ACOUSTIC FEATURES OF AN INFANT HEARING AID USER IN A NATURAL HOME ENVIRONMENT

by

LISA A. DELLERT

(Under the Direction of Sandie Bass-Ringdahl)

ABSTRACT

Two recordings of an infant hearing aid user were obtained in the infant's home environment using LENA technology—recording one (9-months) and recording two (11-months). Target vowel sounds (/a/, /i/, and /u/) were subjected to perceptual and acoustic analysis. When comparing acoustic measures (collapsed across vowel types) to norms, the infant's vocalizations were within normal limits—albeit the lower end of normal. Using ANOVA and Tukey-HSD tests, vowel type, age, vowel interaction over time, and communication partner were tested for association to acoustic measures (F0, F1, F2, F3). Statistical analyses demonstrated vowel type significantly influenced all acoustic measures. Examination of the observed acoustic measures by vowel type revealed the infant's productions deviated from the normative ranges in some instances. F3 was significantly lower for all vowels at both 9-and-11-months. An association between F2 and communication partner was found, indicating the infant's mother significantly impacted the infant's F2 values.

INDEX WORDS: Acoustics, Speech Production, Formant Frequencies, Infant Vowel Productions, Hearing-Impaired Infant Speech, Infant Speech Development

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DEDICATION

For my first two university clinic articulation clients. I have learned so much from both of you and I am dedicated to improving articulation therapy for you and other kids like you.

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"But just as you excel in everything—in faith, in speech, in knowledge, in complete earnestness and in your love for us—see that you also excel in this grace of giving" (2 Corinthians 8:7). Thank you Lord for blessing me abundantly beyond what I deserve. I cannot do anything without you—especially graduate school!

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CHAPTER 1

INTRODUCTION

Speech acquisition for infants and young children involves a complex integration of motor control, sensory processing, audition, speech perception, cognition, and physical development of anatomic structures. This complex integration makes it difficult to separate and identify the process of speech learning. For many children, speech and language learning requires little effort, and occurs naturally. For children who are deaf or hard of hearing, the process of speech and oral language is more complex. In addition, much still needs to be discovered about the process that results in speech and oral language development.

Modern cortical imaging provides support for the theory that hearing is the basis for learning the vocal tract shapes, or “sound maps” of a given language. The dorsal stream is responsible for creating these “sounds maps” (Sarubbo et al. 2015), and dorsal pathway activation has been observed in newborn infants (Friederici, 2011). Although the dorsal stream is present in the newborn brain, it requires outside auditory stimulation in order to activate and fine tune. The cochlea is fully formed in utero at 20 months of age (Graven & Browne, 2008) allowing the fetus to gather their first experiences of sound prior to birth (Skeide & Friederici, 2016). In fact, the auditory system gains auditory experience with speech, language, music, and meaningful environmental sounds during the last 10 to 12 weeks of fetal life (28-30 weeks gestational age) whether in utero, or when in a neonatal intensive care unit (Graven & Brown, 2008).

In utero, frequencies above 300Hz are strongly attenuated so fetuses can, at best, discriminate between vowels that have lower frequency boundaries (around 200Hz), but not between more subtly differing consonants, which in speech typically have higher frequencies, beginning at around 300Hz (Skiede & Friederici, 2016). Because an infant's exposure to vowel "sound maps" begins in utero, the appearance of vowels early in an infant's phonological repertoire is expected. Examining the acoustic measures of an infant's vowel productions over time may demonstrate how the infant is learning to tune his/her particular vocal tract structure to produce acoustically definable contrasts of his/her language environment (Hodge, 1989; Vorperian & Kent, 2007).

Bauer and Kent (1987) suggested that a detailed acoustic taxonomy of typical vocalization behaviors could serve as a metric to evaluate atypical vocal development, as might be the case for infants who are deaf or hard of hearing. Unfortunately, the lack of published acoustic data for vowels produced by infants prevents confident statements about developmental patterns between birth and 2 or 3 years of age (Kent & Read, 2002).

Statement of Problem and Clinical Questions

Challenges exist in the investigation of the acoustic properties of infant vocalizations. Existing studies are limited, and those that have been conducted often have small sample sizes. Elicitation and data collection challenges unique to a young population can impact study findings. In addition, the lack of standard reporting of acoustic measures creates difficulty with meaningful usability of the data both clinically and scientifically. Finally, because of the lack of published formant frequency data for infants with typical hearing, there is little data from which to compare other populations, such as infants who are deaf or hard of hearing.

Given the lack of acoustic measures related to the vocalization development of infants who are deaf or hard of hearing, the current investigation seeks to measure the acoustic properties of an infant hearing aid user's productions of /a/, /i/, and /u/ in the natural home environment over the course of two months. The following questions will be explored:

1) How does the infant hearing-aid user's acoustic measures of target vowel productions (/a/, /i/, and /u/) compare to infants with typical hearing?

2) How does the infant hearing-aid user's target vowel productions change between recording one (9-months-old) and recording two (11-months-old)?

3) How does time of day and/or communication partner influence the acoustic measures of the infant hearing aid user's target vowel productions?

In addition, the following exploratory themes will be discussed.

1) How can the use of "parentese" in the home environment could be measured and compared acoustically?

2) Does the infant hearing-aid user produce canonical babble in the home environment as indicated by a formant transition between consonant and vowel less than 120ms?

3) Does the infant hearing-aid user produce any ingressive vocalizations in the home environment?

CHAPTER 2

LITERATURE REVIEW

A Model of the Ontogeny of the Cortical Language Network (Skeide & Friederici, 2016)

Recent progress in the field of neuroscience provides a number of technologies which allow access to the structural and functional neuroanatomy of the brain basis of language. In adults, the dorsal stream (superior longitudinal fasciculus) is most active during sound processing (Sarubbo et al., 2015). The dorsal pathway activates to a novel spoken word, even when the word is not repeated verbally by the listener (Marinkovic et al., 2003), indicating that the dorsal pathway is auditorily activated for speech learning. Furthermore, listening to sounds such as /p/ and /t/, activate the same areas of the motor cortex as articulating /p/ and /t/. This finding indicates that the dorsal pathway is active in conveying “sound map” information in order for the premotor cortex to assign motor movements needed to reconstruct the “sound map.” Electroencephalogram (EEG) studies on infants and toddlers reveal that the ventral and dorsal pathways are in place at birth (Friederici et al., 2017; Brauer et al., 2013). For dorsal pathways, the D1 pathway activation is observable in newborn infants and is likely to support auditory-to-motor mapping, which is necessary for auditory-motor feedback during babbling and language learning in infancy (Friederici, 2011). In summary, neuroimaging evidence suggests that the dorsal pathway selects speech motor movements needed to recreate vocal tract shapes or “sound maps” for reproducing spoken words, which may be an essential component of speech learning.

Source-Filter Theory

In order to increase understanding of articulatory-acoustic relationships, particularly when referring to components of the vocal tract, it is necessary to briefly discuss the theory commonly known as the *linear source-filter theory of speech production* (Fant, 1970, Kent & Read, 2002). In the case of speech production, the sound source for speech is the vocal folds. What makes it possible for humans to produce the variety of sounds required by a language's phonological system is the fact that the sound wave produced by the vocal fold source can be reinforced or altered by a process called resonance. In speech production, the vocal tract is the filter component of the source-filter theory because it changes the amplitudes of the input signal. This is an acoustic concept and relates to the sound formation capabilities of the system that extends from the vocal folds to the lips or nose (Kent & Read, 2002). Anatomically, the vocal tract refers to the pharyngeal, oral, and nasal cavities of speech production and includes the lips, jaw, tongue, velum, pharynx, and the larynx. In general, the vocal folds determine the fundamental frequency (F0), which is the rate of vocal fold vibration and its perceptual correlate is voice pitch. The vocal tract determines the formants frequencies (F1, F2, F3, and beyond), which perceptually is what distinguishes an /u/ production from an /i/ production and so forth (Speaks, 1999). In summary, the vocal tract acts as a resonator and a filter for all parts of the sound created by the vocal folds. All sounds created by the vocal folds must pass through the vocal tract before they are auditorily perceptible and distinguishable.

Acoustic Properties of Vowels

Vowels are phonemes that are produced with minimal constriction of air flow in the vocal tract (Small, 2016). There are 15 Standard American English vowel sounds which are most clearly defined in the widely accepted classification system of the vowel quadrilateral, which visually portrays the articulatory-acoustic relationship as it displays vowels in a two-dimensional figure schematically representative of the oral cavity. Ultrasonographic measurements of adult tongue contour correlated well to formant frequencies for vowels productions of /a/, /i/, and /u/ (Lee et al. 2015). In general, high F1 frequencies reflect lower tongue position in the oral cavity and low F1 frequencies reflect high tongue position (Lee et al., 2015; Small, 2016; Kent & Read, 2002). While high F2 frequencies reflect tongue advancement (protrusion toward to the front of the mouth), and low F2 frequencies reflect tongue retraction (tongue retracted toward the back of the mouth) (Lee et al., 2015; Small, 2016; Kent & Read, 2002). Generally, F3 frequencies are a determinant for phoneme identification, and have been reported to be related to tongue tenseness and lip rounding; however, much less is known about the articulatory-acoustic relationship of F3 frequencies (Small, 2016; Kent & Read, 2002).

