative" or "reflexive, related to the vegetative activity of the vocal tract, rather than "linguistic" (Oller, 2000). All vocalizations are coded on a scale of "speechiness" from more speech-like to less speech-like based on an adult model of modal or normal phonation. Vocalizations including any vocal behaviour that is not speech-like, for example "squeal-like" or "growl-like" vocalizations are omitted from the analysis. This research draws a valuable link between early speech-like vocalizations and adult language, however it does not provide a total picture on the productive progression of speech.

Table 2-3. Previous phonetic descriptions of infant prelinguistic vocalizations.

Colloquial Terms	Reported in (author)	Phonetic Descriptions
"Crying"	Stark et al. (1975)	reflexive sounds vowel like sounds
	Bauer & Kent (1987)	high degrees of vocal tension
	Wermke et al. (2002)	variations in pitch
	Truby & Lind (1965)	turbulent
"Hyperphonation"	Lieberman et al. (1971)	noisy glottal excitation
	Möller & Schönweiler (1999)	high subglottal pressure
		unstable f0
		very high pitched
"Dysphonation"	Möller & Schönweiler (1999)	noisy and turbulent
"Fusses"	Lieberman et al. (1971)	aperiodic glottal excitation
		high subglottal pressure
		large periodic variations in f0
	Hsu et al. (2002)	negative vocalizations
	Oller (2000)	strong crying, negative emotion

"Squealing" "Shrieking" "Screaming"	Oller (1980; 2000) Koopmans-van Beinum & van der Stelt (1986) Buder, Oller & Magoon (2003)	high pitch substantial vocal tension extremes of f0
"Growling"	Oller (2000) Kent & Murray (1982) Robb et al. (1989)	low pitch (>150 Hz) high degrees of vocal tension, often in creaky voice noisy with friction
"Moan" "Groan"	Scheiner et al. (2002)	noisy call types discomfort sounds
"Cough"	Oller (2000)	reflexive/biological sound
"Pulse" "Glottal Pulse" "Vocal Fry" "Vocal Tremor"	Buder, Oller & Magoon (2003) Stark et al. (1975) Stark et al. (1975) Kent & Murray (1982) Möller & Schönweiler (1999)	extremely low frequency 70 Hz appearance of glottal pulses forceful expulsion of air low pitch, voiced low frequency (9–15 Hz) strained and tense sounding
"Chaos"	Buder, Oller & Magoon (2003)	random appearing vocal waveform
"Pharyngeal Friction"	Stark et al. (1975)	turbulent noise
"Whispering"	Oller (2000) Buder, Oller & Magoon (2003)	low amplitude simple turbulence
"Yelling"	Oller (2000)	high intensity
"Normal"	Buder, Oller & Magoon (2003)	smooth and continuous harmonic structure speech like, normal pitch
"l'r gutturale" Gutteral /r/ "Gazouilles"	Grégoire (1937)	fricative noise "hitting" noise of the voice reflexive, laryngeal vocalizations short duration
"Grunts"	McCune et al. (1996) Stark et al. (1975) Oller (2000)	laryngeal vocalizations sharp, glottalized onset short duration small "throaty" sounds reflexive/vegetative
Gurgle	Lieberman et al. (1971) Grégoire (1937)	short vocalization tense with glottal excitation laryngeal vocalizations reflexive

"Gooing" "Cooing"	Oller (1980; 2000)	normal phonation alternation between opening and closing of vocal tract
	Stark (1980)	velar/uvular articulations
	Roug et al. (1989)	incomplete constrictions against velum or uvula

The dynamic range of phonation and pitch including constricted settings has been cited as the main problem in accounting for infant vocalizations. Though elaborate strategies based on complex theories have been provided, the simple fact is that researchers have ignored a large percentage of vocalizations because they have not had the tools to account for constricted laryngeal sounds. The phonetic description of all infant vocalizations including "vegetative" and other previously ignored categories will be reinterpreted based on the proposed bi-level model of the larynx, considering the vertical laryngeal constrictor and the horizontal laryngeal glottis.

2.4 Summary

The aforementioned studies present valuable models of infant speech development. Their findings have illustrated the importance of phonatory exploration in early infancy. However, these studies do not consider or include the role of the vertical laryngeal constrictor in early phonatory development, and thus lack the ability to adequately describe vocalizations.

Previous descriptions have reported the instance of dynamic laryngeal play in early infancy. Kent and Murray (1982) note an audible instability in pitch control described as vocal tremor with a mean frequency of 15 Hz similar to descriptions of creak or "glottal pulse" characterized by extremely low-frequency f0 (sometimes 70 Hz or lower) reported by Buder, Oller and Magoon (2003), Kent and Bauer (1987) and Stark (1980). Other notable researchers mention "strained and tense" sounding vocalizations with irregular noise components, aperiodicity and high degrees of laryngeal tension (Koopmans-van Beinum & van der Stelt, 1986; Roug et al., 1989, Wermke et al., 2002). Additionally, findings reviewed by Oller (2000) confirm that infants explore phonatory regimes with varying degrees of vocal tension (e.g. aryepiglottic trilling, creak and whispering) and the continuum of pitch (e.g. "growling" at low pitch, "squealing" at the extremes of f0 and "pulses" at low and high pitch). The presence of laryngeal constriction in the exploratory vocalizations of infants is clearly inferred from these acoustic-phonetic descriptions of a number of authors, though no quantitative analysis has included these vocalizations in their analysis.

It can be inferred from these numerous descriptions that vocalizations are first produced in the pharynx and larynx. Furthermore, the first phonatory settings explored by infants include the ranges of the laryngeal mechanism including, degree of laryngeal constriction (i.e. harsh voice, creaky voice and whisper), laryngeal pitch (high, mid, low) and laryngeal voice (voiced and voiceless). The present study will examine the role of laryngeal mechanisms, including the vertical laryngeal constrictor and the horizontal glottis, in the development of infant vocalizations in the first six months of life.

Chapter Three

METHODOLOGY

3.1 Subject

One normally developing female infant, named "Sophia" was investigated in this longitudinal study of early speech development. According to the child's mother and based on medical examinations by the child's family doctor, there was no clinical history of postnatal illness or of any speech or hearing disorders. At a two-year follow-up, the infant exhibited normal language and hearing development. The infant is located in Victoria, British Columbia, Canada, where the ambient language is English. A naturalistic environment was created to ensure that recording sessions were non-invasive or disruptive to the infant's daily routines including, feeding, playing with toys, and sleeping. Recording equipment was turned off during short naps, and recording resumed when the child became vocally alert again.

3.2 Recording procedure

Sophia was recorded on a bi-monthly basis, in her home from two weeks to 28 weeks (six months). In total, 12 recording sessions were conducted, each lasting two hours long. The recording sessions occurred in the late morning hours when Sophia was alert and vocal. All recordings were made in the presence of the mother, who provided natural face-to-face interaction with the infant, and every effort was made to interact with the infant in a natural, responsive way. Both the researcher and mother made an effort to be silent whenever the infant vocalized. Special effort was taken to record a full range of vocal behaviours including, feeding, fussing, crying, playful interaction with the mother and non-interactive vocal play during solitary activity (e.g. picking up blocks, reaching for objects, playing with toys etc.) as reported in McCune et al. (1996) and Ruff (1986). Details on the categorization and coding of infant vocalizations are provided in section 3.3.2. During most recording sessions, Sophia produced the most vocalizations while in a supine position and/or when she was engaged in solitary play.

Broad phonetic transcriptions of vocalizations were noted and discussed during and after recording sessions with the mother, a trained phonetician. Notes of psychological, gestural, phonatory, segmental and suprasegmental development were also kept.

The recording equipment used was an Audio-Technica® PRO 7a unidirectional condenser microphone and a TASCAM DA-P1 Digital Audio Tape (DAT) recorder. To ensure the quality of the recording, the microphone was held by the researcher 20-30cm directly in front of Sophia's mouth. At around five months, various techniques of concealing the microphone were required to prevent large shifts in intensity of the recording amplitude as Sophia's awareness and manual dexterity improved, affecting the quality of the recording.

3.3 Data Analysis

3.3.1 Selection of samples to be evaluated

The corpus of data reported in this study consists of 24 hours of raw data collected from one English-speaking infant as a part of a larger project documenting the role of laryngeal mechanisms in the phonetic development of infants in the first year of life (by Esling, Benner, Bettany & Zeroual, 2004). One of the main goals of this project is the development of a collaborative web-based XML database and analysis network of early infant data recorded from researchers situated in Victoria, Paris, Morocco, and China. This interactive database will allow researchers to share, exchange and compare a large amount of audio and video data of infants from different ages ambient languages.

In order to analyze the utterances perceptually and acoustically, the 24 hours of unedited data from the DAT tapes were transferred onto a personal computer (IBM Pentium III, 450 MHz) at a sampling rate of 22,050 Hz, 16-bit, using the speech editing software Cool Edit Pro LE, manufactured by Syntrillium Software Corporation. The large digitized segments from each of the 12 recording sessions were stored, filed and labeled with the following information: first initial of the infant (S), recording session number, and date of the recording (YY/MM/DD) (e.g. S01-02-05-30). A back-up CD was made of this unedited data. For analysis, the 12 recording sessions were then divided into six groups representing months 1 to 6.

For the analysis of the productive capability of the laryngeal mechanisms of pitch and constriction, all vocalizations produced by the infant in the 12 recording sessions were used in this study. A vocalization or utterance is defined as any discrete sound produced with varying degrees of constriction and pitch occurring within one respiration cycle. The waveforms of a total of 824 vocalizations were edited out of the 24 hours of raw data, using version 1.6.3 of Wavesurfer, a speech analysis program downloaded on October 22, 2003, from the web site http://www.speech.kth.se/wavesurfer/. Vocalizations that were inaudible due to extraneous noise, or produced with an obstructed oral cavity (i.e. toy or hand in mouth) were excluded.

As the exploration of laryngeal constriction and the interaction between constriction and pitch have not been systematically analyzed in infant vocalizations prior to this study, a new system of coding infant vocalizations was required.

3.3.2 Auditory coding of vocalizations

In the next section, I propose the modified criteria for auditorily based coding of early infant vocalizations based on the proposed bi-level model of the larynx incorporating the mechanisms of the glottis and the laryngeal sphincter discussed in section 2.2.1. This section will discuss three important issues in coding infant vocalizations for this study with primary focus on the development of the laryngeal mechanism: (1) the inclusion of all vocalizations including biological sounds (e.g. “vegetative” or “reflexive”) as reported in Stark et al. (1975) and Oller, 1980), (2) auditory training and analysis of constricted phonatory settings and pitch, (3) acoustic analysis of exploratory play involving constriction and pitch.

This study is not concerned with the communicative intent of specific vocalizations but rather with the productive capability of the glottis and the laryngeal constrictor during exploratory play. Therefore, all vocalizations produced by the infant during the 12 recording sessions were considered, including those termed “vegetative” or "reflexive" (i.e. sneezes, yawns, pants, hiccups, coughs, clicks and audible breaths (ingressive and egressive)) reported in Stark et al. (1975) and effort and grunting sounds (i.e. glottal and epiglottal stops and fricatives) reported in McCune et al. (1996), distress vocalizations (i.e. fusses and cries) reported in (Oller, 2000; Wermke et al., 2002) and vocalizations produced with constricted phonation settings (i.e. harsh voice, creaky voice and whisper) and unconstricted phonation settings (i.e. modal voice, falsetto, breath and breathy voice). "Babbled vocalizations" (Oller, 1980) (i.e. sequences of consonant-like and vowel-like utterances; MacNeilage & Davis, 1992) were observed and included in this data beginning in month 4. Researchers cite the onset of the production of babbled vocalizations as occurring between the sixth to eighth month of life, therefore the productive ability of this infant may be slightly advanced (de Boysson-Bardies, 1999). However, previous research has made an effort to include only vocalizations produced with "normal phonation"; therefore it is possible prior studies do not take into account early babbled vocalizations produced with constricted phonatory qualities.

In this study, the phonatory quality and pitch of infant vocalizations was identified with auditorily based assessment by the researcher. Recent findings by numerous researchers demonstrate that auditory phonetic identification is an accurate indicator of the incidence and degree of laryngeal constriction when it occurs in conjunction with shifts in pitch (Buder & Oller, 2003; Hsu et al., 2000; Nathani & Oller, 2001; Oller, 2000; Oller & Lynch, 1992). The auditorily based coding of infant vocalizations is extremely time consuming and requires years of auditorily based training of both adult and infant phonation. The present study is a part of a long-term collaborative project, under the supervision of Dr. J. H. Esling, to develop the theoretical framework of the laryngeal mechanisms involved in adult and infant vocalizations. Training over the past six years has resulted in a good level of agreement within the infant speech research team on the use of phonetic parameters discussed here.

Coding of vocalizations demonstrating a dynamic range of phonatory settings and pitch often required the assistance of acoustic techniques including, the creation of wide- and narrow-band spectrograms from digital waveforms.

3.3.3 Analysis One: Phonatory setting and Pitch

In analysis one, auditorily based assessments were used to determine the phonatory setting and pitch of each utterance. The assessment criteria will be discussed in the following section (3.3.3.1).

3.3.3.1 Auditorily based Coding Criteria

Table 3-1 presents the auditorily based coding criteria used in identifying the incidence of phonation and pitch in each of the 824 vocalizations. The pitch level of harmonic vocalizations including modal voice (300 – 500 Hz) and falsetto (<500 Hz) was identified using narrow-band spectrograms. Auditorily based techniques were used to identify the mean pitch-level of constricted vocalizations due to the finding that the majority of constricted vocalizations produced f0 detection errors. For this reason previous studies excluded laryngeal vocalizations from mean f0 analyses (Amano et al., 2003; Buder & Oller, 2003; Kent & Murray, 1986; Wermke et al., 2002). Ranges for constricted pitch-levels provided in Table 3-1 are based on a sample of vocalizations from this study which did not cause f0 extraction difficulties.

Table 3-1. Auditorily based coding criteria for phonation and pitch in infant prelinguistic vocalizations.

(1) presence of constriction (i.e. strained, tight, or rough phonation)

(2) the degree of constriction:

i. extreme	(harsh voice [voiced])
ii. moderate	(creaky voice)
iii. slight	(whisper [voiceless] and whispery voice [voiced])
iv. none	(modal voice, falsetto and breath)

(3) the level of pitch within constricted vocalizations:

i. low	(90 – 250 Hz)
ii. mid	(250 – 500 Hz)
iii. high	(<500 Hz)

(4) the pitch of unconstricted vocalizations

i. mid to low	(modal voice)	(300 – 500 Hz)
ii. high	(falsetto)	(500 Hz)

For each vocalization, the occurrence and percentage of constriction and pitch were calculated for settings which occur for a duration longer than 0.1 s. The quality of vocalizations less than 0.1 s could not be accurately identified. The occurrence and percentage of individual constricted phonatory settings, i.e. harsh voice (HV), creaky voice (CV), whisper (W) and unconstricted phonatory settings, i.e. modal voice (MV), falsetto (F), breath (B) and breathy voice (BV) were calculated for each vocalization.

The presence of more than one phonatory setting occurred frequently within an utterance in this data set, therefore the method of calculating the occurrence of phonation was devised as follows: (1) each vocalization was calculated as one count (e.g. 1 vocalization = 1); (2) the presence of each phonatory quality occurring within one utterance was calculated as one (e.g. F = 1, CV = 1 and HV = 1).

3.3.4 Analysis two: Range exploration

Prior to this study the exploration of phonation and pitch in infant vocalizations had not been systematically analyzed with acoustic or perceptual analysis. In analysis two, perceptual and acoustic techniques were used to demonstrate the occurrence of exploratory alternations between phonatory settings and pitch in a random selection of 120 vocalizations from months 1 to 6. In the first part of this analysis, auditorily based assessments were used to judge the phonation settings and pitch explored within vocalizations. The perceptual criteria discussed in section 3.3.3.1 were used to code the quality of the vocalizations and the number of alternations occurring within the vocalizations (see section 3.3.4.2).

3.3.4.1 Random Vocalization Sample

For each of the six months, 20 random vocalizations, resulting in a total of 120 vocalizations) were selected for the analysis of range exploration. In order to select a random and unbiased selection of vocalizations, every x number of vocalizations (range from 5 to 11) within each month's data set, was selected for analysis. The range of random selection is due to the fact that each month contains a different number of total vocalizations see Table 3-2 below.

Table 3-2. Random selection of vocalizations for each month in analysis two.

Month	Number of Vocalizations	Sample taken every x vocalizations	Total Number of Vocalizations
1	94	x = 5	20
2	113	x = 6	20
3	116	x = 6	20
4	118	x = 6	20
5	162	x = 8	20
6	221	x = 11	20

3.3.4.2 Duration

The duration of each of the 20 vocalizations for each month was measured using version 1.6.3 of the Wavesurfer software. The total duration of the 20 vocalizations for each month was calculated and averaged. Previous studies measuring the duration of infant vocalizations have not quantitatively analyzed vocalizations produced with one or more timing alternations between different phonatory settings, therefore a new auditory-acoustic technique was developed to measure the duration of phonatory alternations within vocalizations (Kent & Murray, 1982; Oller, 1980; Stark et al., 1975). Two considerations were made to create accurate measurements of duration: (1) the inclusion of silences (2) the starting point of an alternation. In this data, silences were included in the duration measurement of different phonatory settings. The duration of silences in the selected vocalizations gave a clue to the phonatory quality. Current research on the duration of pharyngeal stops in Salish demonstrates that pharyngeal stops, which involve the laryngeal constrictor, were longer in duration than glottal stops, which do not involve constriction (Carlson, Esling & Harris, 2004). The observation that constricted stops are longer than unconstricted stops was also seen in the present data. Four types of silence periods were observed in the vocalizations of this study: (1) long periods of stopping within constricted vocalizations, (2) short, intermittent pulse-like periods within creaky voice high and low pitch vocalizations, (3) short glottal stop during unconstricted vocalizations and (4) uvular, velar, alveolar and labial stops during constricted or unconstricted vocalizations. The quality of silences within constricted and unconstricted settings was judged with the same perceptual criteria as discussed in section 3.3.3.1. The second consideration of determining the start point within vocalization alternations was determined through auditory and acoustic techniques. In most cases, the alternation point was easily noted on broadband spectrograms, see for example Figure 3-1. In this spectrogram the point of the phonatory alternation occurs when the infant switches from a constricted setting (i.e. increased friction caused by a secondary source of vibration) to an unconstricted setting (i.e. less friction). However, rapid transitions between several phonatory qualities were also found. In these vocalizations, auditory techniques, in addition to spectrograms, were necessary to identify the point of alternation. In both cases, the Wavesurfer software was used to calculate the alternations.

3.3.4.2.1 Duration of phonatory settings

In this data, range exploration is defined as the alternation of phonatory settings within an utterance. The change from one phonatory setting to another is counted as one alternation. First, the number of alternations within each vocalization was calculated. Then, the total duration of each phonatory setting alternation within each vocalization was calculated and averaged.

For each vocalization, the duration of each phonation setting occurring within the vocalization was measured by simultaneously examining the digitized waveform and its corresponding broadband spectrogram using Wavesurfer, 1.6.3. First, the phonatory section on the spectrogram was manually isolated using the cursor line in the active spectrogram to determine the start time and end point of the phonatory alternation. The total section of the alternation section was highlighted. From each highlighted section, the program calculated the total time of the alternation was calculated. The values for the total duration and average duration for each phonatory setting for each month were calculated.

3.3.4.3 Statistical Analysis

Excel software 10.0 was used for further statistical correlations including Independent-Samples t-tests comparing the average durations of each phonatory setting alternation and the incidence of alternations within each vocalization for each of the six months.

Chapter Four

RESULTS AND ANALYSIS

This chapter reports the results of the quantitative analyses on the laryngeal features of phonation and pitch in the 824 vocalizations produced by an English-speaking infant in the first six months of life. Auditory and acoustic methods were used to identify the phonatory and pitch characteristics of these vocalizations. Section 4.1 presents the findings from analysis one: the auditory analysis of phonatory settings and pitch. Section 4.2 presents the results from analysis two. The auditory and acoustic analysis of range exploration in 120 randomly selected vocalizations, including the duration of phonatory alternations occurring within vocalizations and the spectrographic findings is presented.

4.1 Analysis one: Phonatory settings and pitch

A total of 824 vocalizations were used in this auditory analysis based on the bi-level model of the larynx incorporating the articulation of the aryepiglottic laryngeal constrictor in constricted phonatory settings. The total number of vocalizations produced by the infant in the six-monthly periods is presented in section 4.1.1. The results of the auditory evaluation of phonation and pitch are provided in sections 4.1.2 and 4.1.3, respectively. A summary of the findings is presented in section 4.1.4.

4.1.1 Vocalization data

The total number of vocalizations evaluated per month in analysis one is provided in Table 4-1.

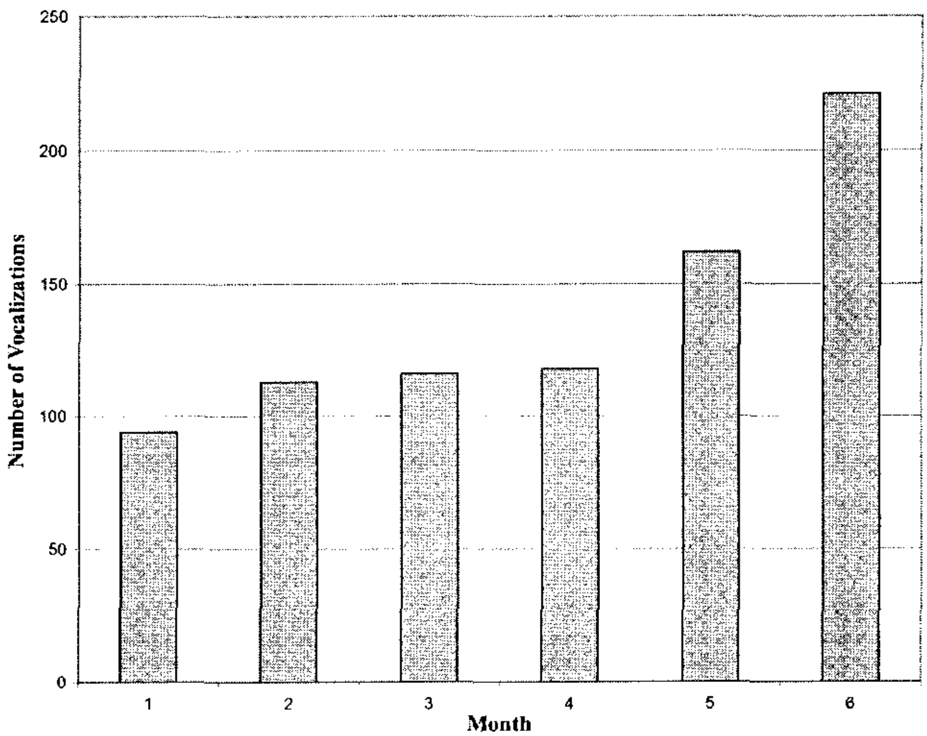
Table 4-1. Total number of vocalizations produced in each month evaluated in analysis one.

Month	Total Number of Vocalizations Analyzed
1	94
2	113
3	116
4	118
5	162
6	221

It is important to note that the total number of vocalizations produced each month is a different amount. In analysis two, an equal set of vocalizations from each month was randomly selected in order to provide statistical comparisons of phonation and pitch variables in the first six months of life.

This analysis presents the overall trends of phonation and pitch during the first six months of life, which can be shown by the increase or decrease in the proportion of phonatory and pitch variables out of the total number of vocalizations produced each month. The total incidence number of phonation and pitch within the total vocalizations produced each month can also provide valuable findings, but the increase in the total number of vocalizations must be noted when considering these results. The increase in the total number of vocalizations produced each month from 94 vocalizations at month 1 to 221 vocalizations at month 6 is shown in Figure 4-1.

Figure 4-1. Increase in the total number of vocalizations produced each month.



The increase in the number of vocalizations produced over the six-month period demonstrates that the infant's productive output is increasing. This finding has been reported in a number of infant speech studies (Hsu et al., 2002; Oller, 2000; Vihman, 1996). Section 4.1.2 summarizes the quantitative analysis calculating the incidence of constricted (i.e. harsh voice, creaky voice and whisper) and unconstricted (i.e. modal voice, falsetto and breathy voice) phonatory settings and three levels of pitch (i.e. low, mid and high) in these vocalizations.

4.1.2 Phonation

The total incidence and percentage of constricted and unconstricted vocalizations produced in the observed six-month period are listed in Table 4-2. These results demonstrate that the majority of vocalizations produced in the first five months are constricted. The percentage of constricted vocalizations is 100% in the first month, 95% in the second month and 89% in the third month. The percentage of constricted vocalizations begins to decline in the fourth and fifth month, 69% and 55%, respectively while remaining greater than half of the total number of vocalizations produced. At six months the total percent decreases to 35%, less than half of the total number. The occurrence of vocalizations with unconstricted phonation is rare in early months, but increases exponentially in the fifth and sixth month. The percentage of constricted vocalizations decreases as the percentage of unconstricted vocalizations increases over the six-month period. A number of observations can be drawn from these results: (1) the dominant phonatory setting in early infancy is laryngeal constriction; (2) the dominant phonatory setting in month six is unconstricted. These results suggest that the initial default setting of laryngeal constriction changes gradually over the first six months of life.

Table 4-2. Number and percentage of constricted and unconstricted vocalizations in the first six months of life.

Month	Total Number of Vocalizations	Number of Constricted Vocalizations	Percentage of Constricted Vocalizations	Number of Unconstricted Vocalizations	Percentage of Unconstricted Vocalizations
1	94	94	100%	0	0%
2	113	107	94.7%	6	5.3%
3	116	103	88.8%	13	11.2%
4	118	81	68.6%	37	31.4%
5	162	89	54.9%	73	45.1%
6	221	78	35.3%	143	64.7%

The comparison between the number and percentage of constricted and unconstricted vocalizations is presented in Figures 4-2 and 4-3 in the following page. The initial dominance of the default setting of laryngeal constriction can be seen in both figures. Figure 4-2 shows the dramatic increase in the production of unconstricted vocalizations over six months with a surge in months 4 to 6. The number of constricted vocalizations does not increase or decrease significantly over the six-month period. The percentage results presented in Figure 4-3 show a decrease in the total number of constricted vocalizations in relation to the total number of vocalizations produced in months 5 and 6.

Figure 4-2. Number of constricted and unconstricted vocalizations.

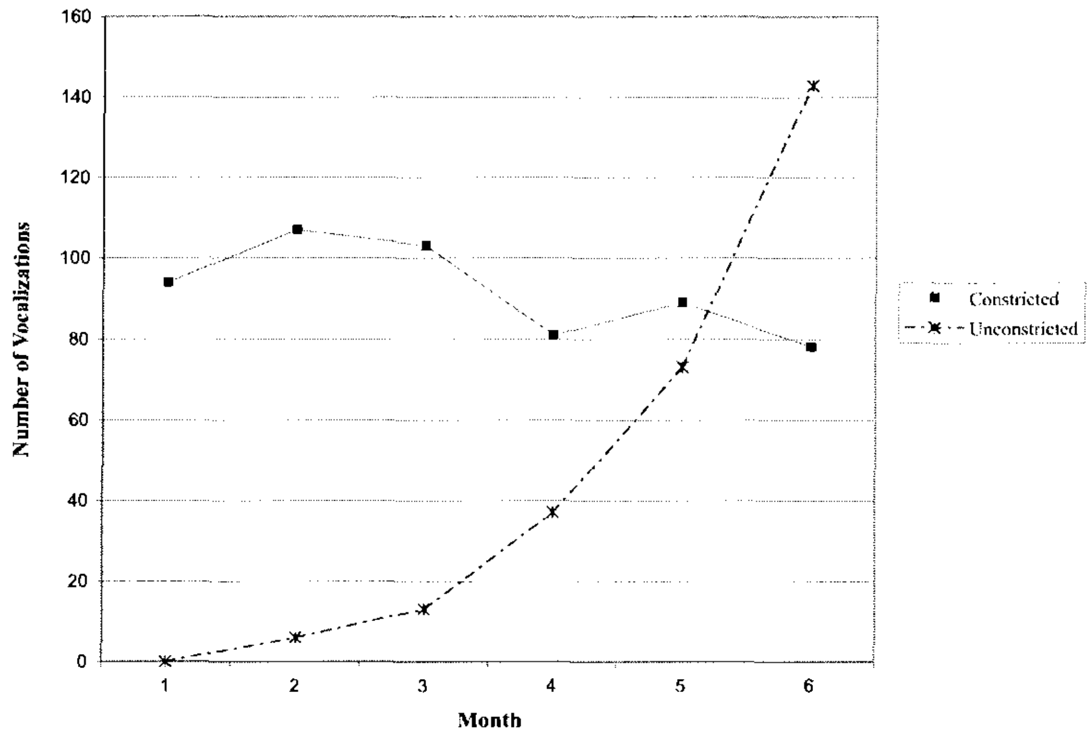
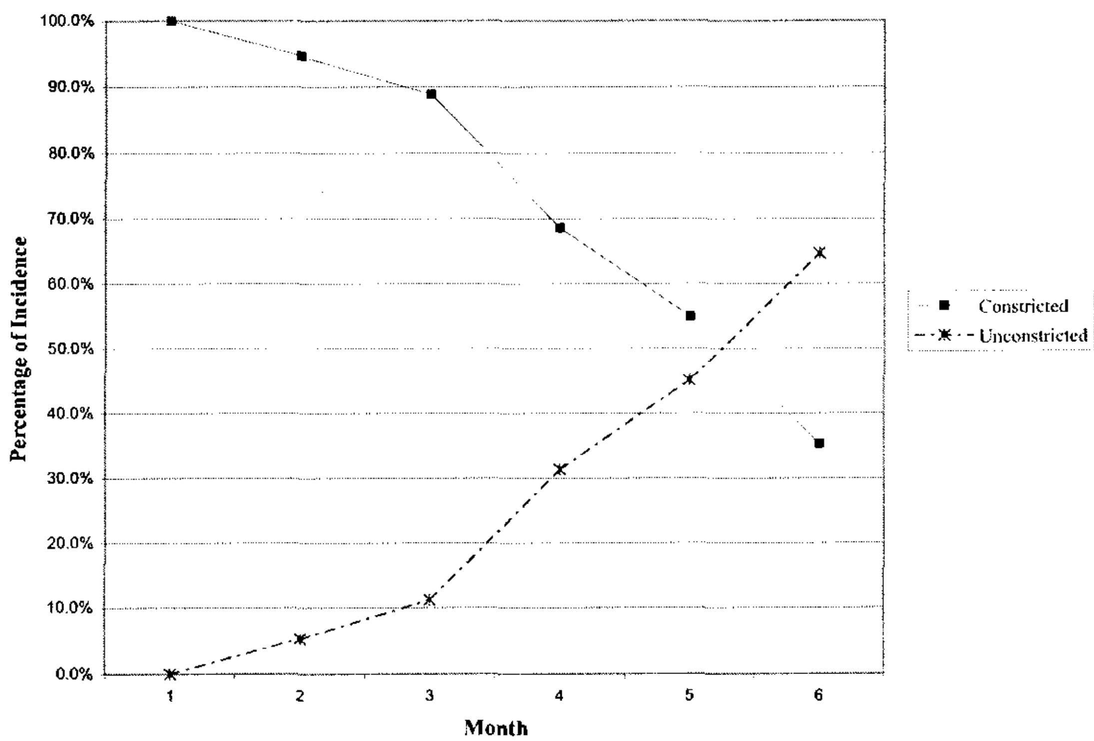


Figure 4-3 shows the trend of the percent of constricted and unconstricted vocalizations in the first six months. This figure shows an inverse correlation of constricted and unconstricted vocalizations over the six-month period. As the percentage of constricted vocalizations decreases from 100% at month 1 to 35% at month 2, the percentage of unconstricted vocalizations increases exponentially from 0% at month 1 to 65% at month 6.

Figure 4-3. Percentage of constricted and unconstricted vocalizations.



There is not a large difference in the percentage of constricted (55%) and unconstricted (45%) vocalizations in month 5. At this point, the default setting of the infant may still be constricted, but the transition towards an unconstricted default setting closer to the infant's ambient language is progressing. The data intersects at a point between the fifth and sixth month when the percentage of unconstricted vocalizations increases to a number greater than the percentage of constricted vocalizations. It is possible that this point marks the onset of a new stage in early infant development when the control required for the production of modal phonation (unconstricted), the most common modality used by adult English-speakers, is attained.

It is interesting to compare these results with the observed onset of babbling, which in this infant was observed to occur in the fourth month of life. According to the presented data, the default setting in the fourth month is constricted. This suggests that early babbled vocalizations produced by this infant (i.e. sequences of consonant-like and vowel-like utterances; MacNeilage & Davis, 1992) are produced with mainly constricted qualities. This finding is contrary to the perceived belief that babbled vocalizations are produced with unconstricted "speech-like" or "normal" phonatory settings (Oller, 1980).

It is important to note that although the default setting appears to have shifted from a constricted setting at month 1 to an unconstricted setting at month 6, the absolute number of constricted vocalizations has remained relatively level over the six-month period. This suggests that the infant is still exploring and playing with constricted settings at this age. When a new unconstricted phonatory setting is acquired, previously acquired constricted settings do not disappear from the infant's repertoire.

In the next section, the incidence and progression of auditorily identified individual phonatory settings is discussed.

4.1.2.1 Progression of phonatory settings

Table 4-3 presents the incidence of vocalizations produced with individual phonatory settings in the first six months of life. The percentage was calculated by comparing the total incidence number of individual phonatory settings to the total incidence number of all phonatory settings occurring in each monthly period. The following abbreviations of each phonatory setting are used in this figure: harsh voice (HV), whisper (W), creaky voice (CV), modal voice (MV), falsetto (F), and breath (B) breathy voice (BV). The incidence of WV was only found in two vocalizations, therefore its incidence will be calculated as a whispery setting (W). The unconstricted setting of breathy voice was absent from the entire sample of infant vocalizations. Breathy voice is produced with abducted vocal folds and an open supralaryngeal vocal cavity. Breathy voice is produced with abducted vocal folds and an open supralaryngeal vocal cavity. It is likely that breath was present in the later months, however it is difficult to identify auditorily and it will be excluded from the ongoing discussion.

Table 4-3. Incidence of individual constricted and unconstricted phonatory settings in the first six months of life.

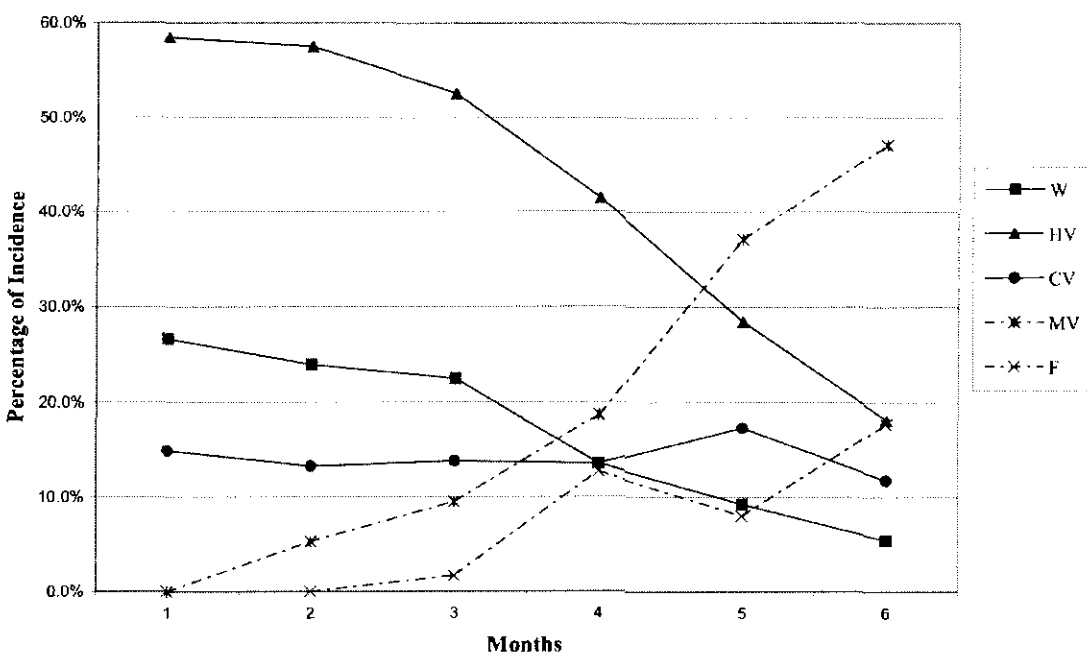
Month	Harsh Voice	Whisper	Creaky Voice	Modal Voice	Falsetto
1	58.5%	26.6%	14.9%	0.0%	0.0%
2	57.5%	23.9%	13.3%	5.3%	0.0%
3	52.6%	22.4%	13.8%	9.5%	1.7%
4	41.5%	13.6%	13.6%	18.6%	12.7%
5	28.4%	9.3%	17.3%	37.0%	8.0%
6	18.1%	5.4%	11.8%	47.1%	17.6%

In the first three months of life, constricted phonatory settings involving the laryngeal constrictor are produced (i.e. harsh voice, creaky voice and whisper). This finding demonstrates that at two weeks of age (i.e. first recording session) the infant was able to manipulate the mechanisms of the laryngeal sphincter to produce a range of constricted settings from an early age. The most frequently produced phonatory regime in the first month is harsh (58.5% of vocalizations), followed by whisper (27% of vocalizations), then creak (15% of vocalizations). Results presented in Stark et al. (1975) also demonstrate that the occurrence of "harsh" and "pharyngeal friction" is high (>50%)

in the "cry" and "discomfort" vocalizations of two infants in the first two months of age. The incidence of whisper and creak in the first months of life is contrary to previous reports by Oller (1980; 2000) which state that "whispering" and "creakiness" settings do not appear until the fifth and sixth month of life.