Formant properties can be useful for defining articulatory-acoustic relationships, but the relationships are not linear in nature (Stevens & House, 1961). Formant frequencies cannot be used reliably to infer specific articulatory movements (Baer & Alfonso, 1984) because the acoustic signal represents the product of the actions of the speech mechanism and depends in a complex way on the positions and movements of the various articulators (Hodge, 1989). Rather, acoustic measures provide valuable information about the vocal tract as inferences about anatomical and physiological behaviors subserving vowel productions are possible through the use of acoustic analysis.

Because oral structures (especially the tongue and pharynx) change during the production of each individual vowel, there is a corresponding change in resonance throughout the entire vocal tract. These changes in resonance not only give each separate vowel a unique acoustic characteristic quality, they also provide acoustic cues to listeners so that each vowel can be recognized individually (Small, 2016). Considering these acoustic cues are only accessible to those who have intact audibility, it would be expected that infants who are hearing impaired would face challenges in speech learning. In addition to the lack of auditory information received from communication partners, lack of auditory feedback (hearing back of oneself) affects voice, speech production and speech perception skills for children with hearing impairment (Srividya et al., 2016). The fact that most vocal tract configurations are not visible, with the exception of movement of the lips and jaw, further complicates the issue of speech learning accessibility for children who are hearing impaired.

Application of Vowel Acoustic Measures in Speech Development

Acoustic measures of children's speech have a number of research and clinical applications, such as clinical assessment of speech disorders, technically based interventions for speech disorders, development of pediatric speech recognition and speech synthesis technologies, in addition to providing valuable acoustic data which can contribute to the study of speech development (Vorperian & Kent, 2007). Some of the most valuable and unique aspects of acoustic measurements are the implications that can be made from them across several domains of speech development, specifically in the areas of anatomy, neuro-cognition, and linguistic development (Buhr, 1980). When compared over time, acoustic measures may show how a child is learning to tune his/her particular vocal tract structures to produce acoustically definable contrasts of his/her language environment (Hodge, 1989).

From a linguistic perspective, elicitation of target sounds from the pre-linguistic population can require flexible data collection methods in research studies. Prior to implementing effective elicitation techniques, target sounds must be chosen and must fall within a pre-linguistic infant's phonological repertoire, which is usually limited developmentally.

However, vowels appear early in an infant's phonological repertoire and are important milestones in the study of speech development. The early acquisition of vowels is a convenient coincidence when considering the acoustic information vowel formant frequencies can offer developmentally, particularly when comparing an infant to him/herself over time (Vorperian & Kent, 2007).

Formant properties can also be reflective of anatomical structural changes of the vocal tract—namely the lengthening of the vocal tract. In a typically developing infant, the vocal tract changes from a one-tube to a two-tube system (Lieberman, 1975;1977), and the restructuring is complete between 3-and 9-months of age (George, 1978). Changes in the vocal tract not only affects the shape of the vocal tract itself, but also the corresponding acoustic properties of individual vowel productions. Considering the significant changes in vocal tract growth that occur during the first years of life (Lieberman, 1975, 1977; Sasaki et al., 1977; George, 1978) the limited amount of published infant vowel formant frequency data is surprising.

Acoustic Data for Typically Hearing Infant Vowel Productions

Although a number of studies have examined acoustic features of infant vocalizations, very limited data for formant frequency values of prelinguistic infant vocalizations have been published. The seminal Peterson and Barney (1952) study demonstrated that infants' vowels overlap with certain adult vowel categories (particularly / ɛ/ and / æ/), but extend the vowel space beyond that used by adult and child speakers. This finding would be expected because infants' vocal tracts are smaller in size, which would result in higher resonant frequencies and correspondingly higher formant frequencies. The restricted vowel space of infants compared to adults, illustrates that the infant's vocal tract is not anatomically capable of producing the full range of formant frequency variation seen in adult and child speakers. Infants produce vowel-like sounds that show substantial acoustic variation (Peterson & Barney, 1952; Kent & Read, 2002). Fundamental frequency of infants is three to four times as high as that of an adult male, and the formant frequencies of an infant's neutral vowel are spaced at intervals of about 2000Hz, compared to 1000Hz for adult males (Kent & Read, 2002). The higher fundamental frequency values are to be expected because, anatomically speaking, infants have the shortest vocal folds and vocal tracts when compared to both adults and children.

Kent and Murray (1982), explored the acoustic characteristics of "vocalic utterances produced during comfort state" of 21 typically hearing infants and reported mean values for the following: 1) Fundamental frequency—400Hz 2) First formant frequency—1000Hz 3) Second Formant frequency---3000Hz 4) Third formant frequency—5000Hz. F1 and F2 ranges are reported in the tables below.

Table 1: Kent and Murray (1982) F1 and F2 Ranges by Age Group

Age (in months)	F1 Range	F2 Range
3	500Hz- 1500Hz	1800Hz- 3800Hz
6	500Hz- 1700Hz	1600Hz- 3800Hz
9	500Hz-1800Hz	1400Hz- 4100Hz

Table 2: Kent and Murray (1982) F1, F2 and F3 Ranges Across All Age Groups

Age Group (in months)	F1 Range	F2 Range	F3 Range
3, 6, & 9	900-1000Hz	Approx. 3000Hz	Approx. 5000Hz

Aside from a small sample size, the study is limited in that the data provides ranges for all vowels, but does not provide acoustic measures by vowel type. Because formant frequencies are an acoustic measure of the configuration of the vocal tract, valuable data demonstrating the differences between the infants' vowel productions across all vowels is missing from the study.

In order to describe formant frequency as a result of increasing age, Gilbert, Robb, and Chen (1997) published formant frequency data that systematically covered the developmental period of 12-to-36-months of age. The main effect of age on F1 value was significant across the 15-to 36-month period, while significant decreases in F1 occurred at 24-and 36-months compared to 15-, 18-, and 21-month age periods. The pattern for F2 development was similar to that for F1 in that there were no differences in F2 between 15-and 21- months, while average F2 was significantly lower at 24-and 36-months when compared to 15-, 18-, and 21-month age periods (Gilbert et al., 1997). The study demonstrated that measurable acoustic change occurred in the infants' vowel productions over time, however, similar to the Kent and Murray (1982) study, the formant frequency data was collapsed across vowel types. Therefore, F1 and F2 measures were compared across infants and across time, but not across vowels.

Buhr's (1980) single case study of a typically developing infant from age 4-months to age 16-months used both perceptual and acoustic analysis to document formant frequency values by vowel sound over time. Overall, the study demonstrated that F1 had some variation, but no consistent change except for a drop at 21-weeks; while F2 showed some variation, but no consistent trend, and F3 overall had tremendous variation (Buhr, 1980). Besides reporting the limitation of a single case study design, Buhr (1980) discussed a recurring dilemma in the acoustic study of infant vocalizations literature. Working with the prelinguistic population presents elicitation challenges which can impact data collection procedures as well as the results of the best designed studies. For example, Buhr's (1980) methods section reported "recordings were made at the home of the mother or in an insulated recording booth at the university.…either one or two tapes were made per session, depending upon how loquacious L.S. was from one session to the next."

Hodge's (1989) methods section, which compared perceptual and acoustic measures of 115 normal speakers whose ages ranged from infancy to adulthood, described simple elicitation procedures for the older populations involved in the study; however, for the two youngest populations the procedures reported were as follows:

> "Attempts to elicit vocalizations included…presentation of bright colored objects and toys…bouncing and other action 'games' …placing an object within sight but out of reach of the infant…. However, vocal output…was low and so recording was undertaken at the subjects' homes…coordinating with the subject's daily routine…. For the one-year-olds and infants, a smaller number of vowel tokens was available…and not all of the vowel categories were attempted by the infants" (Hodge, 1989).

The elicitation limitations of Hodge's (1989) study impacted the completeness of formant frequency data, particularly for the youngest prelinguistic population. In fact, of the 115 total speakers involved in the study, 15 were infants ages 7.7- to 9.5-months old; and not all of the infants produced all of the vowels. Of the 15 infants in this age group, 0 out of 15 infants produced /a/, 3 out of 15 produced /i/, and 2 out of 15 produced /u/. These numbers represent the subjects' mean as it contributed to the group mean and are represented by the number in parenthesis next to the vowel identifier in the table below. The table also displays formant frequency values and standard deviations by vowel for typically hearing infants ages 7.7- to 9.5-months.