In the second month, the phonatory range of the infant expands from the production of constricted settings, i.e. harsh voice (59%), whisper (27%) and creak (14%) to the production of an unconstricted setting, i.e. modal voice (5%). Modal voice is the first unconstricted setting to occur is modal voice, though the total incidence number is small in the second (5%) and third (10%) months. The progression of constricted and unconstricted settings in the first six months of life is presented in Figure 4-4.

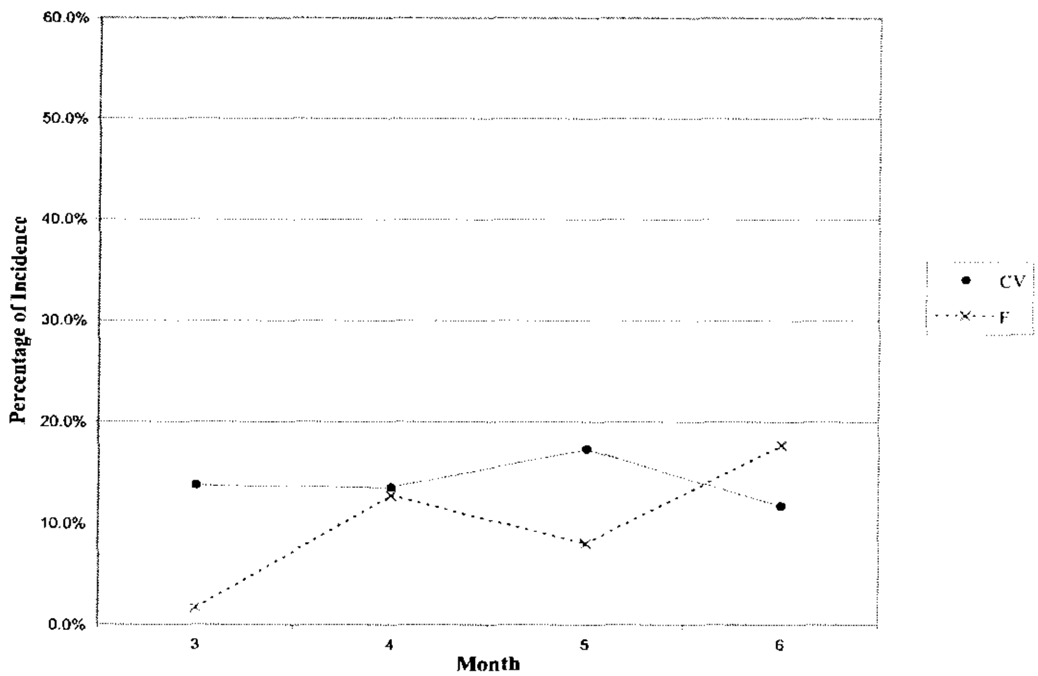
Figure 4-4. Progression of individual constricted and unconstricted phonatory settings in the first six months of life.



In this figure, the percentage of modal voice increases dramatically in the fourth (19%), fifth (37%) and sixth (47%) months. The incidence of falsetto, an unconstricted setting produced with high pitch, is found in the third month (2%). The small percentage (2%) reported in Table 4-2, indicates that this setting is not produced frequently enough to demonstrate significant vocal practice of this setting until the fourth month (13%).

The trend of falsetto (high pitch) in months 3 to 6 seems to be related to the trend observed in creaky voice (low pitch). Both of these settings are defined in relation to pitch (Esling & Harris, 2003). Figure 4-5 presents the relationship of falsetto and creaky voice in months 3 to 6.

Figure 4-5. Progression of falsetto and creaky voice in months 3 to 6.

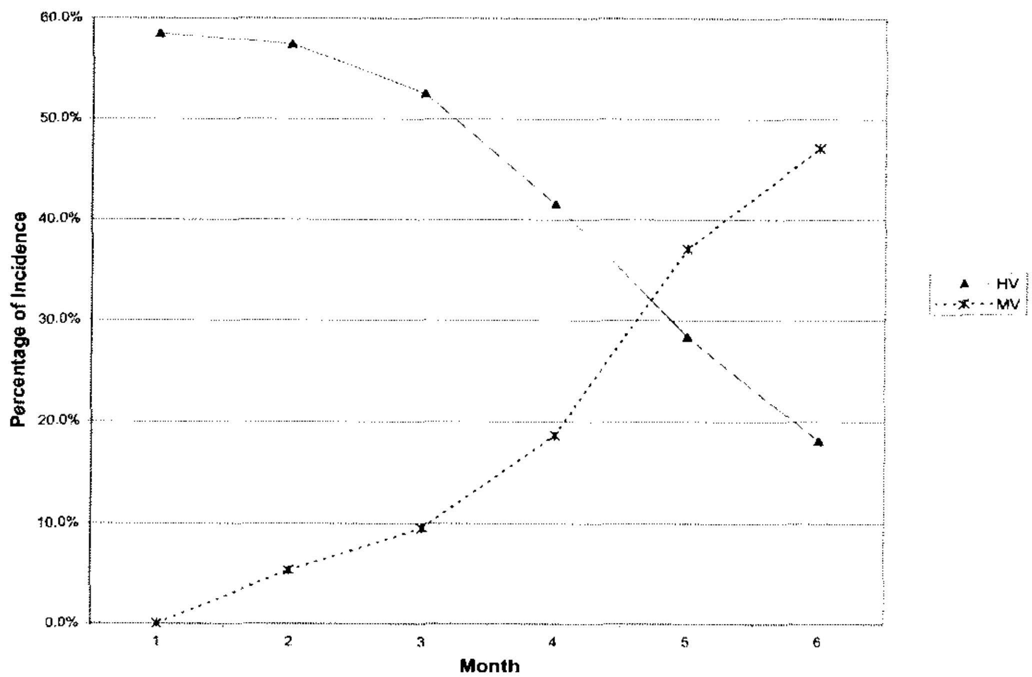


The percentage of falsetto increases from month 3 (2%) to month 4 (13%), decreases slightly from month 4 to month 5 (8%) then increases in the sixth month (18%). The increase in the incidence of falsetto between month 3 and 4 is significant (p<0.05). This pattern of falsetto in the fourth to sixth months seems to be correlated to the increase in the production of creaky voice, which increases from the fourth month (14%) to the fifth month (17%), then decreases in the sixth month (12%).

To summarize, these results demonstrate two important findings: (1) that the infant's phonatory range expands from the production of three constricted settings, to the production of three constricted and two unconstricted settings and (2) that there is a dramatic change in the production of unconstricted settings in months 4 to 6.

The progression of constricted and unconstricted vocalizations seen in Figures 4-2 and 4-3 demonstrates a dramatic increase of unconstricted vocalizations in months 3 to 6. The increase in the incidence of unconstricted settings is illustrated in Figure 4-6, which presents the inverse relationship of harsh voice, the most frequently produced constricted setting, and modal voice the most frequently produced unconstricted setting.

Figure 4-6. Percentage progression of harsh voice and modal voice in the first six months of life.



The percentage of modal voice is seen to increase from 0% to 47%, as the percentage of harsh voice decreases from 59% to 18%. The intersection point of the lines before the fifth month is one month earlier than the point observed in the progression of constricted and unconstricted vocalizations reported in Figure 4-3. The calculation of unconstricted vocalizations data used in this figure included falsetto (i.e. unconstricted high pitch), which is attained later in the six-month period. The intersection points found in both analyses provides an understanding of when certain phonation and pitch features are acquired. Between the fourth and fifth months of life, the infant seems to acquire the ability to produce modal voice, an unconstricted setting, though the ability to produce falsetto, an unconstricted setting involving high pitch, is not yet attained. After the fifth month, the infant has acquired the ability to produce falsetto. At this stage, the infant is able to control the laryngeal features of voice and pitch.

In order to clarify the progression of each phonatory setting over the six-month period, Figures 4-7, 4-8, 4-9, 4-10 and 4-11 are provided. The general trend of constricted settings is to decline over time. This trend is seen in Figures 4-7 and 4-8 as harsh voice and whisper both decrease. Creaky voice does not change greatly over the six-month period. The presence of creaky voice throughout the six months of life may be due to its presence in the ambient language of the child. In most English dialects, creaky voice is often produced at the end of sentences (Laver, 1980). The presence of creak in the vocalizations of a two-week-old infant has not been reported in any study.

Figure 4-7. Incidence progression of whisper over the first six months of life.

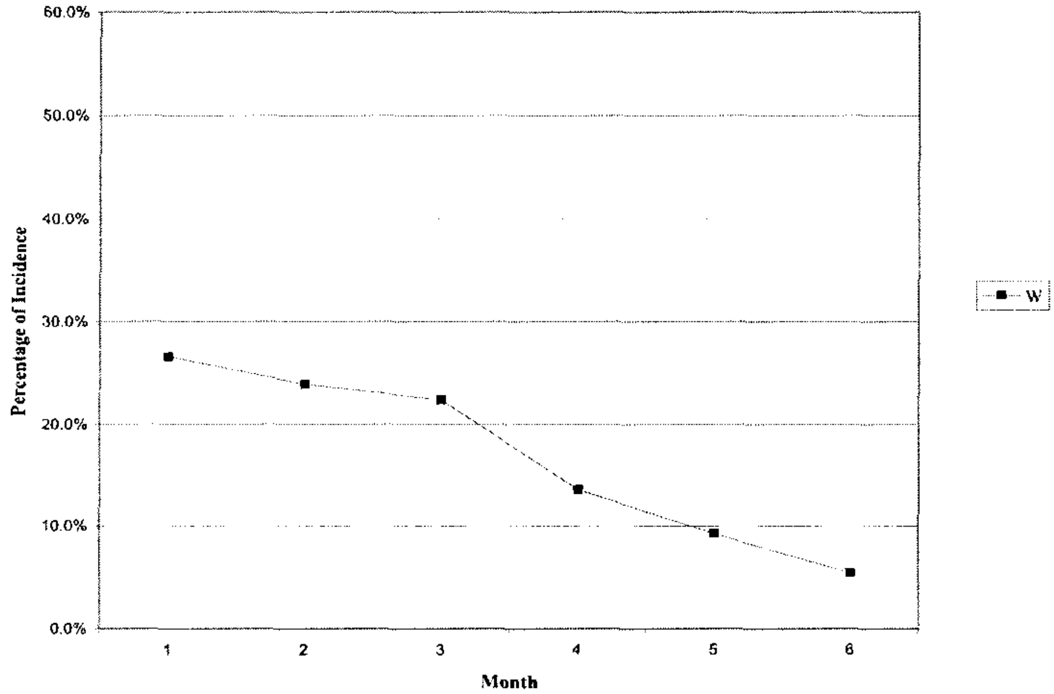


Figure 4-8. Incidence progression of harsh voice over the first six months of life.

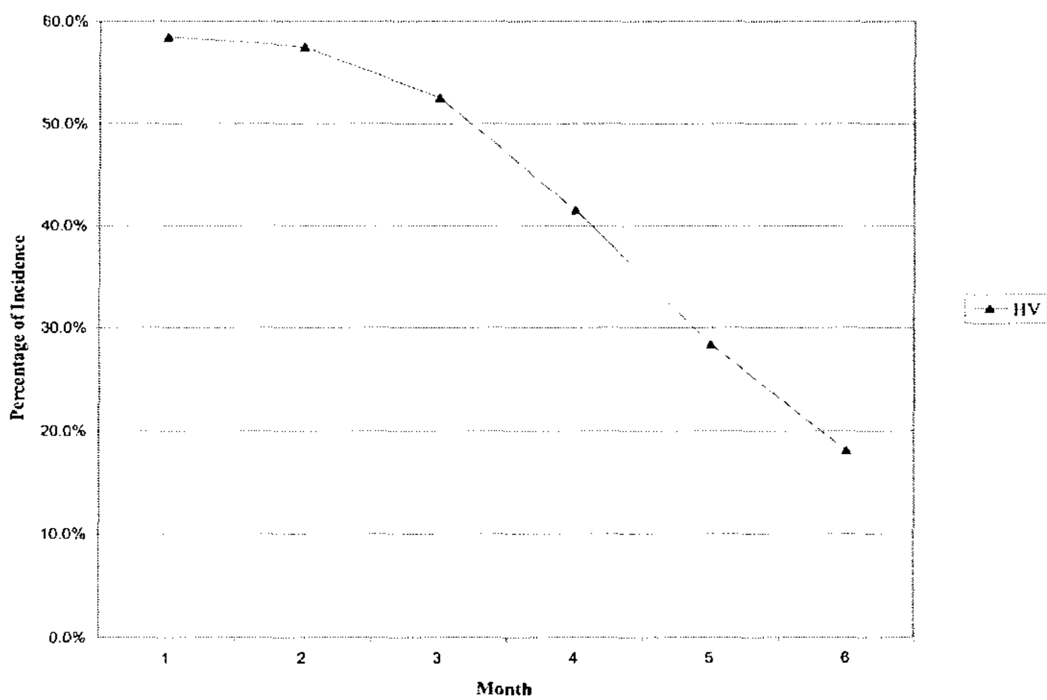


Figure 4-9. Incidence progression of creaky voice over the first six months of life.

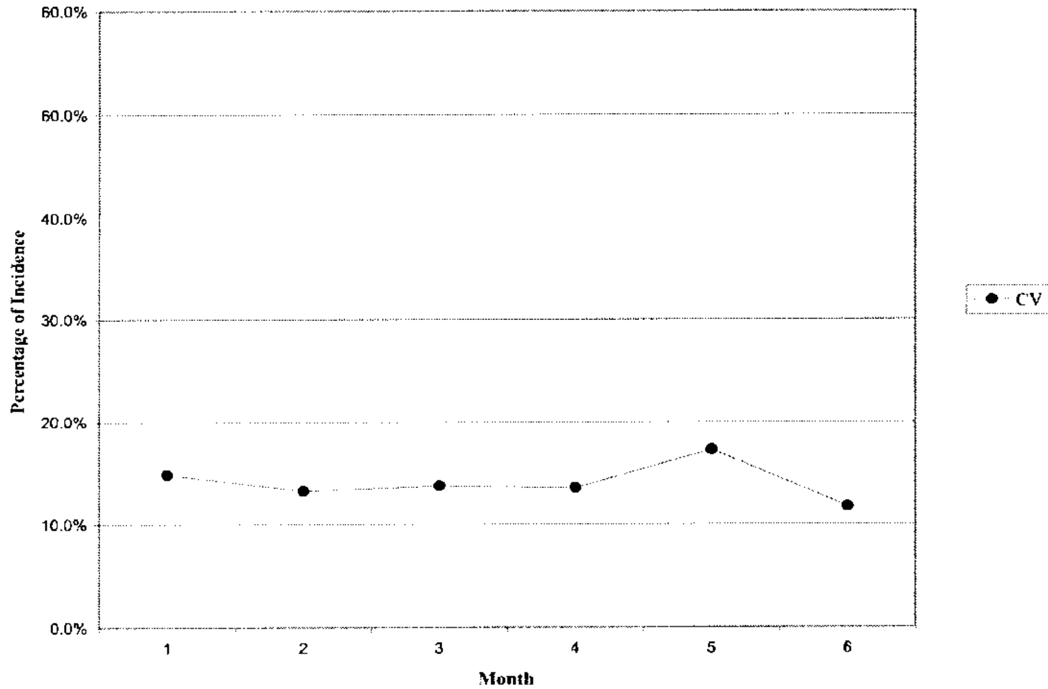


Figure 4-10. Incidence progression of modal voice over the first six months of life.

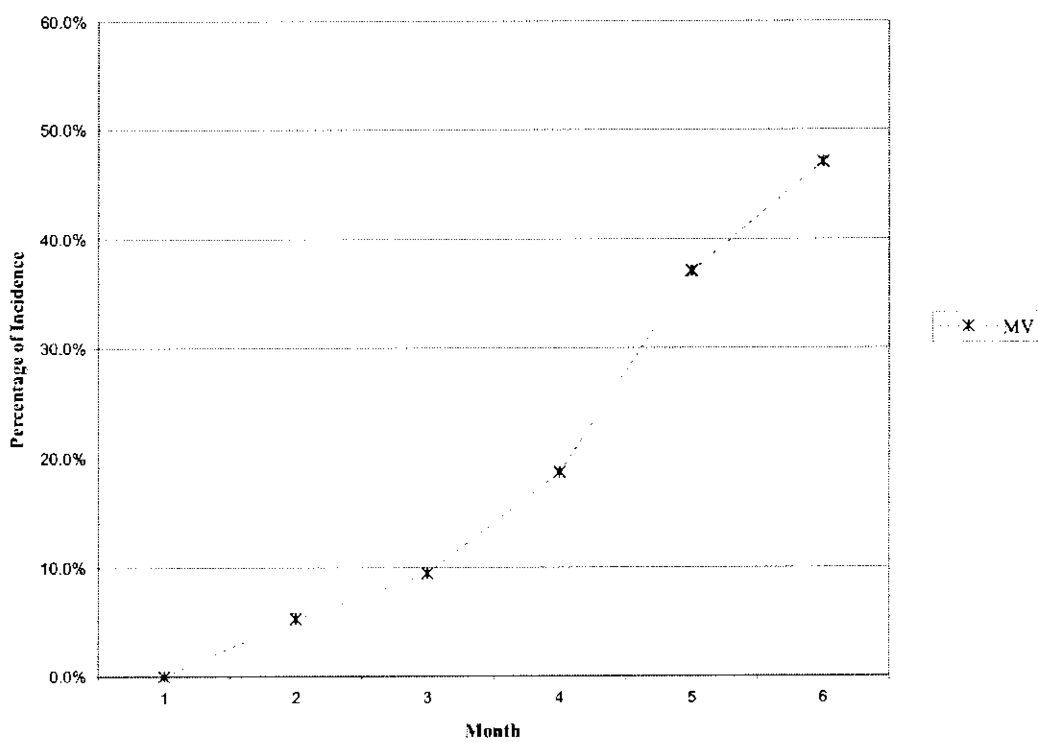
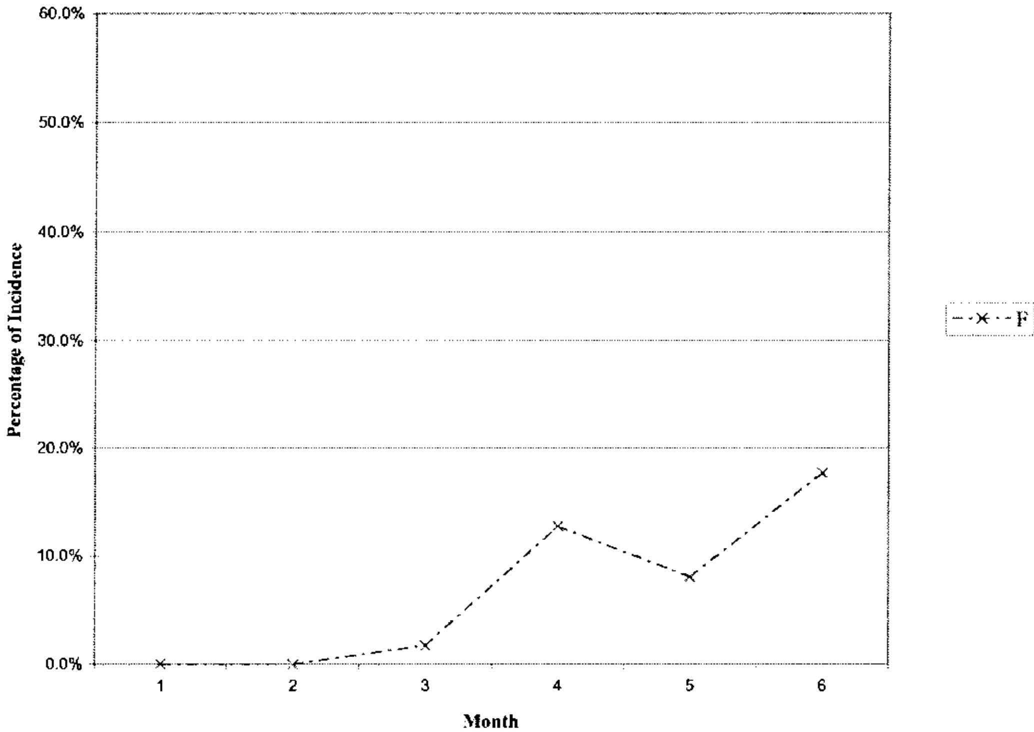


Figure 4-11. Incidence progression of falsetto over the first six months of life.



The close-to-linear increase in unconstricted vocalizations, as previously shown in Figure 4-4, is seen in the progression modal voice presented in Figure 4-10. This increase towards a mainly modal phonation is more closely related to the child's ambient language than the production of mainly constricted settings. The increase in the incidence of falsetto is indicated in Figure 4-11. The general trend of falsetto shown in months 3 to 6 (see Figure 4-5) has been discussed above. In the fifth month, the production of creak was shown to increase in proportion to the decrease in falsetto. The presence of falsetto in the fourth month has not been previously noted in studies. Oller (1980) and Roug et al. (1989) have observed falsetto productions in the sixth through eighth month, though this observation was not quantified.

This section reports findings that identify the incidence and the progression of individual phonatory settings in infant vocalizations in the first month of life. The next section reports results from the auditory analysis of three levels of pitch (i.e. low, mid and high).

4.1.3 Pitch

Since the majority of vocalizations produced in the first five months of life are constricted, this section will focus on the auditorily identified pitch level of constricted vocalizations. Table 4-4 presents the percentage of low, mid and high pitch constricted vocalizations calculated by comparing the total percentage of individual pitch levels by the total number of constricted vocalizations.

Table 4-4. Incidence of low, mid and high pitch in constricted vocalizations.

Month	Total Number of Constricted Vocalizations	Percentage of Constricted Low Pitch Vocalizations	Percentage of Constricted Mid Pitch Vocalizations	Percentage of Constricted High Pitch Vocalizations
1	94	53.2%	35.1%	11.7%
2	107	52.3%	28.2%	19.6%
3	103	53.4%	25.2%	21.4%
4	81	44.4%	34.6%	21%
5	89	44.9%	33.7%	20.2%
6	78	43.9%	30%	25.6%

During the first three months of this study, constricted vocalizations produced with low pitch represented greater than half of all constricted vocalizations produced; 53% at month 1, 52% at month 2 and 53% at month 3. Following this relatively stable period, the proportion of low pitch constricted vocalizations decreased slightly to 45% at month 4 and remained at this level for months 5 and 6. According to observations of the adult pharynx and larynx, the mechanism of the laryngeal constrictor involved in the production of constricted settings, shortens the length of the vocal tract, thereby predisposing low pitch (Esling, 2002). In infancy, constricted vocalizations indicate the same predisposition to low pitch. The tendency towards constricted vocalizations produced with low pitch remains over the six-month period.

Constricted vocalizations produced with mid pitch were also evident throughout the six-month period. At month 1, the proportion of mid pitch vocalizations was 35%, 29% at month 2 and 25% at month 3. This downward trend was reversed in month 4 when mid pitch constricted vocalizations returned to 35% and remained above 30% for month 5 and 6. Mid pitch represented the second most frequent pitch level seen during the first six months of life in this study.

The percentage of high pitch constricted vocalizations was the lowest of the three pitch levels produced during the six-month period. At month 1 the value was 11% increasing to 28% at month 2 and remaining close to this value until month 6. The progression of low, mid and high pitch levels in constricted vocalizations over the six-month period is presented in Figure 4-12.

The time of the greatest change in pitch appears to be between the third and fourth month when the percentage of low pitch vocalizations decreases and the percentage of mid pitch vocalization increases. From the fourth to sixth months the proportion of low, mid and high pitch constricted vocalizations remains essentially the same with the exception of a slight increase in the percentage of high pitch vocalizations. The finding that high pitch is present in infant vocalizations at six months confirms observations of high-pitched "pulses", "squeals", "shrieks" or "screams" by Buder, Oller and Magoon (2003), Koopmans-van Beinum and van der Stelt (1986) and Oller (1980; 2000).

Contrary to these observations is the finding of high-pitched vocalizations throughout the first six months of life.

At around four months the infant's phonatory range expands to include unconstricted phonation settings, including falsetto, a setting involving high pitch. In the production of falsetto, the vocal folds adduct and stretch longitudinally. This mechanism requires a certain level of glottal control.

Figure 4-12. Percentage of constricted vocalizations according to pitch level.

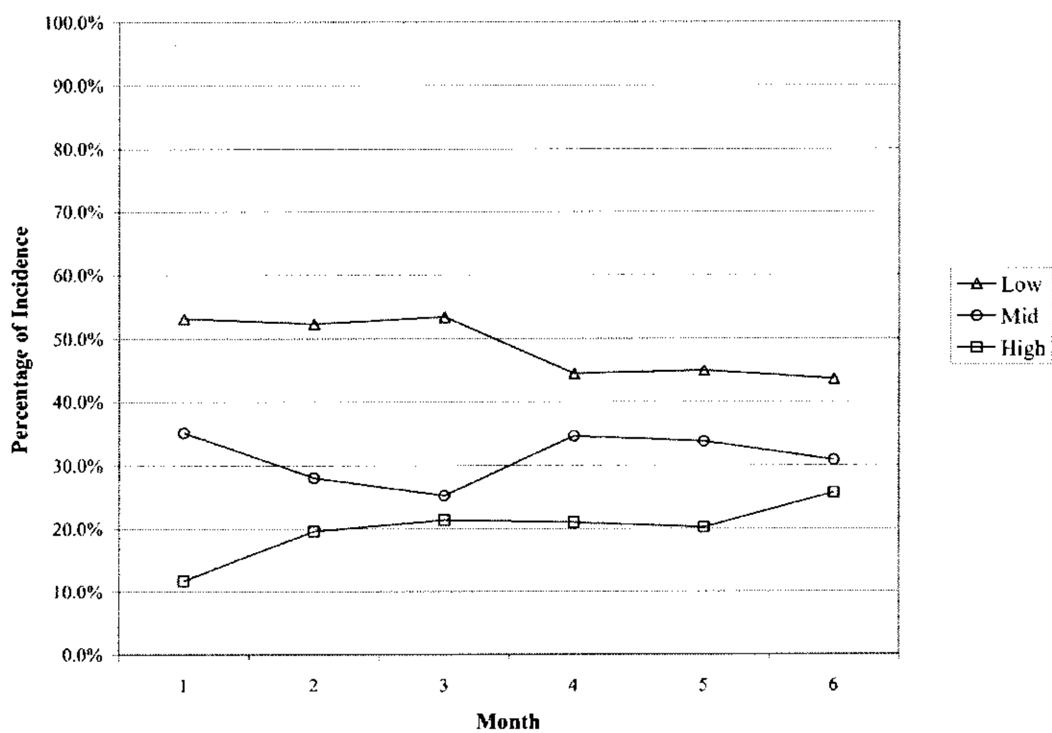


Table 4-5 presents the percentage and number of constricted and unconstricted high pitch vocalizations.

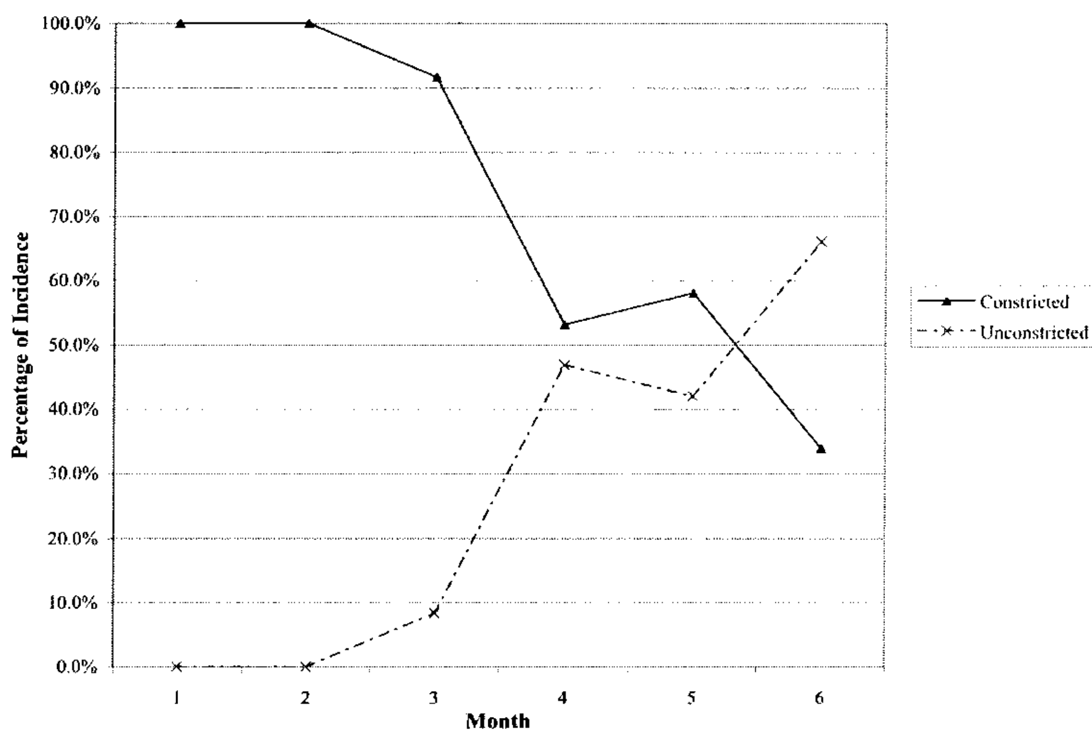
Table 4-5. Number and percent (in parentheses) of high pitch constricted and unconstricted vocalizations.

Month	Total Number of High Pitch Vocalizations	Number of Constricted High Pitch Vocalizations (%)	Total Number of Unconstricted High Pitch Vocalizations (%)
1	11	11 (100%)	0 (0%)
2	21	21 (100%)	0 (0%)
3	24	22 (92%)	2 (8%)
4	32	17 (53%)	15 (47%)
5	31	18 (58%)	13 (42%)
6	59	20 (34%)	39 (66%)

In the first two months, 100% of high-pitched vocalizations recorded were constricted. At three months, the first appearance of unconstricted high pitch vocalizations is reported. In month 3, the percent of high pitch unconstricted vocalizations is not significant (8%) as only two occurrences of this setting were produced. In the fourth month, there is a large increase in the percent of unconstricted high-pitched vocalizations. The percentage of constricted vocalizations decreases from 92% at three months to 53% at four months while the percentage of unconstricted vocalizations increases dramatically from 8% to 50%. By six months, the proportion of unconstricted high pitch vocalizations at 66% of the total high pitch vocalizations has overtaken constricted high pitch vocalizations (34%). This finding suggests that the control over the horizontal glottal mechanisms (i.e. vocal fold adduction and stretching) is attained by the six month of life. This increase in the percentage of unconstricted high pitch vocalizations in comparison to constricted high pitch vocalizations is depicted in Figure 4-13.

These results indicate that in early infancy high pitch always entails the involvement of the laryngeal constrictor. This finding suggests that there is a close interaction between the physiological mechanisms of the laryngeal constrictor and the mechanisms involved in the production of high pitch (i.e. larynx raising). It is unclear from these results, whether or not the horizontal plane of the glottis (i.e. vocal fold adduction and stretching) is involved in the production of early high pitch constricted vocalizations.

Figure 4-13. Progression of unconstricted high pitch in comparison to constricted high pitch.



4.1.4 Summary

This section discussed the incidence of phonatory settings and pitch identified in 824 infant vocalizations produced in the first six months of life. A number of important findings were reported from auditory analysis one. The greatest percent of vocalizations produced in the first months of life are constricted and low pitch. Unconstricted phonation is not produced frequently in the first months of life. Therefore, the only phonatory settings that can be explored in early infancy are whisper, harsh voice and creaky voice. The primary articulator in these settings is the vertical laryngeal constrictor, which is engaged in varying degrees from extreme to slight. Harsh voice (extreme constriction) is the most frequently produced constricted setting. In addition to the degree of laryngeal constriction, the pitch level of vocalizations is explored in infancy as evidenced by the production of low-, mid- and high-pitched constricted vocalizations throughout the six-month period.

The phonatory repertoire of the infant expands as a wider range of phonatory settings including modal voice and falsetto is produced in the fourth month. The trend from the production of predominantly constricted settings to the production of predominantly unconstricted settings is seen in the tendencies of individual settings, particularly the inverse correlation of the incidence of harsh voice and modal voice. At six months, the infant's ability to produce a greater range of phonatory settings with greater frequency suggests that the productive capability and control of the laryngeal mechanisms has increased. The ability to produce unconstricted settings with high pitch, which requires control over glottal features, increases to 66% by the sixth month of life.

The observation of the intersection points on the graphs presenting the inverse progression of constricted and unconstricted vocalizations, and of modal voice and of harsh voice provided an understanding of when certain phonation and pitch features are acquired. These results indicate that there are two stages in the development of phonation and pitch. The first stage occurs between the first and the end of the fourth month of life. During this stage, the infant acquires the ability to produce modal voice, an unconstricted setting. In the second stage, occurring between the end of the fourth month and the end of the sixth month, the infant acquires the ability to produce falsetto, an unconstricted setting involving high pitch. By the sixth month, the infant is able to integrate the laryngeal features of voice and pitch.

The next section will present the results of analysis two, the auditorily based and acoustic analysis of range exploration.

4.2 Analysis Two: Range Exploration

Range exploration is defined as the instance of within-utterance alternations between phonatory settings. In this analysis, the duration of phonatory features during alternations of 20 randomly selected vocalizations for months 1 to 6 (n=120) were calculated by means of auditorily based and acoustic analysis. In section 4.2.1, perceptual methods, based on the bi-level model of the larynx, were used to judge the phonation settings within vocalizations and the number of alternations occurring within the vocalizations. The results of the acoustic analysis, including duration of each vocalization and of the phonatory alternations within the vocalizations is presented in section 4.2.2. Section 4.2.3 presents spectrograms demonstrating range exploration. A summary of the findings is presented in section 4.2.3.

4.2.1 Phonatory alternations

For each of the six-monthly periods, 20 random vocalizations (n=120) were selected for the analysis of range exploration. In this data, range exploration is defined as the alternation of phonatory settings within an utterance. The change from one phonatory setting to another is calculated as one alternation. The production of alternations requires the control over laryngeal mechanisms involve in the production of phonation and pitch. The total incidence of phonatory alternations within each vocalization in the first six months of life is presented in Table 4-6.

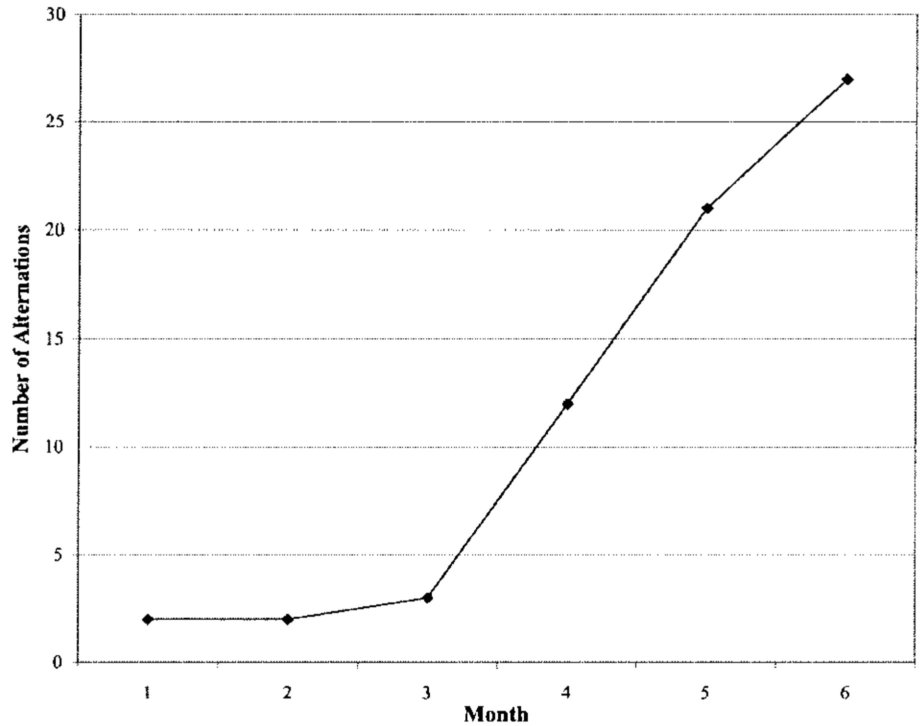
Table 4-6. Incidence of alternations within vocalizations in the first six months of life.

Month	Total Number of Vocalizations	Incidence of Alternations within Vocalizations
1	20	2
2	20	2
3	20	3
4	20	12
5	20	21
6	20	27

The results presented in Table 4-6 demonstrate that infants actively produce phonatory alternations in the first six months. In the first three months, the number of alternations only a small amount of alternations are produced. The incidence of two within vocalization alternations was found at months 1 and 2, and three within vocalization alternations at month 3. In months 4-6, a large increase in the incidence of phonatory alternations from 12 at month 4 to 27 at month 6 was noted. Figure 4-14 displays the increase in the incidence of alternations over the six-month period.

The Independent-Samples T test determined that the increase between the incidence of alternations in months 3 to 4 and 4 to 5 is significant ($p<0.05$). The increase between months 1 to 2 and 5 to 6 is not significant. The dramatic increase between months 1 and 6 is also significant ($p<0.05$).

Figure 4-14. Increase in phonatory alternations within vocalizations in the first six months of life.



This result, demonstrating that range exploration increases in the first six months of life, suggests three main findings: (1) the incidence of within-utterance alternations between phonatory settings is increasing, (2) the productive capability of the infant is increasing, (2) the incorporation of the laryngeal parameters of phonation and pitch into the infant's vocal repertoire is increasing.

In the next section, the duration of phonatory settings within the sample of vocalizations is presented.

4.2.2.2 Duration

To examine the developmental changes in the quantitative parameters of infant vocalizations, the total duration and the mean duration was calculated for each sample of 20 vocalizations for each month. It is important to note that all vocalizations, including "reflexive" utterances, produced by the infant were considered in this measurement. Table 4-7 presents the total duration of vocalizations in the first six months of life.