Table 3: Hodge (1989) F0-F3 Values by Vowel for 7.7- to 9.5-month Infants

Vowel	F0	F1	F2	F3
/i/ (3)	384 (sd 44)	655 (sd 41)	3542 (sd 347)	4538 (sd 438)
/a/ (0)	-	-	-	-
/u/ (2)	351 (sd-)	558 (sd-)	1288-1052 (sd-)	3335 (sd-)

Of the 115 total speakers in Hodge's (1989) study, 20 fell in the one-year-old age category; and not all of the one-year-olds produced all of the target vowels. In fact, 6 out of 20 infants produced /a/, 11 out of 20 produced /i/, and 15 out of 20 produced /u/. These numbers represent the infants' mean as it contributed to the group mean and are represented by the number in parenthesis next to the vowel identifier in the table below. The table also displays formant frequency values and standard deviations by vowel for typically developing one-year-olds.

Table 4: Hodge (1989) F0-F3 Values by Vowel for 1-year-old Infants

Vowel	F0	F1	F2	F3
/i/ (11)	385 (sd 72)	589 (sd 78)	3545 (sd 205)	4392 (sd 217)
/a/ (6)	292 (sd 35)	1072 (sd 110)	1594 (sd 109)	3943 (sd 405)
/u/ (15)	376 (sd 53)	594-574 (sd 51-40)	1581-1423 (sd 250-197)	3486 (sd 196)

In addition to the lack of published studies for the pre-linguistic infant population, there is a lack of uniformity in data reporting, particularly in reporting formant frequency values for this population. This lack of uniformity creates challenges for both clinicians and researchers who are attempting to make comparisons across the published data in a meaningful way. The Kuhl and Meltzoff (1996) study used a systematic reporting of formant frequency data, which was similar to Kent and Read's (2002) table used to report formant frequency data for typical adult male and female speakers. Using this format could be useful in building a detailed acoustic taxonomy of normal vocalization behaviors that could serve as a metric to evaluate atypical vocal development (Vorperian & Kent, 2007; Bauer & Kent, 1986).

There are two studies mentioned above that include infants of a comparable age to the infant hearing aid user in this study: Kent and Murray (1982) and Hodge (1989). Because both studies reported data for typically developing infants, the combination of both of these studies will be used as normative data from which to compare the vocalizations of the infant hearing-aid user in the current study (Tables 1-4).

Acoustic Data for Deaf/Hard of Hearing Infants

Due to the widespread adoption of universal newborn hearing screening, early identification and intervention have been instrumental in helping to prevent communication deficits in infants with hearing loss. However, even when hearing loss is identified early, children who are deaf or hard of hearing (DHH) may not develop speech production skills in the same manner as their peers with normal hearing (NH). DHH infant vocalizations have been reported to resemble the vocalizations of infants who are much younger (Oller et al., 1985), and exhibit limited repetitive canonical babbling when compared to NH infants (Oller et al., 1985; Kent et al., 1987).

Perceptually, DHH speech has been characterized as too loud, too soft, or varying irregularly, most likely due to lack of auditory feedback (Oller et al., 1985; Srividya et al., 2016). Overall, this speech is described as tense, flat, breathy, and harsh with differences in pitch and intonation (Srividya et al., 2016). Acoustically, DHH speech is reported as higher in pitch (higher F0 values) when compared to NH children (Srividya et al., 2016). With early identification and intervention, children who receive cochlear implants (CIs) eventually achieve typical voice parameters—though the range of outcome variability is typically higher compared to NH children (Srividya et al., 2016).

Acoustic measures have demonstrated the importance of hearing in speech production skills of infants. Children who had otitis media early (before 6 months) showed a reduced F2 range when compared to children with late-onset otitis media (after 6-months) (Rvachew et al., 1996). The children with early-onset otitis media were delayed in acquiring the extent of tongue placement in the front-back dimension, as measured by F2 standard deviation. This finding illustrates the importance of early audition to vowel acquisition.

Kent et al. (1987) studied the vocal development of identical twin boys, one with NH and the other with profound hearing loss bilaterally using acoustic analysis. The twin boys differed primarily in: 1) formant frequencies of vocalic segments; 2) syllable structures; and 3) consonant repertoire, especially with respect to place of articulation and use of fricatives, affricates, and trills. The DHH infant demonstrated a more restricted data set than his NH brother in every acoustic measure except one—fundamental frequency (F0). The DHH infant exhibited a larger F0 range within an utterance when compared to NH brother (Kent et. al, 1987).

McGowan et al. (2008) compared the speech production of 12-month-old DHH infants with those of 12-month-old NH infants (10 infants in each group). The speech inventories of DHH children differed from the inventories of NH children in that DHH infants had fewer multisyllable utterances with consonants, fewer fricatives, and fewer stops with alveolar-velar stop place than children with NH (McGowan et al., 2008). When analyzing vowel formant frequencies, the study found more restricted front-back tongue positions (F2) for vowels of DHH infants than NH infants; while there appeared to be only slight differences in the use of tongue height (F1) between the two groups. The pattern of lower F2 values for DHH infants compared to NH infants was replicated by infants who spoke different languages: Standard American English (McGowan et al., 2008) and Belgian Standard Dutch (Baudonck et al., 2001) respectively.

According to ASHA's Clinical Practice Guidelines for Hearing Loss Assessment and Intervention for Young Children (Age 0-3 Years), vowel sounds should be among the first sounds selected as therapy targets for DHH children because a variety of clear vowel sounds constitutes a foundation for the development of natural voice (NYS Department of Health 2007). Because variation in vowel formant frequencies has been demonstrated in acoustic studies of DHH infants (Kent et. al, 1987; McGowen et al. 2008; Baudonck et al., 2011), measuring and publishing the fundamental frequency and formant frequency values of these early developing vowel sounds for prelinguistic DHH children may provide insight into the variability patterns occurring in DHH infants' speech.

In summary, differences in speech development, speech production, and perceptual speech quality have been demonstrated in published acoustic analysis studies of DHH infant vocalizations when compared to their NH peers. Vowel sounds have been identified as not only early developing sounds in a NH infant's phonological repertoire, but also recommended as initial speech therapy targets for DHH infants. Replicated studies demonstrate that lowered F2 values in the vowel productions of DHH infants may provide measurable insight into the perceptual differences between DHH infant vocalizations and NH infant vocalizations.

The current investigation hopes to demonstrate some examples of data reporting so that fundamental frequency and formant values can be meaningfully compared not only intra-subject over time, but also across other studies. In answering the research questions posed, this investigation will demonstrate how Praat and LENA technologies can be used to overcome some of the elicitation and data collection challenges prevalent in previous studies. A brief description of both the Praat and LENA systems follows, in addition to an overview of their presence in the current literature particularly in the pediatric DHH infant literature.

Praat

Praat (Boersma & Weenink, 1992-2020) is a computer program for analyzing, synthesizing and manipulating speech and other sounds. It is open source, available free of charge for all major computer platforms, and can be downloaded from praat.org. Praat's acoustic analysis screen displays both the waveform and spectrogram of audio files. The waveform of a sound is the direct visualization of the sound as recorded by a microphone and represents the air pressure as a function of time. In the waveform, one can directly see when there is silence and how long the utterances are, but inferences regarding other acoustic properties of speech such as intensity can be made from the waveform as well (Boersma, 2013).

The spectrogram shows the frequency contents of a sound as a function of time, and thereby follows the capabilities of the basilar membrane in the inner ear, which also divides up the sound into its frequency components at every point in time (Boersma, 2013). Some examples of the waveform and spectrogram display in Praat are shown below.

Figure 1: Praat Waveform and Spectrogram of Infant Producing /a/

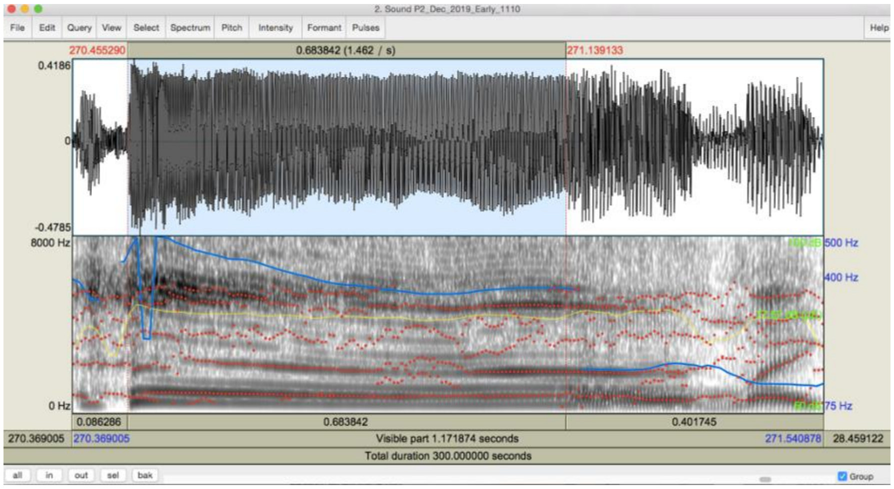


Figure 2: Praat Waveform and Spectrogram of Infant Producing /i/

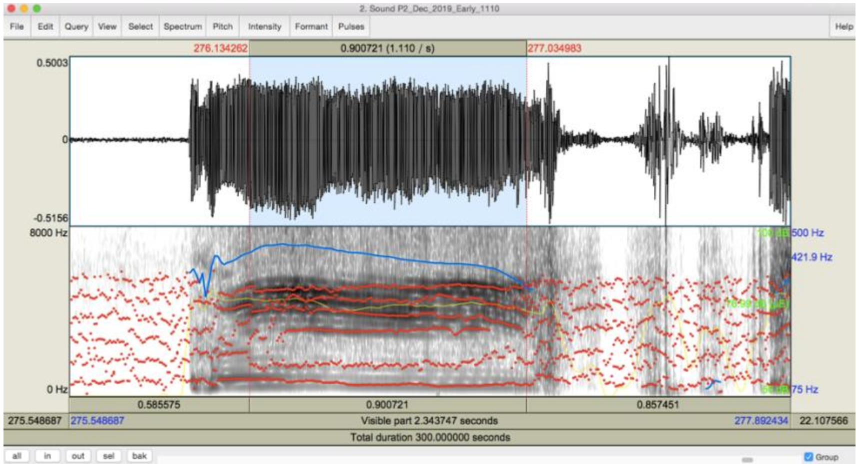
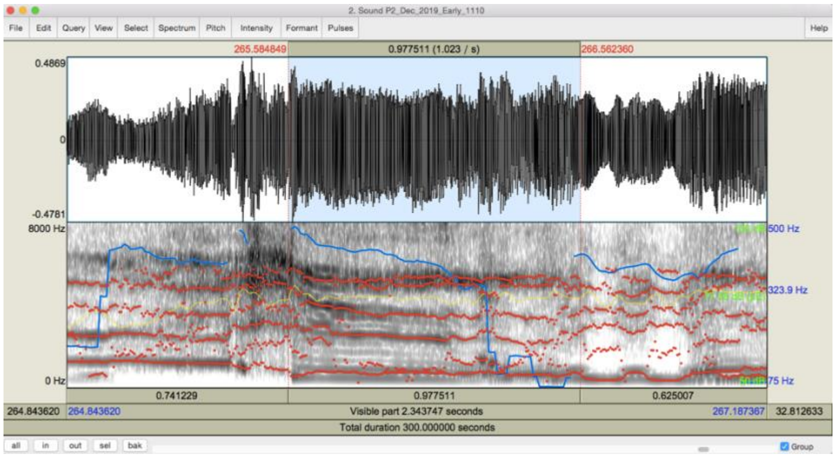


Figure 3: Praat Waveform and Spectrogram of Infant Producing /u/



In the spectrogram, time runs from left to right and frequency runs from bottom to top. The vertical stripes represent vocal fold vibrations and the dark horizontal bands are the formants, which are a visual representation of the vocal tract configuration. Praat uses a reverse all-pole filtering algorithm to extract formants. The algorithm manages to separate the source signal (vocal folds) from the filter signal (vocal tract) to some extent. Even though the automated formant analysis algorithm can be inaccurate under certain conditions, an automated formant measurement is the most commonly used method for acoustically analyzing vowel quality, and using this method can make vowel quality data comparable with data published by others (Boersma, 2013).

Praat generates accurate and comparable F0 and F1-F4 data for both synthesized vowels and adult male natural vowels (Burris et al., 2014); however, results have been shown to be less consistent for vowel productions of women and children. Improved output values for these populations were demonstrated with the manipulation of program default settings; however, software packages are highly variable and manuals do not provide explicit guidance on how settings should be adjusted to accommodate differences in speaker characteristics (Burris et al., 2014).

Some general published program setting guidance in the pediatric acoustics literature includes ensuring settings are set to the number of formants expected plus two, and to consider that infants have large ranges of fundamental frequency, with minimum values reaching down to the adult male range and maximum values extending to 1000Hz or higher (Burris et al., 2014, Kent & Read, 2002). Guidance for F0 settings for infant vocalizations can be derived from Kent and Murray (1982) who published a mean fundamental frequency of 400Hz for 21 typically developing infants (ages 3-, 6-, and 9-months).

In summary, Praat is a free, open source computer program which can be used for analyzing, synthesizing and manipulating speech as well as other sounds. Praat displays the waveform, a visual representation of air pressure as a function of time, and the spectrogram, a visual representation of frequency contents of a sound as a function of time. In addition to the visual information the waveform and spectrogram provide individually and collectively, Praat's reverse all-pole filtering algorithm can be used to extract formant frequency values. Praat has been shown to generate accurate and comparable vowel F0 and formant frequency values for F1-F4 when compared to other AASPs (Burris et al., 2014). Praat holds a prominent presence in recent DHH children's research, and some examples include examination of acoustic parameters of NH children's vocalizations compared to the vocalizations of children with CIs (Souza et al., 2012), and comparing vowel productions between NH, hearing-aided, and CI Dutch children (Verhoeven et al., 2016).

Language ENvironment Analysis (LENA)

The most prominent, pioneering system for collecting and analyzing audio of children and families in their natural home environments is the Language ENvironment Analysis (LENA) system. The LENA system was first developed in the mid-2000s and is currently in use by over

200 universities, school districts, hospitals, and other research institutions (LENA Foundation, 2020).

The primary components of the LENA system are the Digital Language Processor (DLP) and related software. The DLP is an acoustic recording device that weighs 2 ounces and is approximately the size of a deck of cards. The device is worn by the child in a chest pocket on an outer piece of specially-designed clothing. The clothing allows for the DLP to be worn comfortably and unobtrusively for a full day while maintaining the microphone at a relatively fixed distance from the child's mouth. The DLP records up to 16 hours of raw audio, which is transferred to a computer after the recording is complete and can be analyzed with the associated software.

The proprietary speech recognition software segments the audio and uses complex algorithms to analyze the audio file. The algorithms are trained to identify and differentiate adult speech, child speech, and tv/electronic noise. The software then generates objective, actionable feedback reports for caregivers on the quantity and quality of talk in their child's environment. The reliability and validity of LENA segment categorization has been tested and the software accurately identified 82% of the adult speech segments, with 2% erroneously coded as child speech and 4% erroneously coded as television, when compared to a human transcriber (Xu et. al (2009).

The LENA technology's presence in recent pediatric DHH research focuses mainly on language outcomes of DHH children (Aragon & Yoshinaga-Itano, 2012; VanDam et al., 2015) One of the criticisms of the LENA software is that it can only record and analyze oral linguistic input and does not capture other important components of communication such as gestures and body language (Sultana et al., 2019). While this may be a limitation of the LENA when investigating language outcomes, it is not a limitation when referring to data collection for acoustic analysis of vocalizations. Ko et al. (2016) utilized LENA in order to capture recordings of mother-child (infants and toddlers) dyads, and used Praat technology for acoustic analysis. However, the study did not analyze formant frequency values for this population as only F0 values were reported.

In summary, utilizing LENA technology allows researchers to automatically analyze very large datasets of naturalistically-collected child speech; however, it is currently difficult to assemble a generalized or comprehensive picture of speech and vocal development in DHH children. Many factors contribute to this: data collection differences, differences in research questions and goals, inconsistent definitions and groupings of variables, and varying levels of reporting (Moeller et al. 2007a, b).

CHAPTER 3

METHODS

Participants

All research activities were conducted with the approval of the University of Georgia Institutional Review Board in August of 2019. The child participant was recruited from the Auditory-Verbal Center, Inc (AV Center) in Atlanta, GA. Inclusion criteria included: 1) between 2- and 48-months of age at enrollment, 2) English as primary language with no sign use in the home to supplement communication, 3) enrolled in auditory verbal (AV) therapy at participating AV Center, 4) no reported cognitive or intellectual disabilities at the time of data collection, and 5) no comorbid disorders.

Recruitment Procedures

Families received study information from the AV Center, Inc or Atlanta Speech School. Families indicated interest in being contacted by the research team by completing a permission-to-be-contacted form, or they could directly contact the research team using the contact information provided by the staff at the AV Center, Inc. or the Atlanta Speech School. A member of the research team contacted the family, and the family participated in a phone screening for eligibility. Consent documents were reviewed at this time and/or a copy of the documents were sent to the family via mail or email. A face-to-face visit was scheduled at the family's home in which the informed consent and HIPAA authorization forms, as well as the study criteria were discussed in detail. An informed consent was signed indicating the family's willingness to participate.

Using the methods listed above, one family was recruited for this single-case pilot. The infant participant was enrolled in the study at 8.5-months of age. During the time of the first recording, the infant participant was approximately 9-months of age; and for the second recording, he was approximately 11-months of age. The infant lives at home with his father, mother, and older brother. The mother is a stay-at-home mom and is the primary caregiver for the majority of the day.