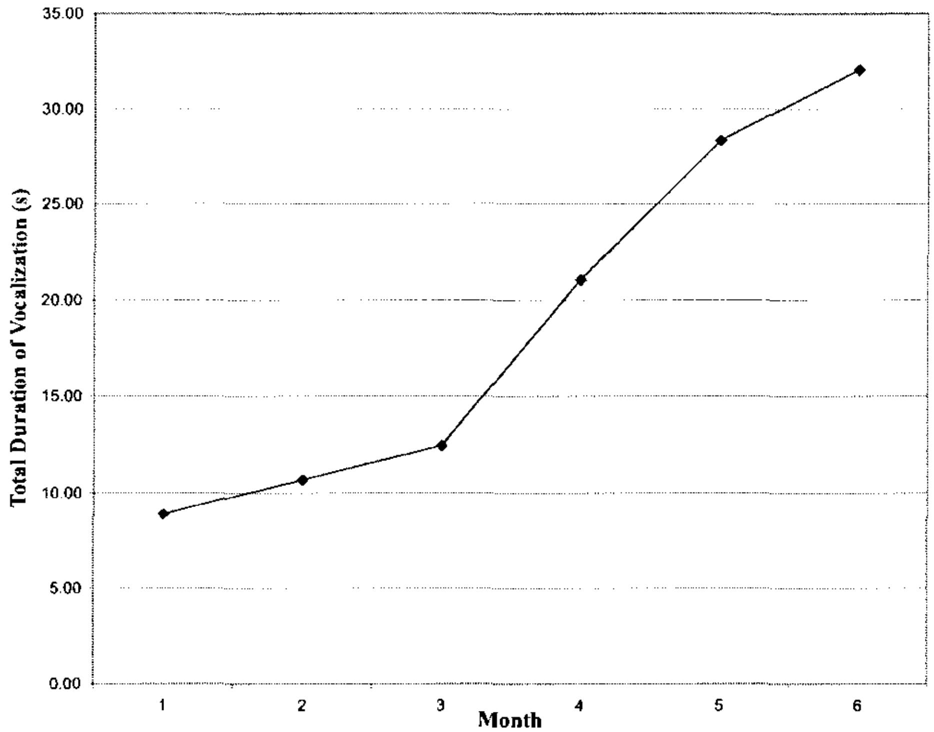
Table 4-7. Total duration of sampled vocalizations in the first six months of life (s).

Month	Total Duration of Vocalizations
1	8.89 s
2	10.69 s
3	12.44 s
4	21.05 s
5	28.34 s
6	32.07 s

In the first three months, the total duration of the sample of 20 vocalizations for each month is less than 13 s. In the next three months, the total duration of vocalizations nearly doubles from 12.44 s in months 4 to 21.05 s and increases steadily to 28.34 s in month 5 and 32.07 s in month 6. Figure 4-15 displays the finding that the duration of vocalizations increases in the first six months of life.

The preceding results will demonstrate that the mean duration of vocalizations increases over time with a significant surge between the third and fourth months ($p<0.05$).

Figure 4-15. Total duration of vocalizations in the first six months of life (s).



The mean duration and standard deviation of vocalizations in the first six months of life is presented in Table 4-8.

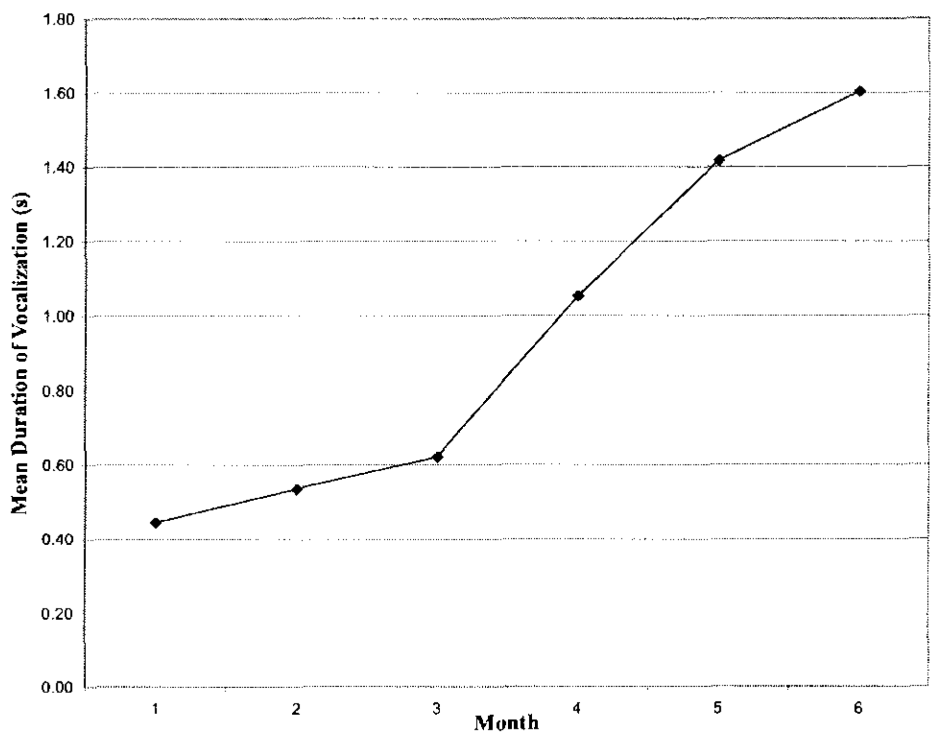
Table 4-8. Mean duration and standard deviation in the first six months of life (s).

Month	Mean Duration	Standard Deviation
1	0.44 s	0.228
2	0.53 s	0.218
3	0.62 s	0.300
4	1.05 s	0.600
5	1.42 s	1.021
6	1.60 s	0.856

In the first three months, the mean duration of 0.44 s at month 1, 0.53 s at month 2 and 0.62 s at month 3, does not change significantly. A significant increase in the mean duration from 0.62 s at month 3 to 1.05 s ($p<0.05$) and a steady increase from months 4 to 6 can be seen. Figure 4-16 displays the increase in mean duration. The standard deviation at five months shows a 1.021 s range of deviation from the mean duration of 1.42 s. This result demonstrates that at five months the infant is experimenting with the parameter of duration, producing increasingly longer vocalizations.

During this time, the infant rib cage develops into an adult-like configuration and neuromuscular control of the intercostal and diaphragm muscles emerges (Wermke et al., 2002). A dramatic increase in the mean length of vocalization from 0.2 – 0.6 s at one month to 1.5 s at six months has been noted in numerous studies (Delack & Fowlow, 1978; Kent & Murray, 1982; Oller, 2000; Stark, 1993; Vihman, 1996).

Figure 4-16. Mean duration of vocalizations in the first six months of life (s).



The mean duration of vocalizations, including "vegetative" sounds has not been previously calculated. The average duration of vocalizations produced in months 4 to 6 (1.05 s, 1.42 s and 1.60 s) presented in this study is longer than previous reports. The mean duration of infant vocalizations reported in previous studies, which exclude vegetative vocalizations, is less than 0.4 s (Laufer & Horii, 1976; Delack & Fowlow, 1978).

In order to provide further findings on the development and exploration of phonation and pitch in infancy the duration proportion of each phonatory setting within vocalizations was calculated with a spectrographic analysis.

4.2.2.1 Duration of phonatory alternations

Table 4-9 presents the total duration of phonatory settings within vocalizations over the six-month period. In the first month, only constricted settings are produced. The total duration of the proportion of vocalizations produced with harsh voice is the highest at 4.83 s. Creaky voice is the next highest at 2.09 s and then whisper at 1.97 s. Unconstricted settings are not produced in the first month of life. At two months, an insignificant total duration of modal voice is produced at 0.14 s. The incidence of falsetto was not found until the fifth month when a total of 1.53 s is found.

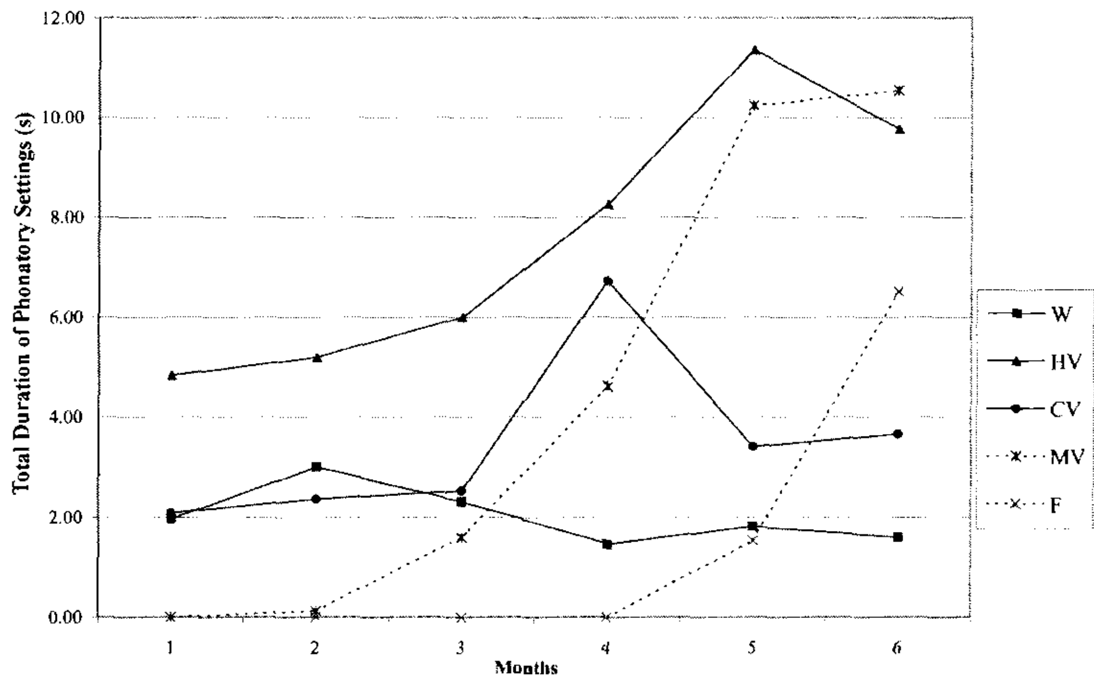
Table 4-9. Total duration of phonatory settings within vocalizations in the first six months of life (s).

Month	W	HV	CV	MV	F
1	1.97 s	4.83 s	2.09 s	0.00 s	0.00 s
2	3.00 s	5.19 s	2.37 s	0.14 s	0.00 s
3	2.32 s	5.99 s	2.54 s	1.60 s	0.00 s
4	1.47 s	8.25 s	6.72 s	4.61 s	0.00 s
5	1.81 s	11.35 s	3.41 s	10.24 s	1.53 s
6	1.60 s	9.77 s	3.66 s	10.54 s	6.50 s

Figure 4-17 presents the progression in the total duration of phonatory settings. The most significant finding is the dramatic increase in the total duration of modal voice from

0.14 s in month 1 to 10.54 s in month 6. Two periods of increase in this progression is between the second (0.14 s) to third month (1.6 s) and the fourth (4.61 s) to fifth month (10.24 s). At the fifth month, the duration of harsh voice decreases as the production of modal voice increases. An increase in the total duration of falsetto in the fifth to sixth month is shown. A dramatic surge in the production of creaky voice at month 4 is likely related to the practice of this setting in combination with other parameters such as duration and intensity. The total duration of whisper remains relatively stable.

Figure 4-17. Total duration of phonatory settings within vocalizations in the first six months of life (s).

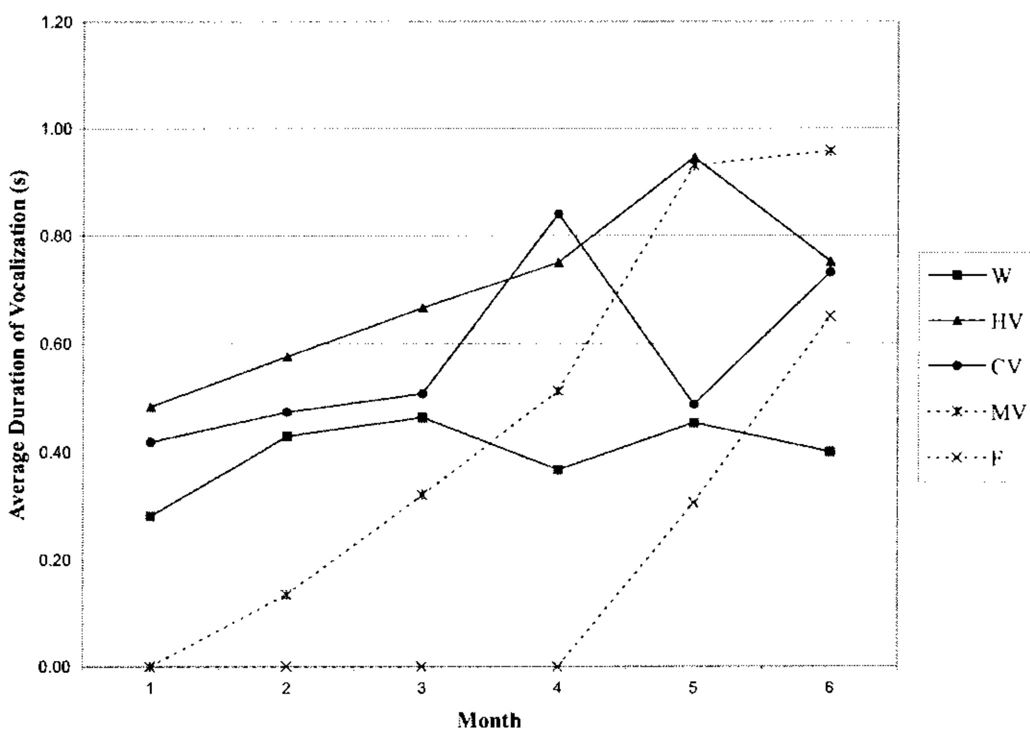


The mean durations of phonatory settings are presented in Table 4-10. Previous results in this study have suggested that the incidence of harsh voice decreases to a proportion less than that of modal voice by six months of age. The result shown in Table 4-10 suggests that although the incidence of harsh voice decreases as the incidence of modal voice increases over the six-month period, the mean duration of harsh voice at six months is significant. This indicates that infants still produce constricted settings at six months. The trend in this data is shown in Figure 4-18.

Table 4-10. Mean duration of phonatory settings within vocalizations in the first six months of life (s).

Month	W	HV	CV	MV	F
1	0.28 s	0.48 s	0.42 s	0.00 s	0.00 s
2	0.43 s	0.58 s	0.47 s	0.14 s	0.00 s
3	0.46 s	0.67 s	0.51 s	0.32 s	0.00 s
4	0.37 s	0.75 s	0.84 s	0.51 s	0.00 s
5	0.45 s	0.95 s	0.49 s	0.93 s	0.31 s
6	0.40 s	0.75 s	0.73 s	0.96 s	0.65 s

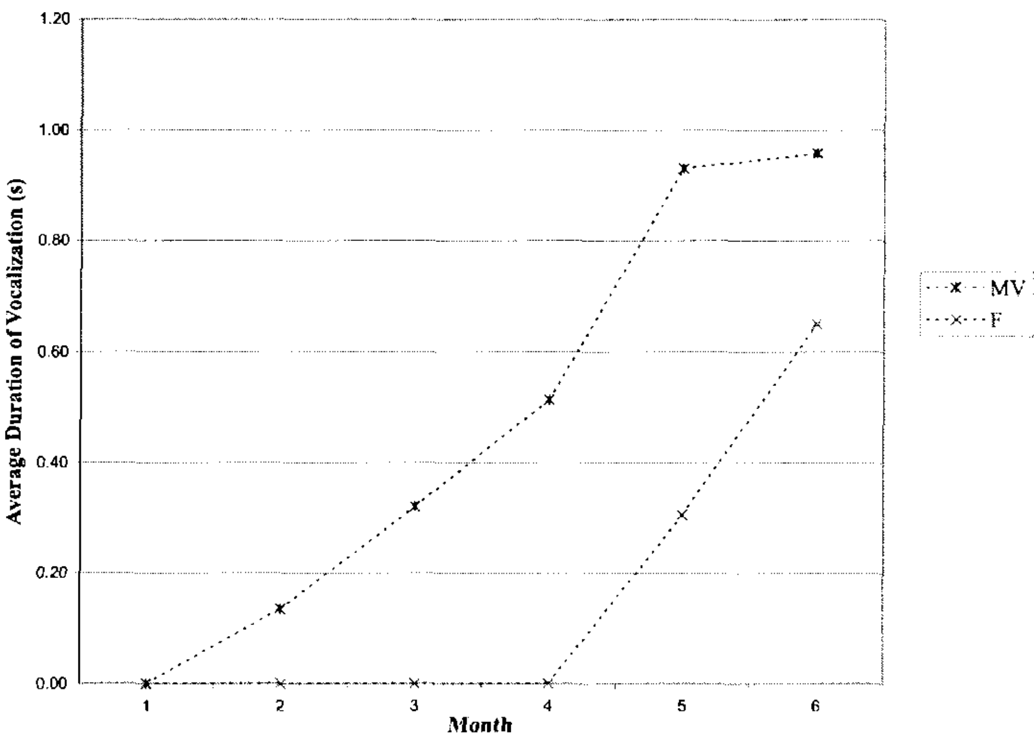
Figure 4-18. Progression of mean duration of phonatory settings in the first six months of life (s).



The mean duration of harsh voice, creaky voice, modal voice and falsetto increase. The mean duration of whisper remains steady ranging from 0.28 s to 0.45 s. This provides an indication that the type of vocalizations produced with whisper. In this study, whispered vocalizations were identified as voiceless "coughs" and "grunts", considered "vegetative" in previous studies.

The most significant increase in mean duration over the six-month period is seen in modal voice and falsetto, highlighted in Figure 4-19. The greatest increase in modal voice is from 0.51 s at month 4 to 0.91 s at month 5. Falsetto is not produced until month 5 at 0.31 s, though significantly increases 0.65 s at month 6. The increase in the mean length of unconstricted settings suggests that the infant is gaining control of laryngeal parameters.

Figure 4-19. Mean duration of unconstricted settings in the first six months of life (s).



The results discussed above demonstrate that the phonatory repertoire of infants expands dramatically in the fourth month of life to include settings that require control over laryngeal features. At this time, an increase in the incidence of range exploration is also found. These results suggest that control of laryngeal features is attained through productive practice of phonation and pitch. The proliferation of phonatory settings in the first six months of life is presented in Figures 4-20 to 4-25. These figures compare the total duration of vocalizations (x-axis) with the total duration of individual phonatory settings (y-axis) for each month. When the total duration of a vocalization (e.g. 1.3 s) equals the total duration of one phonatory setting (e.g. CV = 1.3 s), the vocalization points fall along a diagonal line. In these vocalizations, no phonatory alternations occur as only one phonatory setting is produced.

Figure 4-20. Total duration of vocalizations in comparison to the total duration of phonatory settings within vocalizations at one month (s).

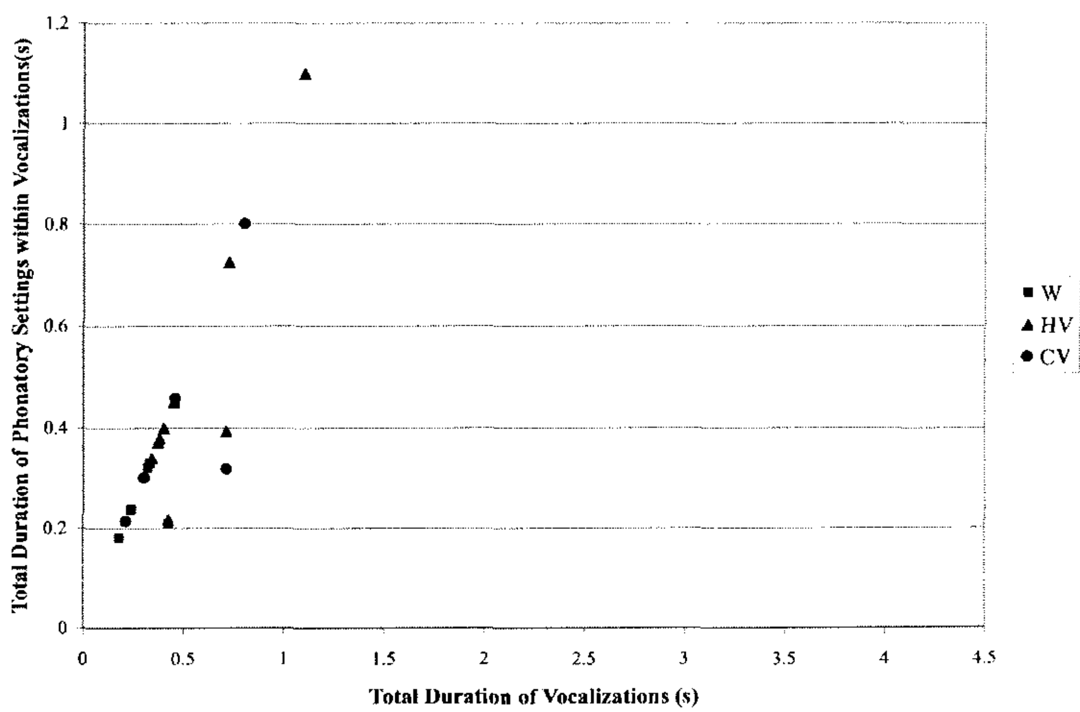
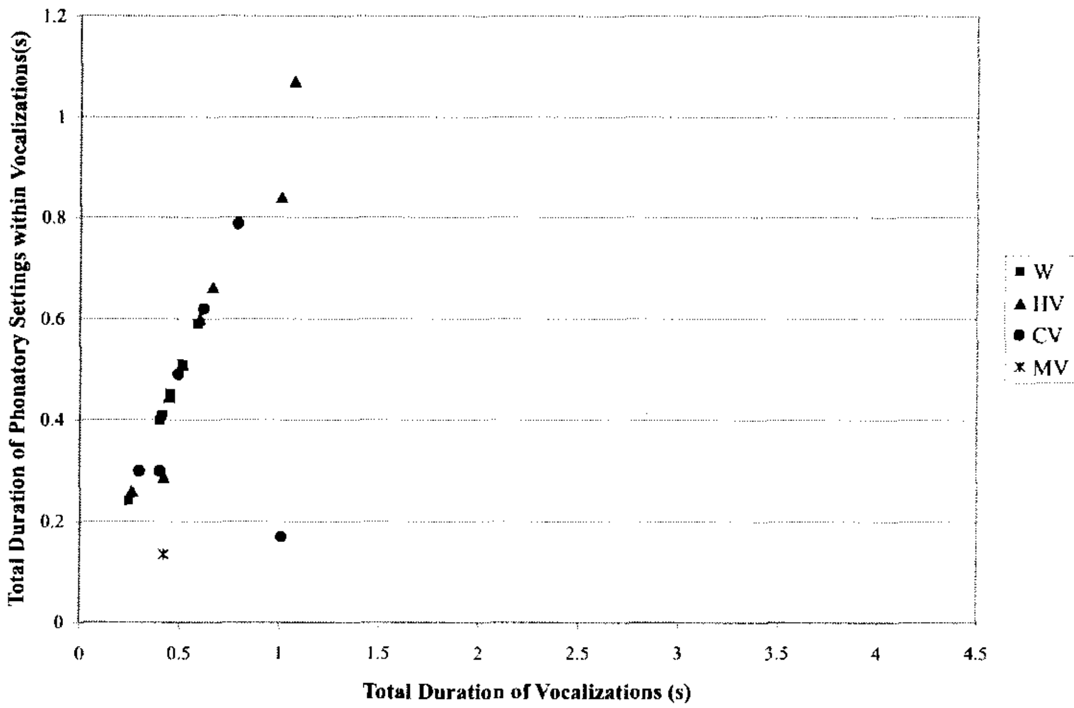


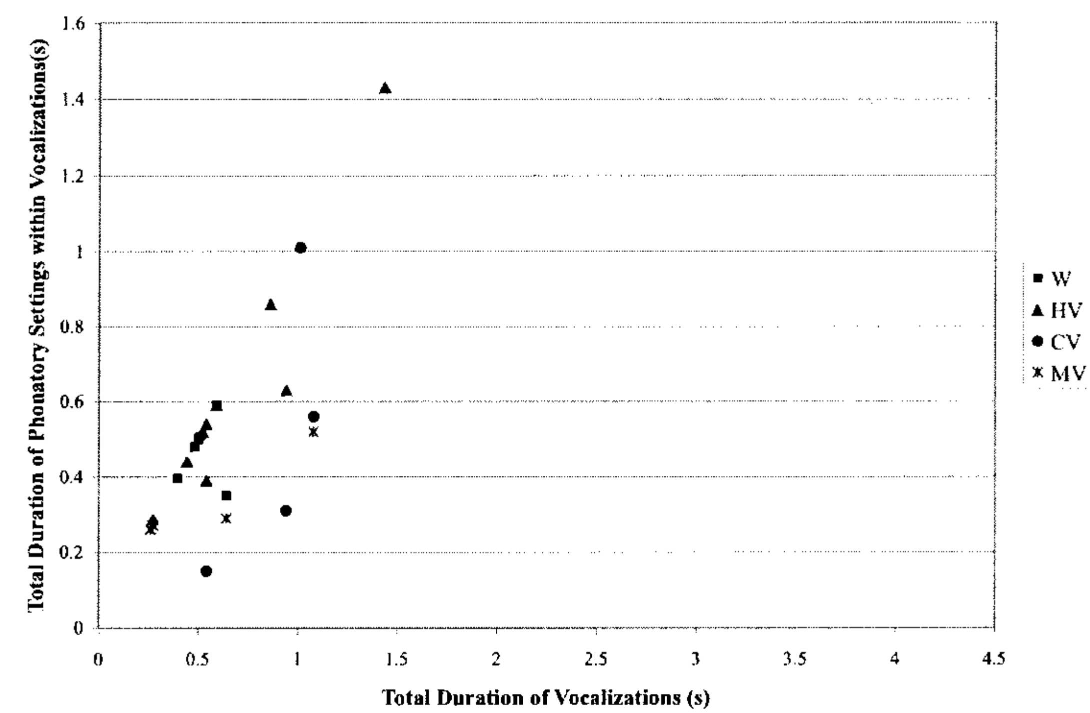
Figure 4-21. Total duration of vocalizations in comparison to the total duration of phonatory settings within vocalizations at two months (s).



In months 1 and 2, displayed in Figures 4-20 and 4-21, a high concentration of vocalizations produced with only one constricted phonatory setting is located below 0.5 s at month 1 and 0.75 s at month 2. The incidence of range exploration is low in month 1 and does not increase in month 2 as seen in the linear progression of vocalization points in these figures. A total of two vocalizations out of the sampled 20 are produced with one alternation between two constricted settings in months 1 and 2. The production of an unconstricted setting (i.e. modal voice) is only produced in one vocalization for a short duration (0.45 s).

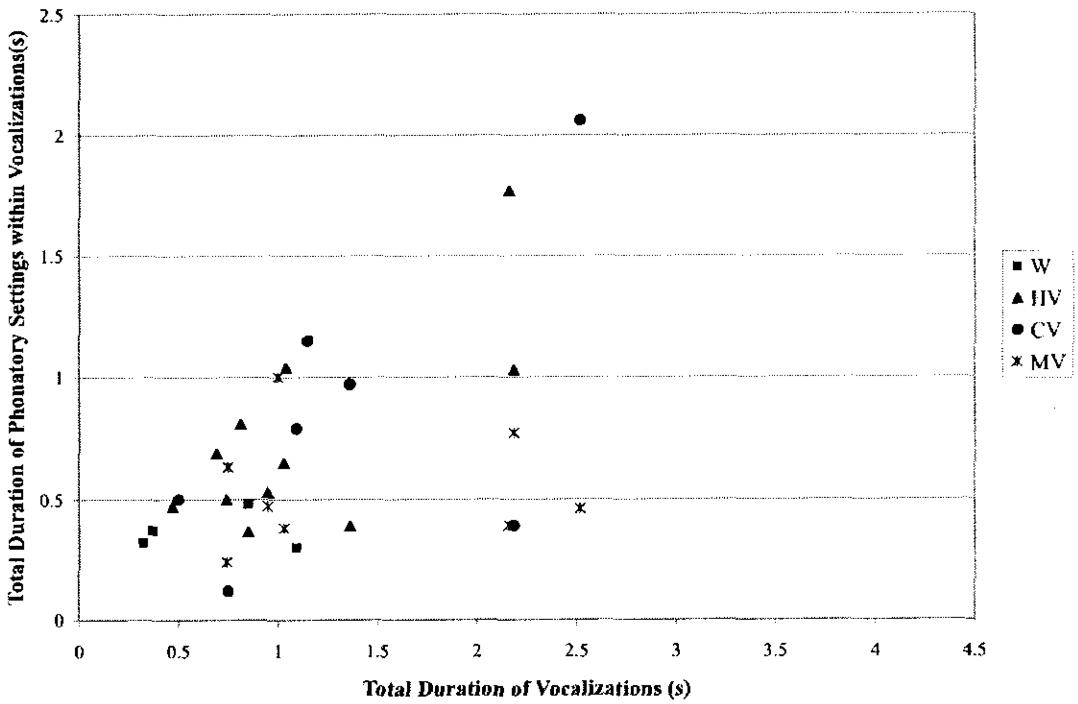
In month 3, the number of points displayed below the diagonal line increases, indicating an increased incidence of phonatory alternations produced with predominantly constricted settings (see Figure 4-22). At this age the infant only produces one alternation between two settings in a total of four vocalizations. The duration of vocalizations increases slightly, though the majority of vocalizations are produced with a duration below 0.65 s. Vocalizations with the longest duration are harsh voice (1.43 s) and creaky voice (1.01).

Figure 4-22. Total duration of vocalizations in comparison to the total duration of phonatory settings within vocalizations at three months (s).



In month 4, a dramatic increase in the proportion of vocalizations exhibiting range exploration, 11 out of 20, is reported (see Figure 4-23). Of this total, ten vocalizations are produced with one alternation and one vocalization is produced with two alternations. The total duration of vocalizations and number of modal voice alternations increases slightly. The duration range of modal voice alternations is 0.28 s – 1 s.

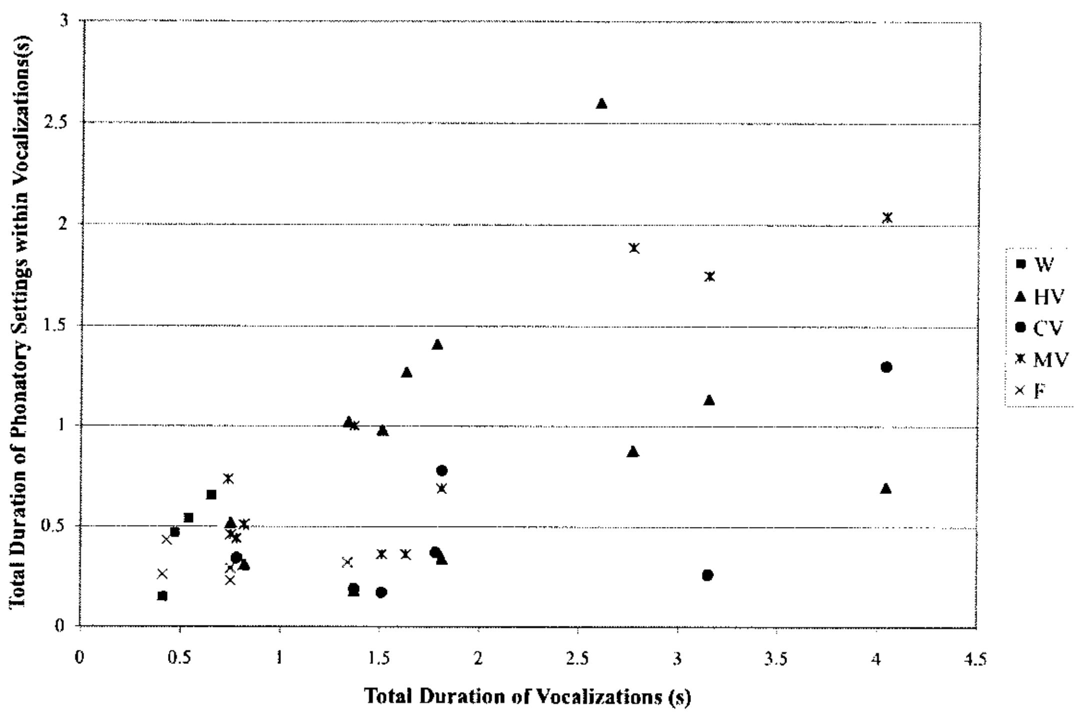
Figure 4-23. Total duration of vocalizations in comparison to the total duration of phonatory settings within vocalizations at four months (s).



The elaboration of the infant's phonatory range at five months is noticeable with the occurrence of modal voice and falsetto alternations reported in Figure 4-24. The incidence of vocalizations produced with phonatory exploration is common with 14 out of 20 vocalizations demonstrating alternations of more than one phonatory setting. The infant produced a total of eight vocalizations with one alternation, six vocalizations with two alternations. At five months, the infant is able to produce three different phonatory settings within one vocalization (e.g. harsh voice, creaky voice and modal voice).

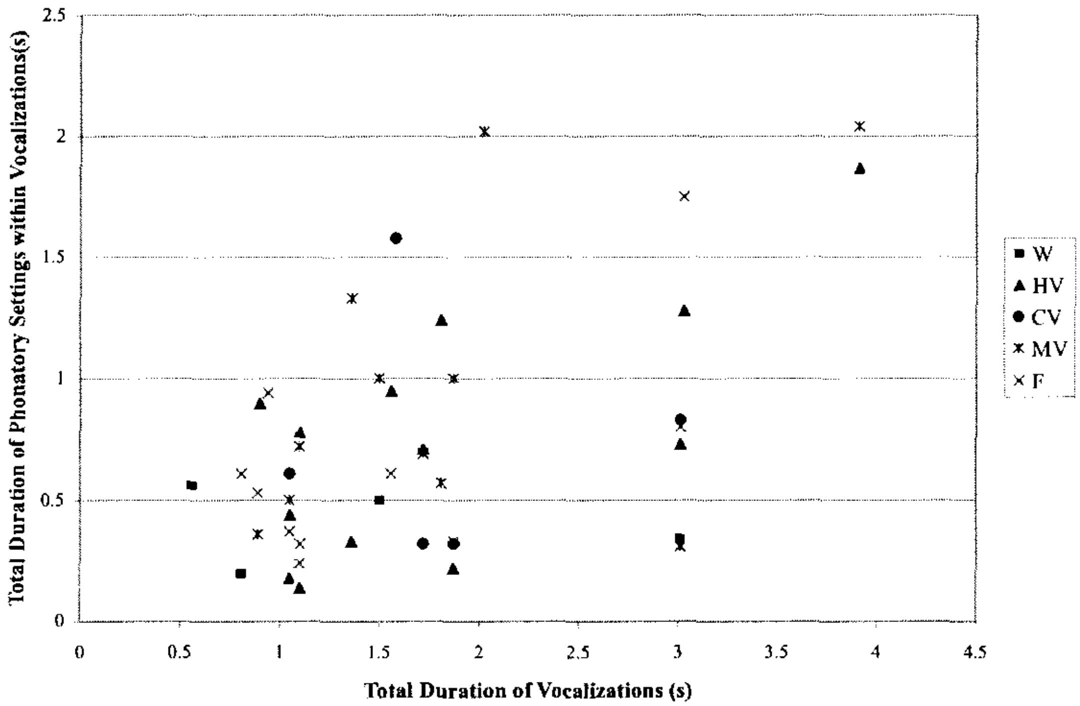
The duration of vocalizations and within-vocalization modal voice alternations increases (0.36 s – 2.04 s). The ability to produce a 2 s vocalization with modal voice demonstrates a certain level of phonetic control. The large range in modal voice alternations suggests that the infant is able to produce longer vocalizations, but chooses to produce shorter alternations in other vocalizations. The duration range of falsetto is much smaller (0.23s – 0.43 s) indicating that control of this parameter has not been attained at 5 months.

Figure 4-24. Total duration of vocalizations in comparison to the total duration of phonatory settings within vocalizations at five months (s).



This trend of increased elaboration of phonatory settings, incidence of alternations continues and duration range of phonatory settings continues in month 6 (see Figure 4-25). By six months the infant is able to produce four alternations within vocalizations. Alternations between constricted (e.g. harsh voice) and unconstricted settings (e.g. modal voice) occur frequently. The range of modal voice (0.36 s – 2.04 s) and falsetto (0.25 s – 1.75 s) demonstrates that the infant has acquired phonetic selection over phonetic parameters, including the glottis.

Figure 4-25. Total duration of vocalizations in comparison to the total duration of phonatory settings within vocalizations at six months (s).



These graphs provide three main findings suggesting that phonetic control is acquired through systematic alternation practice: (1) the incidence of phonatory alternations increases, (2) the range of phonatory settings increases and, (3) the duration range of phonatory alternations increases. In the first months of life, the infant is only able to produce constricted alternations. Exploration of the laryngeal mechanisms begins with harsh voice, creaky voice and whisper. As the phonatory repertoire of the infant expands in the fourth and fifth months, the infant is able to produce vocalizations with short alternations of modal voice within predominantly constricted vocalizations. By the sixth month of life, the infant is able to produce both short and longer phonatory alternations of modal voice and falsetto, as evidenced by the increase in the duration range. These results demonstrate that at six months of age, the infant is able to exercise selection over the phonetic parameters of phonation and pitch.

4.2.4 Summary

The results of the auditorily based and acoustic analysis of 120 randomly selected vocalizations indicate that infants actively explore a wide range of constricted and unconstricted phonatory settings through timing alternations. Over the six-month period, the number of phonatory alternations produced within vocalizations. Instrumental results derived from the duration component of this analysis present several findings which suggest that the infant gains control over laryngeal mechanisms through the process of range exploration. The most dramatic changes were observed in the fourth and fifth month, when the incidence of unconstricted phonation settings and the incidence of phonatory alternations increased significantly. The increase in the average duration of vocalizations and duration range of unconstricted phonatory alternations also increases significantly. Previous studies have reported a similar increase in the mean duration of "speech-like" or modal phonation (Hsu et al., 2002; Oller, 2000; Wermke et al., 2002). These researchers suggest that the increase in the ability to sustain vocalizations for longer durations demonstrates an increase the control of sub-glottal pressure. Therefore, the increase in the duration of constricted modalities which integrate pitch reported in this study demonstrate an increase in the control of laryngeal parameters above and below the glottis.