The etiology of the infant's symmetrical, bilateral, moderate sensorineural hearing loss is Connexin 26, and both his mother and father tested positive for the gene. The infant was identified at age 3-months, and the results of his initial hearing evaluation, VRA with warble tones using insert earphones, showed mild hearing loss 250Hz-1000Hz, sloping to moderate hearing loss 2000Hz-8000Hz in both ears. He was fit with hearing aids at 4-months of age, and in the aided condition, speech signals were audible across all frequency ranges at 25dB for both right and left ears. At the time of his 9-month recording, his audiogram was similar to his initial audiogram. However, at the time of his 11-month recording, his audiogram showed similar results for the right ear, but his left ear showed evidence of middle ear pathology with his thresholds in the moderate range for 250Hz-1000Hz.

The infant and his mother attend AV therapy one day per week for 1-hour sessions, using a mixed teletherapy and in-person approach. The AV Center serves children from birth to 18 years and their families, providing a range of clinical services that include initial diagnosis of hearing loss and audiological follow-up services. The AV therapy approach is designed for children with hearing loss to develop natural spoken language and hearing abilities through family training.

The infant’s AV therapist reported the infant had stronger receptive language skills than expressive. The infant's mother received AV training in several techniques during the timeframe of the study including 1) serve and return (mom imitates any vocalizations the infant makes), 2) singing songs, 3) singing with babbling (singing a song on a CV syllable to encourage babbling), 4) wait time (looking at infant with an expectant look and giving him time to vocalize), 5) learning to listen- function words (incorporating target words in weekly routine), and 6) learning to listen- sounds (building associations between objects and sounds, such as saying "moo" when holding a cow).

Data Collection

During the face-to-face meeting, the parent/caregiver was provided with verbal and written instructions on the care and use of the LENA device, the LENA device itself, a LENA clothing item (vest or T-shirt), and activity log sheet for each day of recording, and a postage-paid envelope for return of the materials after completion of recording. The infant’s parents also completed a parental self-efficacy and involvement scale as well as the vocal development screening and demographic questionnaire.

To collect the audio recordings, the family was instructed to begin recording as soon as the child woke in the morning and to have the child wear the device for the full day. Using the directions provided at the face-to-face meeting, the family then completed a full day LENA recording (12 to 16 hours) that the parent/caregiver felt was representative of a “typical day.” The parent/caregiver was asked to complete the hourly activity log for the day being recorded, which detailed what activities occurred during the recording period and when they occurred.

On the day following the recording, the parent/caregiver returned the LENA device, clothing, and activity log via mail using the provided envelope. Parents/caregivers had the option to withdraw consent to use any or all of the recorded data at any time during the study. Upon receipt of the device and materials, a member of the research team contacted the family by phone to confirm if any of the sections of recording needed to be removed from analysis. If the family requested exclusion of a segment or the entirety of a recording, the request would have been honored and these portions of the recording would have been immediately destroyed. The family who participated in this single case study did not request exclusions of any data provided.

For the second recording, the family was contacted via phone two months after the first recording was submitted. After agreeing to record a second recording, the family was provided a new LENA device, LENA clothing item (vest or T-shirt), and activity log sheet, as well as a postage-paid envelope for return of the materials via mail. After completing the recording and mailing the materials back, the researchers confirmed if any sections of the recording needed to be removed from analysis; and once again the family did not request any exclusions.

Data Extraction

The audio clips were extracted from the LENA device onto a laboratory desktop computer using the LENA software. The LENA "Child Vocalizations" algorithm was used to determine the times of day when the child produced the highest number of vocalizations. The audio files identified by the LENA algorithm were broken down to the smallest time segment the program allows—five-minute segments. In order to ensure a good representation of the infant's vocalizations throughout the day, the files were divided into three sections per day. For the first recording (9-months-old), the times were divided into Early (10:00-15:00), Mid (15:00-19:00), and Late (19:00-22:00). For the second recording (11-months-old), the times were divided into Early (10:55-14:55), Mid (14:55-18:55), and Late (18:55-22:55). The variably of the timeframes in each section between the two recordings was due to when the child woke from sleeping through the night.

The researcher listened to each five-minute segment to ensure the LENA algorithm correctly identified vocalizations produced by the infant participant. Occasionally, the algorithm identified times of high child vocalization when in fact, the vocalizations were not produced by the infant participant, but by someone or something else, such as his older brother, background television, or “talking” toy. Five-minute segments were excluded from further acoustic analysis if 1) the majority of the vocalizations were not produced by the infant, or 2) the number of algorithm-identified infant vocalizations were more vegetative in nature (e.g., coughing, burping, sneezing, breathing heavy) rather than speech-like utterances. This process continued until 12-audio segments from each portion of the day were pulled, resulting in 36-audio segments from recording one (9-months-old) and 36-audio recording segments from recording two (11-months-old). A total of 360-minutes of recording underwent acoustic analysis described below.

Acoustic Analysis

The 72 five-minute audio recordings (36 from recording one and 36 from recording two) were then exported from the LENA program onto an encrypted thumb drive. The researcher imported one five-minute audio file at a time into Praat. In order to account for some of the inconsistency and variability the Praat software system has demonstrated when measuring infant vocalizations, the guidance detailed in the literature review above as published by Kent et al. (2014), and Kent and Read (2002) was followed. All laboratory computers used for acoustic analysis in this study were set to following: 1) Maximum formant (Hz): 6000.0, 2) Number of formants: 6.0, 3) Window length (s): 0.025, 4) Dynamic range (dB): 60.0, and 5) Dot size (mm): 1.0

Using Praat's play feature, the researcher listened to the segment while simultaneously watching the wave file and spectrogram. The researcher coded infant vowel productions as /a/, /i/, or /u/. When one of the target vowel sounds was identified by the researcher, the zoom feature was used to clearly identify the boundaries of the vowel production and the highlight feature was used to isolate the portion of the wave file representative of the vowel production. In order to systematically organize target vowel productions, files were identified by a time stamp which included the month and year of recording, which segment of the day the vocalization occurred, and the starting time in seconds as displayed in Praat (e.g., Dec 2019 Early Praat: 45.70983). The time stamps were organized in an Excel spreadsheet by vowel production (/a/, /i/, or /u/) and month (Oct= recording one, Dec= recording two).

The time stamped vowel productions that were documented on the Excel spreadsheet were then secondarily coded in order to systematically categorize communication environment. Because the recordings were made in a home environment, there were multiple levels of the communication environment. For simplicity, the coding aggregated as follows: 1) "alone" (alone or with family members in the background) 2) "mom" (communication with mom regardless if other family members are in the background), 3) "without mom" (communication with dad or brother), 4) "more than mom" (communication with mom and other family members).

The time stamp clearly identified the start time portion of the vowel production desired for further acoustic analysis. In order to clearly identify the end time, the researcher used the highlighted vowel production in the wave file to derive the length of the vowel vocalization in seconds. The length of vocalization was recorded next to the time stamp on the Excel spreadsheet. Vowel productions were excluded from acoustic analysis if 1) the background noise interfered with the quality of the recorded vocalization, or 2) multiple family members were speaking at the same time, making it too difficult to separate and analyze the infant's vowel production in isolation.

Two trained undergraduate research assistants from the Pediatric Auditory and Early Speech Development Lab at the University of Georgia used the time stamp and length of vocalization measurement reported in the Excel spreadsheet to locate the desired vocalization in Praat. Each research assistant independently analyzed the time-stamped segments identified by the lead researcher for Mean F0 (fundamental frequency or pitch), Mean F1 (formant 1 or tongue height), Mean F2 (formant 2 or tongue advancement), Mean F3 (formant 3 or tongue tenseness). The research assistants acoustically analyzed a total of 571 infant vowel productions: 88 /a/ productions on recording one and 109 /a/ productions on recording two; 117 /i/ productions on recording one and 161 /i/ productions on recording two; 24 /u/ productions on recording one and 72 /u/ productions on recording two.