The results provided in analysis one and two provide a new understanding of the productive capabilities of infants in the first six months of life. A discussion of the main findings of this study is provided in the next chapter.

Chapter Five

DISCUSSION

The aim of this study is to identify the role and development of the laryngeal mechanisms of pitch and constriction, which comprise a large part of the infant's vocal productions in the first six months of life. The research focused on three main topics: (1) the development of phonation and pitch, (2) the dynamic process of "range exploration", and (3) the phonetic description of infant vocalizations produced in the larynx. In section 5.1, the progression of phonation and pitch demonstrated in the results of analysis one and two will be discussed. In section 5.2, I will reinterpret the existing infant speech literature and present a new phonetic description of infant vocalizations considering the vertical and horizontal levels of the larynx.

5.1 Development of laryngeal mechanisms

In this section, I will answer the research question posed in chapter one: is it possible to provide an accurate phonetic description of infant vocalizations demonstrating a dynamic range of phonation and pitch in the first six months of life?

It has been suggested that infant vocalizations are complex, as they display dramatic fluctuations in phonation and pitch (Nathani & Oller, 2001). The difficulty of coding infant vocalizations with auditory and acoustic methods has been cited in numerous research studies (Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Oller, 2000; Roug et al., 1989). These researchers believe that because the adult and infant vocal tracts differ in size, as well as configuration, comparisons between adult and infant vocalizations cannot be made. This aforementioned literature views the vocal tract as a simple tube with the configuration of a gently sloping arc. The vibratory source of infant vocalizations is described in this literature as an underdeveloped glottis. According to Lieberman et al. (1971), the aperiodic noise found in the spectrum of newborn cries is a result of the underdeveloped vocal folds being "blown apart" by the force of increased airflow from the lungs (p. 719). This interpretation is not accurate, as the opening of the glottis is slight when the vocal folds adduct to create voicing in "cry" type vocalizations, and because the source of the observed "strained" and harsh quality of infant vocalizations does not originate from the glottis but from a secondary source above the glottis.

In order to understand the role of the laryngeal mechanism, it is necessary to consider the main articulator of the larynx and pharynx: the laryngeal sphincter. The action of the physiological features involved in laryngeal sphinctering causes a narrowing of the epilaryngeal tube, creating the potential for a secondary source, which can cause increased friction within the vocal tract. When the pharyngeal cavity is decreased during laryngeal sphinctering, the resonant formant frequencies change to a high f1 and low f2.

The occurrence of constriction and its interaction with pitch were determined through acoustic and auditorily based analysis.

The present study was able to accurately identify phonation and pitch exploration in prelinguistic vocalizations. This is the first auditory-acoustic examination of phonatory settings and pitch that considers the horizontal and vertical planes of the larynx. The application of adult canonical profiles of laryngeal sounds involving the laryngeal constrictor was possible due to the fact that the aryepiglottic laryngeal sphincter mechanism is present and active in infants from birth. According to the medical literature, the primary purpose of the laryngeal sphincter is to protect the airway, allowing the infant to swallow suckled fluids over the top of the trachea into the esophagus without the risk of inundation (Crelin, 1973). The configuration of the infant vocal tract, which maintains a respiratory passageway from the larynx to the posterior nares, allows the infant to breath easily through the nose while feeding. Existing research on prelinguistic vocalizations has considered the productive capability of infants to be "limited" by these "primative" and "underdeveloped" mechanisms of the infant larynx (Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Lieberman et al., 1971; Oller, 1980). This view of infant vocalizations ignores the precise coordination of the laryngeal sphincter, which is controlled in early infancy.

In this study, the efficient control of this valve-like mechanism is evidenced by the infant's ability to produce vocalizations with varying degrees of sphincteric engagement. Extreme (harsh voice), moderate (creaky voice) and slight (whisper) constricted settings were identified in vocalizations produced at one month of age. These results suggest that the laryngeal sphincter is the first articulatory mechanism used by infants in a productive and exploratory way. A certain degree of glottal control is present, as evidenced by the infant's production of voiced and high pitch constricted vocalizations.

In the first three months of life, the laryngeal constrictor is always engaged, therefore the manipulation of laryngeal mechanisms required for the production of high and low levels of pitch, only occurs in constricted settings. The default setting of constriction was found to be low pitch. High-pitched constricted vocalizations were produced less frequently than both mid and low pitch. This finding is contrary to previous findings by Bauer and Kent (1987), Lieberman et al. (1971) and Wermke et al. (2002) suggesting that early infant vocalizations, especially "cries" and "fusses", are produced with high pitch, due to the smaller size of the infant vocal tract and vocal folds.

Researchers investigating the f0 of infant vocalizations, mainly "non-distressed" or "cry" types, predict that as the infant vocal tract grows in size over the first year of life, the average f0 of infant vocalizations will decline (Amano et al., 2003; Delack & Fowlow, 1978; Kent & Murray, 1982). However, no reported findings demonstrate a relationship between the growth of the infant vocal tract, and a change in the average f0 of analyzed vocalizations. In these studies, vocalizations with laryngeal constriction and pitch fluctuations were not included.

There are two main problems with this research. First, the developmental changes of any phonetic parameter, including pitch, cannot be accurately assessed unless all vocalizations are included in the analysis. The calculation of average f0 has been cited as a difficult parameter to measure in early infant vocalizations (Amano et al., 2003). It may be more important to identify the ranges of pitch practiced within vocalizations and within each month of development, rather than the trend of average f0. Furthermore, these studies do not consider the dependency of pitch and constriction. The findings presented in this paper indicate that pitch is intrinsically linked to the mechanism of the aryepiglottic constrictor, rather than to the size and shape of the infant vocal apparatus. In early infancy, the action of the laryngeal sphincter and its concomitant features may be responsible for the infant's tendency towards vocalizations with constricted low pitch. According to findings by Esling (2002), the mechanism of the laryngeal constrictor causes the length of the vocal tract to shorten, thereby predisposing low pitch (Esling, 2002).

It is unclear what role the horizontal plane of the glottis plays in early pitch productions. Previous anatomical literature cites the infant glottis as "untensed" and underdeveloped" (Lieberman et al., 1971). This conclusion suggests that the glottis may not be involved in the production of pitch in early infancy. The level of pitch seems to be dependent on the mechanism of the laryngeal sphincter and its interaction with pitch, rather than the glottis.

In the third month of life, the productive range of the laryngeal mechanism expands as the infant's repertoire of phonation increases to include unconstricted settings, modal voice and falsetto. Until the fourth month, infants are unable to produce high-pitched vocalizations without engaging the laryngeal constrictor. Falsetto, an unconstricted phonation with high pitch, did not occur at all in months 1-2, and only infrequently in month 3. This finding suggests that infants at this age are unable to separate glottal and aryepiglottal functions in early infancy. In the fifth and sixth months, the increase in the production of falsetto indicates that the infant is able to control the glottal mechanism involved in voicing and in high pitch. The control necessary to produce vocalizations with five different phonatory settings, involving sphincteric engagement and glottal adduction and stretching, is present by the end of six months.

The theoretical models provided in existing studies have focused on the constraints of the infant vocal tract, reporting on the articulatory limitations of infant prelinguistic vocalizations. This study aimed at discovering the productive possibilities of the infant laryngeal mechanism by identifying what phonatory settings and pitch levels were produced in the first six months of life. In order to chart the productive ranges of these laryngeal features, a bi-level model considering the horizontal and vertical levels of the larynx was applied to the vocalizations of one English-speaking infant.

Table 5-1 charts the phonatory settings produced by the infant each month in the first six months.

Table 5-1. Phonation settings produced in the first month of life.

Month	Setting	Engaged	Degree	Voicing	Pitch
1 to 2	Harsh Voice	Yes	Extreme	Voiced	Low, Mid, High
	Creaky Voice	Yes	Moderate	Voiced	Low, High
	Whisper	Yes	Slight	Voiceless	Mid
3	Harsh Voice	Yes	Extreme	Voiced	Low, Mid, High
	Creaky Voice	Yes	Moderate	Voiced	Low, High
	Whisper	Yes	Slight	Voiceless	Mid
	Modal Voice	No	None	Voiced	Mid
4 to 6	Harsh Voice	Yes	Extreme	Voiced	Low, Mid, High
	Creaky Voice	Yes	Moderate	Voiced	Low, High
	Whisper	Yes	Slight	Voiceless	Mid
	Modal Voice	No	None	Voiced	Mid
	Falsetto	No	None	Voiced	High

The following table maps out the productive capabilities of the infant laryngeal mechanisms of the laryngeal sphincter and the glottis in the first six months of life. During the first months of life, the infant cannot disengage the laryngeal sphincter. In months 1 and 2, the infant explores the ranges of this setting, producing vocalizations with extreme, moderate and slight degrees of constriction. Within each of these settings, the infant also tests out the limits of pitch, producing harsh voice at low, mid and high pitch and creaky voice at low and high pitch. All possible combinations of constriction and pitch appear to be practiced through alternations between settings. In month 3, the infant begins to practice settings without sphincteric engagement, which expands the phonatory possibilities to include modal voice and falsetto. The results indicate that the infant explores high pitch from the first month of life, but does not produce unconstricted high pitch (i.e. falsetto) until the fourth month of life. By the sixth month of life, the infant is able to alternate between four different settings within one utterance, controlling both the mechanisms of the laryngeal sphincter and the glottis. The findings presented in this study can be used to develop a developmental hierarchy of phonation and pitch in the first six months of life.

The hierarchical progression of phonation and pitch determined by the number and percentage incidence rate reported in this study is shown in Table 5-2.

Table 5-2. Hierarchy of phonatory settings acquired in the first six months of life.

Stage	**Hierarchy of Phonation**	**Age Acquired**
Stage 1	1. Harsh Voice	Birth
	2. Whisper	Birth
	3. Creaky Voice	2 weeks
Stage 2	4. Modal Voice	4 months
Stage 3	5. Falsetto	5 months

The stages shown in this table represent the successful phonetic use of phonatory settings attained by the infant at a certain age. These results clearly indicate that the first laryngeal mechanism mastered by the infant is the laryngeal constrictor. In the first stage, occurring in the first months of life, the infant is able to produce degrees of constriction. The data presented in this study does not include the first two weeks of life. Therefore, only predictions can be made regarding the first setting produced by newborn infants.

It is in the opinion of this researcher that the first setting produced is harsh voice (i.e. extreme constriction). Results of newborn cries by Lieberman et al. (1971) and Möller & Schönweiler (1999) indicate that these first vocalizations including "cries" are produced with harshness. It is difficult to say whether the first glottal state is Voice when the glottis is adducted or Breath, when the glottis is abducted (voicelessness). We can assume that the glottis is open much of the time, for breathing - in and out, however the production of Breath, audible breathing, did not occur. This study posits the constrictor is always engaged in early infancy. All voiceless vocalizations observed in this study had audible friction, which was identified as Whisper, not Breath. Voicing was easily identified in newborn vocalizations and has been documented by other researchers (Lieberman et al., 1971, Stark et al., 1975).

By the second week of life, the infant is able to produce both creaky voice and whisper. In order to determine which of these constricted settings are attained first, the results from the second week and first month of life were consulted. These findings show that creaky voice is produced more frequently in the second week. Only two instances of whisper were produced, indicating that this setting may not be acquired until the end of month one. The acquisition of constricted settings must occur before the infant is able to explore unconstricted settings.

In stage two, beginning in the fourth month, the infant acquires the ability to produce modal voice, an unconstricted setting. The ability to produce falsetto, an unconstricted setting involving high pitch is attained in the fifth month. At this stage, the infant is able to control the laryngeal features of voice and pitch.

The above table provides an increased understanding of when certain phonation and pitch features are acquired. In section 5-2, previous descriptions of prelinguistic vocalizations discussed in the literature review will be reinterpreted considering the findings presented in this study.

5.2 Phonetic description of prelinguistic vocalizations

The existing literature on infant prelinguistic vocalizations has provided valuable research on the developmental trend of "speech-like" vocalizations produced with "normal" (i.e. modal) phonation towards the onset of babbling and later speech development. However, these "speech-like" vocalizations comprise a very small percentage of vocalizations produced in early infancy. Existing studies have observed laryngeal vocalizations described as "vegetative" or "reflexive" which exhibit irregular phonatory and pitch features. Unable to accommodate the dynamic variations of "vegetative" with theoretical models based on the constraints of the infant vocal tract and the horizontal plane of the larynx (i.e. glottis), generalized colloquial terms such as "growling", "squealing", "croaking", "yelling" and "groaning" and acoustic descriptions such as "aperiodic noise" and "friction" were used to describe laryngeal sounds. Nathani and Oller (2001) included impressionistic terms in opposition to "speech-like" vocalizations. In this study, vocalizations were determined on scales of "speechiness". If a vocalization had a large portion of "squealiness" or "growliness", it was excluded from the data set. These researchers lamented at the complexity of coding vocalizations in this way, since the scales of "squealiness" and "growliness" also had to be developed. Apart from the research on grunts by McCune et al. (1996) and on "vegetative" vocalizations by Stark et al. (1975), studies focusing the progression towards language excluded laryngeal vocalizations because they were not seen as linguistic precursors.

Theses colloquial terms, representing the observed vocal behaviours produced in early infancy, do not provide accurate phonetic descriptions of the dynamic range phonation and pitch practiced then used in early infancy. The application of the canonical profiles of adult laryngeal phonation and pitch provided by Esling et al. to infant vocalizations reinterprets the previous phonetic descriptions presented in Table 2.3 (see p. 27) into a simplistic and understandable chart presented in Table 5-3 below.

Table 5-3. Modified phonetic description of infant vocalizations considering the vertical and horizontal levels of the larynx.

New Term	Previous Terms	Reported by (Author)
Constricted		
	"Strained"	Kent & Murray (1982)
	"Tense"	Koopmans-van Beinum & van der Stelt (1986), Oller (1980)
	"Noisy excitation"	Lieberman et al. (1971), Robb et al. (1989)
	"Turbulent noise"	Lieberman et al. (1971), Möller & Schönweiler (1999), Stark et al. (1975)

Whisper

"Cough"	Oller (2000)
"Pulse"	Buder, Oller & Magoon (2003)
"Pharyngeal friction"	Stark et al. (1975)
"Whispering"	Oller (2000)
"Grunts"	McCune et al. (1996), Oller (1980), Stark et al. (1975)

Harsh Voice
Low Pitch

"Crying"	Bauer & Kent (1987), Lieberman et al. (1971), Stark et al. (1975), Wermke et al. (2002)
"Fusses"	Hsu et al. (2002), Lieberman et al. (1971), Oller (2000)
"Hyperphonation"	Lieberman et al. (1971), Möller & Schönweiler (1999)
"Disphonation"	Möller & Schönweiler (1999)
"Gurgle"	Lieberman et al. (1971)
"Grunts"	McCune et al. (1996), Oller (1980), Stark et al. (1975)
"Growling"	Kent & Murray (1982), Oller (2000), Robb et al. (1989)
"Cough"	Oller (2000)
"l'r gutterale"	Grégoire (1937)
"Gazouilles"	Grégoire (1937)
"Moan"	Scheiner et al. (2000)
"Groan"	Scheiner et al. (2000)
"Chaos"	Buder, Oller & Magoon, (2003)
"Pharyngeal friction"	Stark et al. (1975)

Mid Pitch

"Crying"	Bauer & Kent (1987), Lieberman et al. (1971), Stark et al. (1975), Wermke et al. (2002)
"Fusses"	Hsu et al. (2002), Lieberman et al. (1971), Oller (2000)
"Hyperphonation"	Lieberman et al. (1971), Möller & Schönweiler (1999)
"Disphonation"	Möller & Schönweiler (1999)
"Gurgle"	Lieberman et al. (1971)
"Grunts"	McCune et al. (1996), Oller (1980),
"l'r gutterale"	Grégoire (1937)
"Gazouilles"	Grégoire (1937)
"Cough"	Oller (2000)
"Moan"	Scheiner et al. (2000)
"Groan"	
"Chaos"	Buder, Oller & Magoon, (2003)
"Pharyngeal friction"	Stark et al. (1975)

High Pitch		
	"Fusses"	Hsu et al. (2002), Lieberman et al. (1971), Oller (2000)
	"Squealing"	Buder, Oller & Magoon (2003),
	"Screaming"	Koopmans-van Beinum & van der Stelt (1986)
	"Shrieking"	Oller (1980; 2000)
	"Pharyngeal friction"	Stark et al. (1975)
Creaky Voice		
	"Pulse"	Buder, Oller & Magoon, (2003)
	"Glottal Pulse"	Stark et al. (1975)
	"Vocal Fry"	Stark et al. (1975)
	"Vocal Tremor"	Kent & Murray (1982) Möller & Schönweiler (1999)
<u>Unconstricted</u>		
	"Normal phonation"	Oller (1980; 2000)
	"Speech-like"	Oller (1980; 2000), Stark (1980)
Modal Voice		
	"Gooing"	Oller (1980; 2000), Stark (1980)
	"Cooing"	Roug et al. (1989)
	"Yelling"	Oller (2000)
Falsetto		
	"Squealing"	Buder, Oller & Magoon, (2003)

The observations of infant vocalizations using auditorily based analysis and considering laryngeal constriction and laryngeal pitch provided in this study condense the complex milieu of existing colloquial terms into two main categories: constricted (i.e. involving the engagement of the vertical laryngeal constrictor) and unconstricted (i.e. involving the horizontal level of the glottis). These two primary categories can be broken down into more precise and descriptive categories of phonatory settings. Constricted settings include whisper, harsh voice and creaky voice. Unconstricted settings include modal voice and falsetto.

These terms cover the wide range of laryngeal features explored in infancy within constricted and unconstricted settings including the following: (1) degree of constriction, i.e. harsh voice (extreme constriction), creaky voice (moderate constriction), whisper (slight constriction), and modal voice and falsetto (no constriction), (2) presence of voicing, i.e. harsh voice (voiced constriction), whisper (voiceless constriction), modal voice and falsetto (voiced and voiceless constriction), (3) low pitch, i.e. harsh voice low pitch (constricted low pitch), (4) mid or neutral pitch, i.e. harsh voice mid pitch (constricted mid pitch) and modal voice (unconstricted mid pitch) and (5) high pitch, i.e. harsh voice high (constricted high pitch) and falsetto (unconstricted high pitch).

5.3 Summary

The two descriptive charts presented in Table 5-1, 5-2 and 5-3 can be used to develop canonical profiles of infant laryngeal vocalizations produced in the first six months. The phonetic charts of each month, presented in Table 5-1, account for the incidence and tendencies of phonation and pitch exploration in infant vocalizations. This chart clarifies the role and interaction of constriction and pitch by showing the following developmental trends: (1) the default constricted setting in early infancy, (2) the default low pitch level with constricted vocalizations and, (3) the expanding range of phonatory settings and pitch levels. These results show a definite progression in the productive capability of the laryngeal mechanism. Infants are born with the ability to engage the laryngeal sphincter in varying degrees. This is the first articulatory tool available in the exploration of speech, and therefore is the first mechanism acquired. Glottal features are acquired second. The phonetic parameters of constriction, pitch and voicing are present and integrated by the sixth month of life.