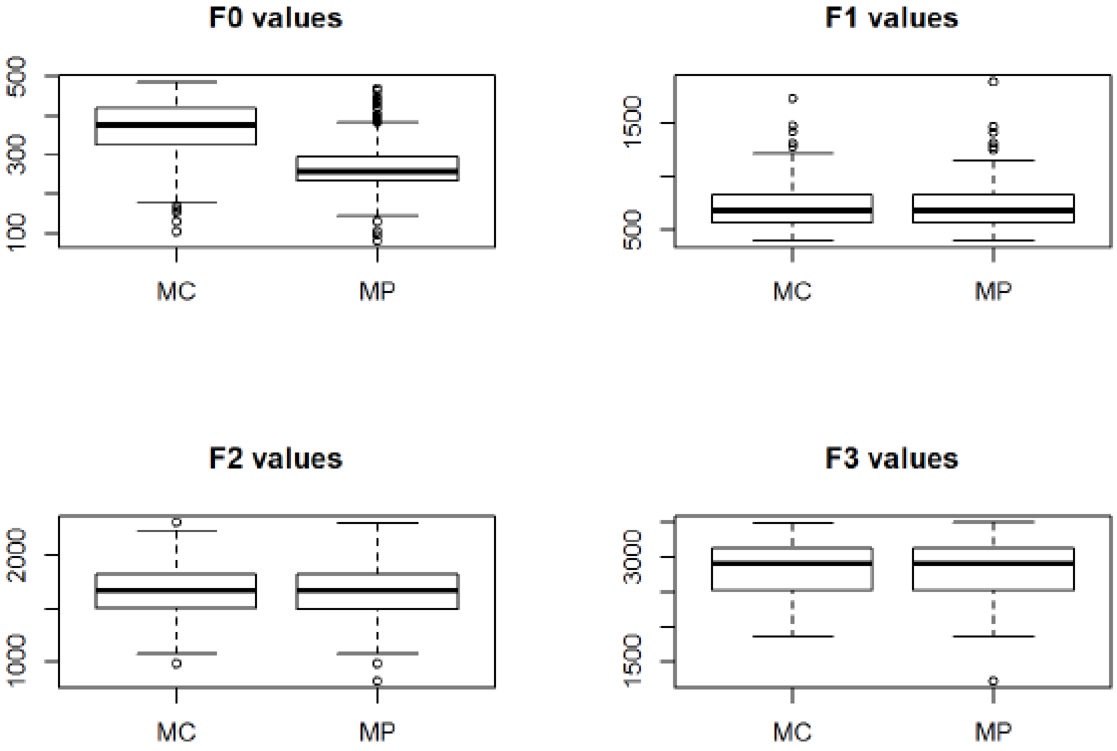
Reliability

For this study, inter-rater agreement of the acoustic analysis performed in Praat was determined by having both undergraduate research assistants complete 100% of the measures across vowels, recordings, and acoustic parameters (F0, F1, etc.). The two trained research assistants (denoted as "MC" and "MP") analyzed the same data independently of each other, thus yielding a pseudoreplication. To enhance reliability, research assistants were trained by the lead researcher simultaneously, and the formant settings in the Praat software of all three lab computers were calibrated to the same values (listed in the methods section).

Prior to analyzing data independently, research assistants analyzed segments that were previously analyzed by the lead researcher to test their rating reliability. After adjusting the formant settings to the settings listed in the methods section above, both research assistants obtained values of Mean F0, Mean F1, Mean F2, and Mean F3 within 1Hz of the lead researcher.

To evaluate the reliability of the two data-sets, intraclass correlation coefficient (ICC) statistical analysis was used to measure the consistency of the two replications (Figure 6). The data revealed that the ICC values for F1, F2, and F3 were approximate to 1, indicating strong agreement; however, the ICC value for F0 was not significantly different from 0.

Figure 4: ICC Reliability Results: F0 95% Confidence Interval: -0.029< ICC< 0.046; F1 95% Confidence Interval: 0.949< ICC < 0.963; F2 95% Confidence Interval: 0.975< ICC< 0.982; F3: Confidence Interval: 0.987< ICC< 0.991



The measures from the two research assistants were very close with the exception of F0 values. Thus, instead of using the average of the replicates, in analysis of F0 values, only the data recorded by “MC” will be reported and used in further statistical analysis tests. “MC”’s data set was chosen because the F0 values reported were closer to normative infant values. For F1, F2, and F3 values, the average of the replicates (“MC” and “MP”) will be used.

CHAPTER 4

RESULTS

Summary Data Relative to Tokens Collected

Tables 5-8 summarize data characteristics from the study. Table 5 reports the number of tokens analyzed for each vowel across both recordings as well as the changes in number of production. It should be noted that Table 5 reflects only a portion of the infant's vocal output. The infant produced vowels other than the target vowels (/a/, /i/, and /u/) and some of the target vowels were not acoustically analyzed due to poor audio quality (e.g., multiple speakers talking at once, background noise interference, etc.). The most produced token at both 9-months and 11-months of age was /i/, followed by /a/, and the least produced token at both 9-months and 11-months of age was /u/. Overall, the infant increased productions of all three target vowels (/a/, /i/, and /u/) from recording one (9-months) to recording two (11-months).

Table 5: Number of Tokens Based on Vowel Over Time

	# of /a/ tokens	# of /i/ tokens	# of /u/ tokens
9-months	88	117	24
11-months	109	161	72
Difference	21	44	48

Tables 6 and 7 show distribution of tokens analyzed based upon the time of day in which they were produced for the 9-and-11-month recordings, respectively. The majority of tokens analyzed for the 9-month recording came from the Late and Early portions of the day.

The tokens analyzed for the 11-month recording were more evenly split between all three portions of the day. Overall, a representative sample was analyzed from all portions of the day for both recordings.

Table 6: Distribution of Tokens Based on Time of Day

Age	Vowel	Early	Mid	Late
9-mos	/a/ (n= 88)	31 (35.23%)	23 (26.14%)	34 (38.64%)
9-mos	/i/ (n= 117)	45 (38.46%)	31 (26.50%)	41 (35.04%)
9-mos	/u/ (n= 24)	8 (33.33%)	3 (12.50%)	13 (54.17%)
11-mos	/a/ (n= 109)	40 (36.70%)	42 (38.53%)	27 (24.77%)
11-mos	/i/ (n= 161)	47 (29.19%)	64 (39.75%)	50 (31.06%)
11-mos	/u/ (n= 72)	26 (36.11%)	21 (29.17%)	25 (34.72%)

Table 7 provides summary information related to the length of vowel production for the tokens analyzed. This table includes the infant's mean length of production, and range across the three vowels investigated. The infant's mean length of /a/ productions decreased by 0.056 seconds from recording one (9-months) to recording two (11-months). The infant's mean length of /i/ productions increased by 0.096 seconds from recording one (9-months) to recording two

(11-months). The infant's mean length of /u/ productions decreased by 0.141 seconds from recording one (9-months) to recording two (11-months). In general, the infant's /i/ productions were the longest in length out of the three target vowels, and the infant's productions of /a/ were the shortest in length.

Table 7: Length of Tokens by Age and Vowel

Age & Vowel	Min (sec)	Max (sec)	Mean (sec)
9-months /a/	0.098	3.636	0.506
9-months /i/	0.104	1.619	0.618
9-months /u/	0.218	1.320	0.675
11-months /a/	0.060	1.947	0.450
11-months /i/	0.145	3.038	0.714
11-months /u/	0.232	1.366	0.534

Table 8 provides the mean and standard deviation values for the acoustic parameters measured across vowels and recordings in this study. This table serves as the basis for the comparisons to follow relative to normative data for infants with typical hearing, as well as comparisons between the infant's own productions at 9-months and 11-months. The table displays the average acoustic measures and standard deviations derived from the two undergraduate research assistants' records. For Mean F0, only one research assistant's data was used ("MC"), as the data recorded was closer to published infant norm values. Mean F1, Mean F2, and Mean F3 are average values of the replicates.

Table 8: Mean and SD Values by Age, Vowel, and Acoustic Measurement

Age	Vowel	F0 (SD) in Hz	F1 (SD) in Hz	F2 (SD) in Hz	F3 (SD) in Hz
9-mos	/a/	336.47 (74.35)	874.18 (177.46)	1684.28 (230.83)	2600.27 (258.58)
9-mos	/i/	384.69 (59.68)	620.46 (107.31)	1661.07 (213.42)	3142.40 (184.61)
9-mos	/u/	382.63 (56.63)	653.35 (147.15)	1510.89 (153.01)	2468.83 (297.35)
11-mos	/a/	343.51 (65.62)	863.66 (145.42)	1616.70 (253.47)	2523.25 (303.51)
11-mos	/i/	396.62 (56.87)	632.21 (129.97)	1737.11 (207.38)	3094.74 (164.96)
11-mos	/u/	343.69 (73.68)	596.35 (115.51)	1553.33 (221.96)	2591.91 (326.50)

Comparison of Observed 9-Month Values to Normative Data (Across Vowels)

Kent and Murray (1982) published normative F1 and F2 values for “vocalic utterances recorded during infants’ comfort states” at 9-months of age. Individual vowel type and distribution were not reported. Figures 5 and 6 show the current study’s values compared to the Kent and Murray (1982) values. Due to a lack of published standard deviation values from the

Kent and Murray (1982) normative data, an assumption was made that the standard deviations for the normative data are the same as the standard deviations found for the observed values in the current study. By calculating the probability of observed values within the normative range, and conducting a t-test between the observed distribution and the normative distribution, histograms were generated to show where the observed values fall when compared to the Kent and Murray (1982) normative values. The observed mean value of F1 was 721.4Hz which falls below the mean normative value of F1; however, the majority of observed F1 values (i.e., 92.58%) are located within the lower limit of the normative range. The observed mean value of F2 was 1654.21Hz which falls below the mean normative value of F2. Similar to F1 values, the majority of observed F2 values (i.e., 84.72%) are within the lower limit of the normative range.

Figure 5: Distribution of F1 Values at 9-months

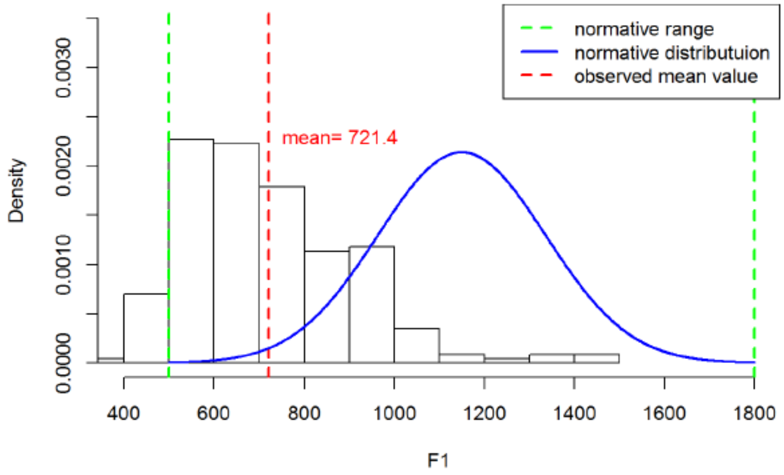
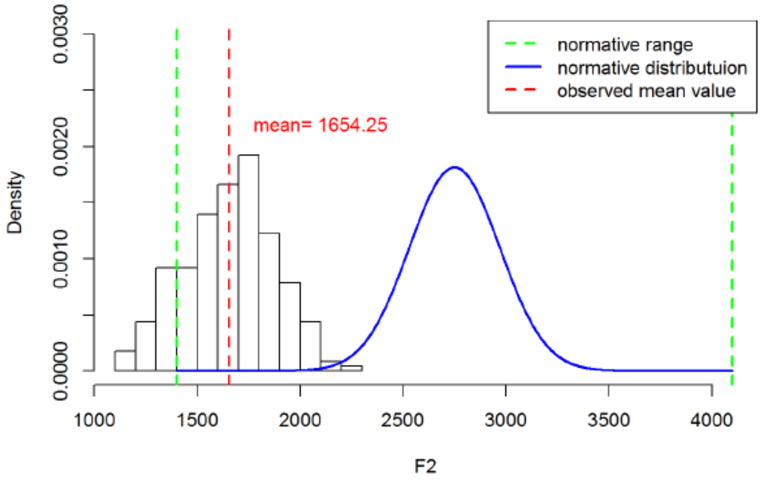


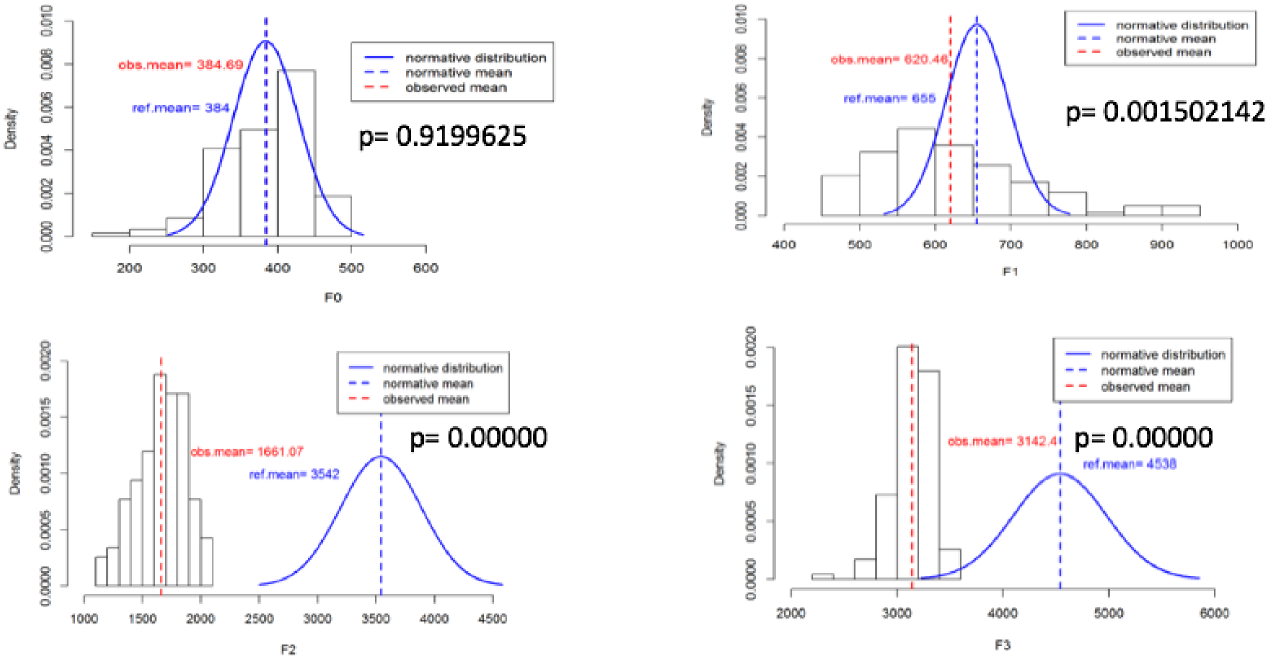
Figure 6: Distribution of F2 Values at 9-months



Comparison of Observed Values to Normative Data (Individual Vowels)

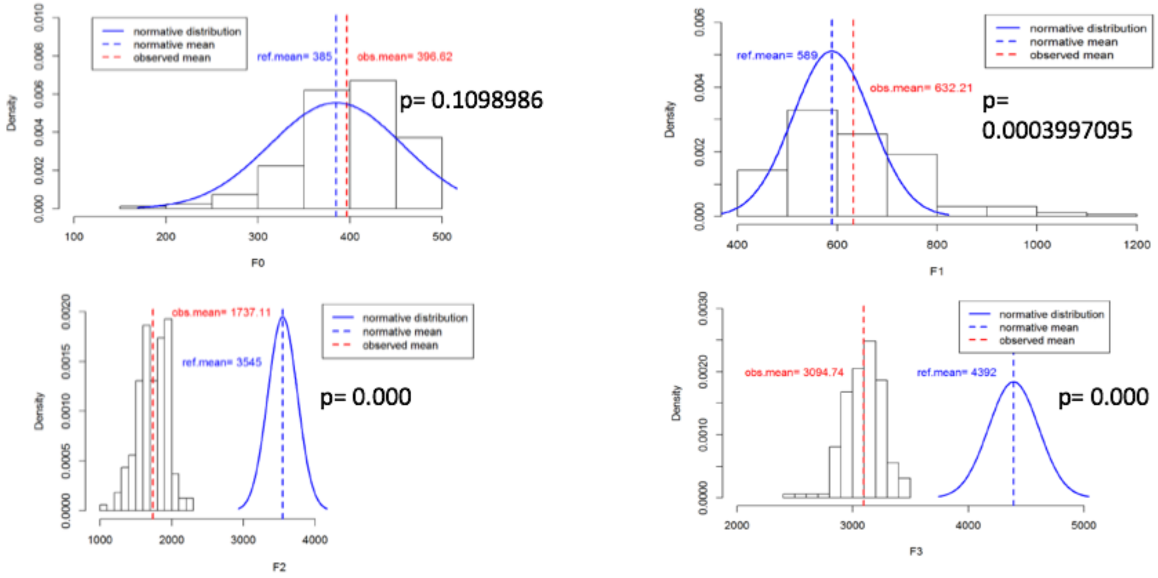
The observed acoustic measures for each vowel (/a/, /i/, and /u/) were compared to the acoustic measures of vowels produced by typically hearing infants as reported by Hodge (1989). The data in this section is first reported by vowel type (/a/, /i/, or /u/) in histograms (Figures 7-12), to provide a visual description of the data in relation to the normative values. Figures 7-12 demonstrate that the observed values fit the normative distribution quite well. Second, t-tests were conducted between the two normal distributions for each acoustic measure of each vowel type to determine if significant differences exist. Results of the t-tests are reported in Tables 9-11 following presentation of the histograms in Figures 7-12.