Chapter Six

CONCLUSION

The purpose of this chapter is to summarize and provide perspective for the findings presented in previous chapters. A summary of this thesis is given in section 6.1. Section 6.2 will discuss how this study contributes to the knowledge of early phonatory development.

6.1 Summary

This study investigates phonation and pitch in early infant vocalizations, in order to identify the development and role of the laryngeal mechanism in the first six months of life. In Chapter 2, I presented a literature review on the existing research on infant prelinguistic vocalizations. In previous studies, researchers observed "strained" vocalizations produced with "high degrees of vocal tension", "noisy turbulence" and "aberrant pitch variations" in early vocal practice (Kent & Murray, 1982; Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980; Stark, 1980). These researchers were unable to provide accurate phonetic descriptions of these laryngeal vocalizations with theoretical models based on the constraints of the infant vocal and the horizontal plane of the larynx (i.e. glottis). In order to chart the ranges of the these laryngeal features, a bi-level model considering the horizontal (i.e. glottal) and vertical (i.e. laryngeal constrictor) levels of the larynx was applied to the vocalizations of one English-speaking infant in the first six months of life.

Two quantitative analyses of infant vocalizations in the first six months of life were reported. In analysis one, the auditory analyses of 824 vocalizations were performed using an auditorily based analysis of laryngeal phonatory settings (i.e. states of the glottis). In analysis two, the phonatory features involved in "range exploration" were quantified, by means of an acoustic analysis. 120 randomly selected vocalizations (20 from each of the six months) were used in this analysis. The durations of the vocalizations and of individual phonatory settings within each vocalization were calculated using spectrographic analyses.

A number of important findings were reported in auditory analysis one. The default setting in early infancy is constricted and low pitch. This claim is supported by the following findings. The greatest percent of vocalizations in the first months of life was produced with harsh voice. A range of constricted settings is produced at two weeks of age, i.e. harsh voice (extreme constriction), creaky voice (moderate constriction), whisper (slight constriction). The pitch level of constricted vocalizations is also explored in early infancy as evidenced by the production of low-, mid- and high-pitched constricted vocalizations throughout the six-month period. These findings suggest that the primary articulator in infant vocalizations is the laryngeal constrictor. The ability to produce vocalizations without engaging the laryngeal constrictor is not present in the first months of life.

The infant's repertoire of phonatory settings was shown to expand at around four months to include unconstricted phonatory settings with voicing and pitch (i.e. modal voice and falsetto) as the percentage of unconstricted vocalizations increased and the constricted vocalizations decreased. The average duration of these settings also increased at four months. The expanding range of the infant demonstrates the acquisition of laryngeal control.

In analysis two, the incidence of range exploration was found to dramatically increase at four months. By six months of age, the infant was able to produce numerous alternations between constricted and unconstricted settings with varying levels of pitch. The increased proliferation of phonation settings produced during alternations and the increased rate of alternations indicates that the infant has attained control over laryngeal features.

This study demonstrates three important findings: (1) that the default setting in early infancy is constricted laryngeally and low-pitched (2) that infants practice a range of constriction and pitch from two weeks of age, despite the constraints of their anatomy, and (3) that control over phonatory features is attained by six months of age.

6.2 Future Research

In the last several years, Esling et al. have identified the aryepiglottic laryngeal sphincter as a primary articulator in the production of laryngeal vocalizations, including a number of phonatory settings (i.e. harsh voice, creaky voice, whispery voice and whisper). Based on laryngoscopic observations from a large sampling of languages, the phonetics research team at the University of Victoria has been able to develop canonical profiles of adult laryngeal productions based on a bi-level model of the larynx, considering both the horizontal plane of the glottis and the vertical plane of the laryngeal sphincter. In this study, this parametrical model of the larynx was applied to infant vocalizations in order to describe phonetically the productive capability of the laryngeal mechanism in the first six months of life.

Prior to this study, there was little understanding of the role and development of laryngeal mechanisms involved in the wide range of phonation and pitch observed in infant prelinguistic vocalizations. Previous studies did not have an adequate model or auditory tools required to accurately describe laryngeal vocalizations produced by infants in the first six months of life.

This study provides several important findings regarding the role of the aryepiglottic laryngeal sphincter and its interaction with pitch in the first six months of life. Similar to adults, the laryngeal sphincter is engaged during the production of constricted settings. In early infancy, the default setting in infancy is constricted low pitch. At this age, infants explore constricted phonatory settings with a pitch tendency towards low and mid levels. Glottal mechanisms involved in the production of high pitch are not acquired until the end of the first six months of life. These results indicated that the laryngeal sphincter is the first articulatory mechanism utilized, practiced, and controlled in infant prelinguistic vocalizations.

Based on the auditory-acoustic findings presented in this study, canonical profiles of infant laryngeal vocalizations produced in the first six months were developed. The phonetic charts of each month, presented in Table 5-1, account for the incidence and tendencies of phonation and pitch exploration in infant vocalizations. This chart clarifies the role and interaction of constriction and pitch by showing the following developmental trends: (1) the default constricted setting in early infancy, (2) the default low pitch level with constricted vocalizations and, (3) the expanding range of phonatory settings and pitch levels. These results show a definite progression in the productive capability of the laryngeal mechanism. Infants are born with the ability to engage the laryngeal sphincter in varying degrees. This is the first articulatory tool used in the exploration of speech, and therefore is the first mechanism acquired. Glottal features are acquired second. To summarize these findings, the phonetic parameters of constriction, pitch and voicing are present and integrated by the sixth month of life.

The findings in this study demonstrate that the phonatory setting and pitch level produced in infant laryngeal vocalizations can be identified with the auditorily based techniques developed for the description of laryngeal and phonetic articulations in adult speech. In order to identify greater developmental trends in infant vocalizations in the first year of life, it would be necessary to analyze measurable phonetic parameters involved in laryngeal constriction and glottal pitch.

The longitudinal research of one English-speaking infant reported in this study is a part of a larger cross-cultural infant-speech project under the supervision of Dr. J. H. Esling in the Department of Linguistics at University of Victoria. Presently, a team of researchers situated in Victoria, Paris, Morocco, and China are collecting video and audio data of infants from a number of ambient languages (Benner, Bettany & Wang, 2004; Esling, Benner & Bettany, 2004a; 2004b; Esling, Benner, Bettany & Zeroual, 2004). A preliminary goal of this project is produce an interactive web-based XML database and analysis network of early infant data, allowing researchers to share, exchange and compare a large amount infant vocalization data. The collaboration of these researchers is expected to enhance our understanding of the role of laryngeal mechanisms in the phonetic development of infants in the first year of life.

The results presented in this thesis will constitute a baseline against which the vocalizations of other infants in the first six months of life can be tested.

REFERENCES

Amano, S., Nakatani, T., & Kondo, T. (2003). Fundamental frequency analysis of longitudinal recording in a Japanese infant speech database. *Proceedings of the 15th International Congress of Phonetic Sciences, Barcelona, 2*, 512-518.

Bauer, H. R., & Kent, R. D. (1987). Acoustic analysis of infant fricative and trill vocalizations. *Journal of the Acoustical Society of America, 81*, 505-511.

Benner, A., Bettany, L., & Wang, Q. (2004). *Natural language processing in the first year of life.* Poster presentation, Advanced Systems Institute Exchange, Vancouver, March 8, 2004.

Boysson-Bardies, B. de. (1999). *How language comes to children: From birth to two years.* Cambridge MA: MIT Press.

Buder, E. H., Oller, K. D., Magoon, J. C. (2003). Vocal intensity and phonatory regimes in the development of infant protophones. *Proceedings of the 15th International Congress of Phonetic Sciences, Barcelona, 3*, 2014-2018.

Catford, J. C. (1977). *Fundamental Problems in Phonetics.* Edinburgh: Edinburgh University Press.

Carlson, B. F., Esling, J. H., & Harris, J. G. (2004). A laryngoscopic phonetic study of Nlaka'pamux (Thompson) Salish glottal stop, glottalized resonants, and pharyngeals. In D. B. Gerdts & L. Matthewson (Eds.), *Studies in Salish linguistics in honor of M. Dale Kinkade, Occasional Papers in Linguistics No. 17* (pp. 58-71). Missoula: University of Montana Press.

Crelin, E. S. (1973). *Functional Anatomy of the Newborn.* New Haven: Yale University Press.

Delack, J. B., & Fowlow, P. J. (1978). The ontogenesis of different vocalization: Development of prosodic contrastivity during the first year of life. In N. Waterson & D. Snow (Eds.), *The Development of Communication* (pp. 93-110). New York: Wiley.

Eckel, H. E., Koebke, J., Sittel, C., Sprinzl, G. M., Pototschnig, C., Stennert, E. (1999). Morphology of the human larynx during the first five years of life studied on whole organ serial sections. *Annals of Otolaryngology, Rhinology and Laryngology, 108*(3), 232-238.

Esling, J. H. (1984). Laryngoscopic study of phonation type and laryngeal configuration. *Journal of the International Phonetic Association, 14*, 56-73.

Esling, J. H. (1994). Voice Quality. In R. E. Asher, & J. M. Y. Simpson (Eds.), *The encyclopedia of language and linguistics* (pp. 4950-4953). Oxford: Pergamon Press.

Esling, J. H. (1996). Pharyngeal consonants and the aryepiglottic sphincter. *Journal of the International Phonetic Association, 26*, 65-88.

Esling, J. H. (1998). Laryngoscopic analysis of pharygeal articulations and layrnx-height voice quality settings. *Proceedings of the 5th International Conference on Spoken Language Processing, Vol. 2* (pp. 543-546). Sydney: ASSTA.

Esling, J. H. (1999a). The IPA categories "pharyngeal" and "epiglottal": Laryngoscopic observations of pharyngeal articulations and larynx height. *Language & Speech, 42*, 349-372.

Esling, J. H. (1999b). Voice quality setting of the pharynx. *Proceedings of the14th International Congress of Phonetic Sciences, 3*, 2449-2452.

Esling, J. H. (2000). Crosslinguistic aspects of voice quality. In R. D. Kent, & M. J. Ball (Eds.), *Voice quality measurement* (pp. 49-58). San Diego: Singular Publishing Group.

Esling, J. H. (2002). *The laryngeal sphincter as an articulator: Tenseness, tongue root and phonation in Yi and Bai.* Paper presented at the LSA annual meeting, January 2002, San Francisco.

Esling, J. H., Ball, M. J., & Dickson, B. C. (2000). The transcription of voice quality. In R. D. Kent, & M. J. Ball (Eds.), *Voice quality measurement* (pp. 49-58). San Diego: Singular Publishing Group.

Esling, J. H., Benner, A., & Bettany, L. (2004a). *Phonetic structure and acquisition of laryngeal and pharyngeal articulations: Text-analysis considerations*. Paper presented at the Canadian Symposium for Text Analysis, University of Victoria, November 18, 2003.

Esling, J. H., Benner, A., & Bettany, L. (2004b). *Phonetic articulatory control in the first year of life*. Paper presented at the 2004 Conference of the British Association of Academic Phoneticians, Cambridge University, March 24-26, 2004.

Esling, J. H., Benner, A., Bettany, L., & Zeroual, C. (2004). Le contrôle articulatoire phonétique dans le prébabillage. *Actes des XXV^es Journées d'Etude sur la Parole, 19-22 avril 2004, Fès, Maroc.* Aix-en-Provence: Association Francophone de la Communication Parlée.

Esling, J. H., & Edmondson, J. A. (2002). The laryngeal sphincter as an articulator: Tenseness, tongue root and phonation in Yi and Bai. In A. Braun & H. R. Masthoff (Eds.), *Phonetics and its applications: Festschrift for Jens-Peter Köster on the occasion of his 60th birthday*. Stuttgart: Franz Steiner Verlag.

Esling, J. H., & Gao, M. (2003). Articulatory Features of Tones in Whispered Chinese. *Proceedings of the 15th International Congress of Phonetic Sciences, Barcelona, 3,* 2629-2632.

Esling, J. H., & Harris, J. G. (2003) An expanded taxonomy of states of the glottis. *Proceedings of the 15th International Congress of Phonetic Sciences, Barcelona, 3,* 1049-1052.

Fitch, W. T., & Giedd, J. (1999). Morphology and development of the human vocal tract: A study using magnetic resonance imaging. *Journal of the Acoustical Society of America, 106*, 1511-1522.

Fried, M. P., Kelly, J. H., Strome, M. (1982). Comparison of the adult and infant larynx. *The Journal of Family Practice, 15*, 557-561.

Fry, D. B. (1966). The development of the phonological system in the normal and the deaf child. In F. Smith and G. Miller (Eds.), *The Genesis of Language: A Psycholinguistic Approach* (pp. 160-183). Cambridge, MA: MIT Press.

Goldfield, E. C. (2000). Exploration of vocal tract properties during serial production of vowels by full term and preterm infants. *Infant Behavior and Development, 23*, 421-439.

Grégoire, A. (1937). *L'apprentissage du langage: Les deux premières années.* Paris: Félix Alcan.

Hsu, H. C., Fogel, A., & Cooper, R. B. (2000). Infant vocal development during the first 6 months: Speech quality and melodic complexity. *Infant and Child Development, 9*, 1-16.

Jakobson, R. (1941). Kindersprache, Aphasie, und Allgemeine Lautgesetze. Uppsala: Almqvist & Wiksell.

Kent, R. D. (1981). Articulatory-acoustic perspectives on speech development in language behavior in infancy and early childhood. In R. E. Stark (Ed.), *Language behavior in infancy and early childhood* (pp. 105-126). New York: Elsevier North Holland.

Kent, R. D. (1997). *The Speech Sciences.* San Diego, CA: Singular Publishing Group.

Kent, R. D., & Murray, A. D. (1982). Acoustic features of infant vocalic utterances at three, six, and nine months. *Journal of the Acoustical Society of America, 72*, 353-365.

Kent, R. D., & Vorperian, H. K. (1995). Development of the craniofacial-oral-laryngeal anatomy: A review. *Journal of Medical Speech-Language Pathology, 3*, 145-190.

Koopmans-van Beinum, F. J. & van der Stelt, J. M. (1986). Early stages in the development of speech movements. In B. Lindblom, & R. Zetterström (Eds.), *Precursors of early speech* (pp. 279–308). Basingstoke, Hampshire: MacMillan.

Laver, J. (1980). *The phonetic description of voice quality.* Cambridge: Cambridge University Press.

Lieberman, D. E., McCarthy, R. C., Hiiemae, K. M., & Palmer, J. B. (2001). Ontogeny of postnatal hyoid and larynx descent in humans. *Archives of Oral Biology, 46*, 117-128.

Lieberman, P. (1985). The physiology of cry and speech in relation to linguistic behavior. In B. Lester & C. F. Z. Boukydis (Eds.), *Infant Crying: Theoretical and Research Perspectives* (pp. 37-52). New York: Pleum Press.

Lieberman, P., Harris, K. S., Wolff, P., & Russell, L. H. (1971). Newborn infant cry and nonhuman primate vocalization. *Journal of Speech and Hearing Research, 14*, 718-727.

McCune, L., Vihman, M. M., Roug-Hellichius, L., Bordeneave, D., & Gogate, L. (1996). Grunt communication in human infants (homo sapiens). *Journal of Comparative Psychology, 110*, 27-37.

Nathani, S., & Oller, D. K. (2001). Beyond ba-ba and gu-gu: Challenges and strategies in coding infant vocalizations. *Behavior Research Methods, Instruments, & Computers, 33*(3), 321-330.

Oller, K. D. (1980). The emergence of the sounds of speech in infancy. In G. Yeni-Komshian, J., Kavanaugh, & C. Ferguson (Eds.), *Child Phonology* (pp.93-112). New York: Academic Press.

Oller, D.K. (2000). *The Emergence of the Speech Capacity*. Mahwah, NJ: Lawrence Erlbaum Association.

Papaeliou, C., Minadakis, G., & Cavouras, D. (2002). Acoustic patterns of infant vocalizations expressing emotions and communicative functions. *Journal of Speech Language and Hearing Research, 45*, 311-317.

Robb, M. P., Saxman, J. H., & Grant, A. A. (1989). Vocal fundamental frequency characteristics during the first two years of life. *Journal of the Acoustical Society of America*, 85, 1708-1717.

Roug, L., Landberg, I., & Lundberg, L. J. (1989). Phonetic development in early infancy: A study of four Swedish children during the first eighteen months of life. *Journal of Child Language, 16*, 19-40.

Ruff, H. (1986). Components of attention during infants' manipulative exploration. *Child Development*, 57, 105-114.

Sasaki, C. T., Levine, P. A., Laitman, J. T., & Crelin, E. S. (1977). Postnatal descent of the epiglottis in man. *Archives of Otolaryngology, 103*, 169-171.

Sheppard, W. C., & Lane, H. L. (1968). Development of the prosodic features of infant vocalizing. *Journal of Speech & Hearing Research, 11*, 94-108.

Scheiner, E., Hammerschmidt, K., Jürgens, U., & Zwirner, P. (2002). Acoustic analyses of Developmental Changes and emotional expression in the preverbal vocalizations of infants. *Journal of Voice, 16*(4), 509-529.

Stark, R. E. (1980). Prespeech segmental feature development. In G. Yeni-Komshian, J. Kavanaugh, & C. Ferguson (Eds.), *Child Phonology* (pp.73-92). New York: Academic Press.

Stark, R. E., Bernstein, L. E. & Demarest, M. E. (1993). Vocal communication in the first 18 months of life. *Journal of Speech and Hearing Research*, 36, 548-558.

Stark, R. E., Rose, S. N., & McLagen, M. (1975). Features of infant sounds: The first eight weeks of life. *Journal of Child Language, 2*, 205-222.

Thelen, E. (1991). Motor aspects of emergent speech: A dynamic perspective. In N.A. Krasnegor, D. M. Rumbaugh, R. L. Schiefelbusch, & M. Studdert- Kennedy (Eds.), *Biological and behavioral determinants of language development* (pp. 339-362). Hillsdale, NJ: Lawrence Erlbaum Associates.

Truby, H. M., & Lind, J. (1965). Cry sounds of the newborn infant. In J. Lind (Ed.), *Newborn infant cry*. Uppsala: Almqvist & Wiksell.

Vihman, M. M. (1996). *Phonological development: The origins of child language.* Oxford: Blackwell.

Vorperian, H. K., Kent, R. D., Gentry, L. R., & Yandell, B. S. (1999). Magnetic resonance imaging procedures to study the concurrent anatomic development of vocal tract structures: Preliminary results. *International Journal of Pediatric Otorhinolaryngology, 49*, 197-206.

Wermke, K., Mende, W., Mangredi, C., & Bruscaglioni, P. (2002). Developmental aspects of infant's cry melody and formants. *Medical Engineering & Physics, 24*(8), 501-14.