Figure 7: Histograms for /i/ Productions at 9-months vs 9-month Norms (Hodge, 1989)



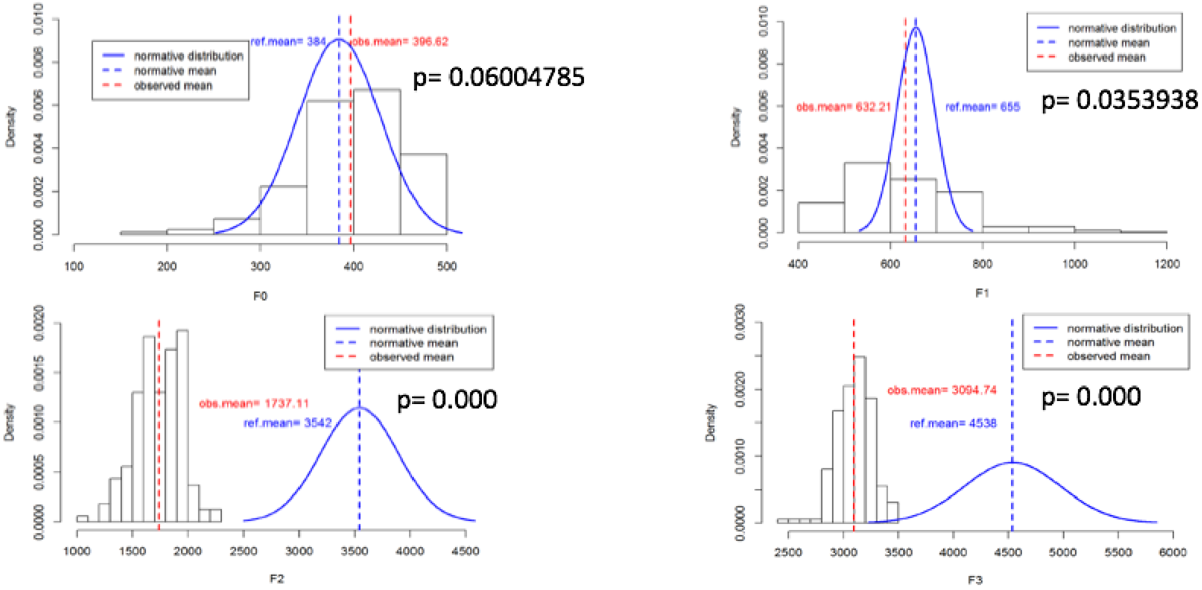
The observed Mean F0 for /i/ at 9-months was not significantly different from the normative mean (p= 0.920 from Table 9). The observed Mean F1 for /i/ at 9-months was significantly lower than the normative mean (p= 0.002 from Table 9). The observed Mean F2 for /i/ at 9-months was significantly lower than the normative mean (p= 0.000 from Table 9). The observed Mean F3 for /i/ at 9-months was significantly lower than the normative mean (p= 0.000 from Table 9).

Figure 8: Histograms for /i/ Productions at 11-months vs 1-year Norms (Hodge, 1989)



The observed Mean F0 for /i/ at 11-months was not significantly different from the normative mean (p= 0.110 from Table 9). The observed Mean F1 for /i/ at 11-months was significantly higher than the normative mean (p= 0.000 from Table 9). The observed Mean F2 for /i/ at 11-months was significantly lower than the normative mean (p= 0.000 from Table 9). The observed Mean F3 for /i/ at 11-months was significantly lower than the normative mean (p= 0.000 from Table 9).

Figure 9: Histograms for /i/ Productions at 11-months vs 9-month Norms (Hodge, 1989)



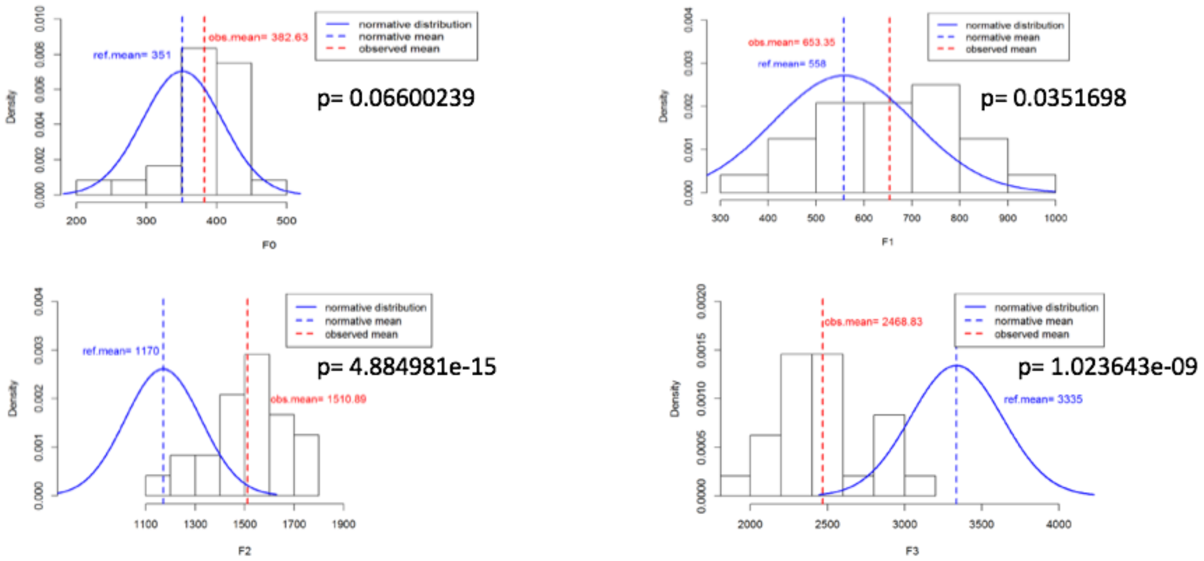
Although the norms used for comparison in Figure 9 are for infant's younger than the infant's chronological age group during recording two (11-months), it is worth noting how the observed values compare to the normative values of children who are younger than the participant. The comparison takes into account the infant's hearing age, as he was fitted with hearing aids at 4-months of age. When considering his hearing age, the infant would technically be 7-months of age; therefore, it would be reasonable to compare his 11-month productions to the 7.7 to 9-month norms.

The observed Mean F0 for /i/ at 11-months was not significantly different than the 9-month normative mean (p= 0.060 from Table 9). The observed Mean F1 for /i/ at 11-months was significantly lower than the 9-month normative mean (p= 0.035 from Table 9). The observed Mean F2 for /i/ at 11-months was significantly lower than the normative 9-month mean (p= 0.000 from Table 9). The observed Mean F3 of /i/ at 11-months was significantly lower than the normative 9-month mean (p= 0.000 from Table 9).

Table 9: T-tests and Significance Level for /i/ Production Comparisons (Hodge, 1989)

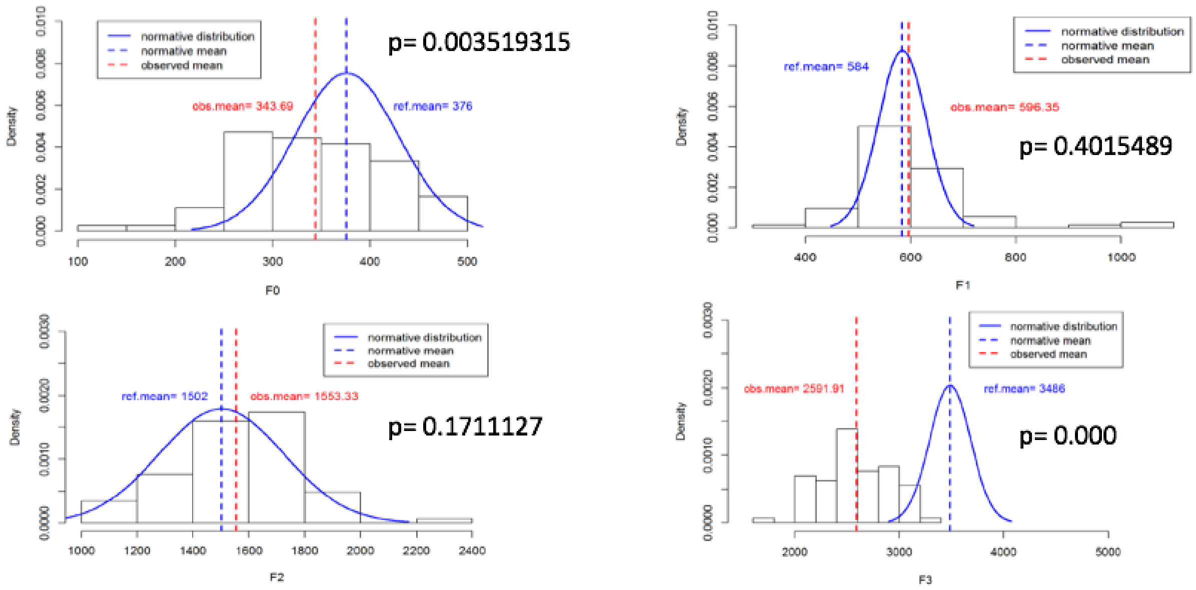
Vowel	Comparison	Acoustic Measure	t-value	p-value
/i/	9-mos vs 9-mos norms	F0	-0.101	0.920
	9-mos vs 9-mos norms	F1	3.2524	0.002
	9-mos vs 9-mos norms	F2	49.942	0.000
	9-mos vs 9-mos norms	F3	31.759	0.000
	11-mos vs 1-yr norms	F0	-1.608	0.110
	11-mos vs 1-yr norms	F1	-3.617	0.000
	11-mos vs 1-yr norms	F2	78.667	0.000
	11-mos vs 1-yr norms	F3	60.386	0.000
	11-mos vs 9-mos norms	F0	-1.899	0.060
	11-mos vs 9-mos norms	F1	2.122	0.035
	11-mos vs 9-mos norms	F2	56.652	0.000
	11-mos vs 9-mos norms	F3	39.127	0.000

Figure 10: Histograms for /u/ Productions at 9-months vs 9-month Norms (Hodge, 1989)



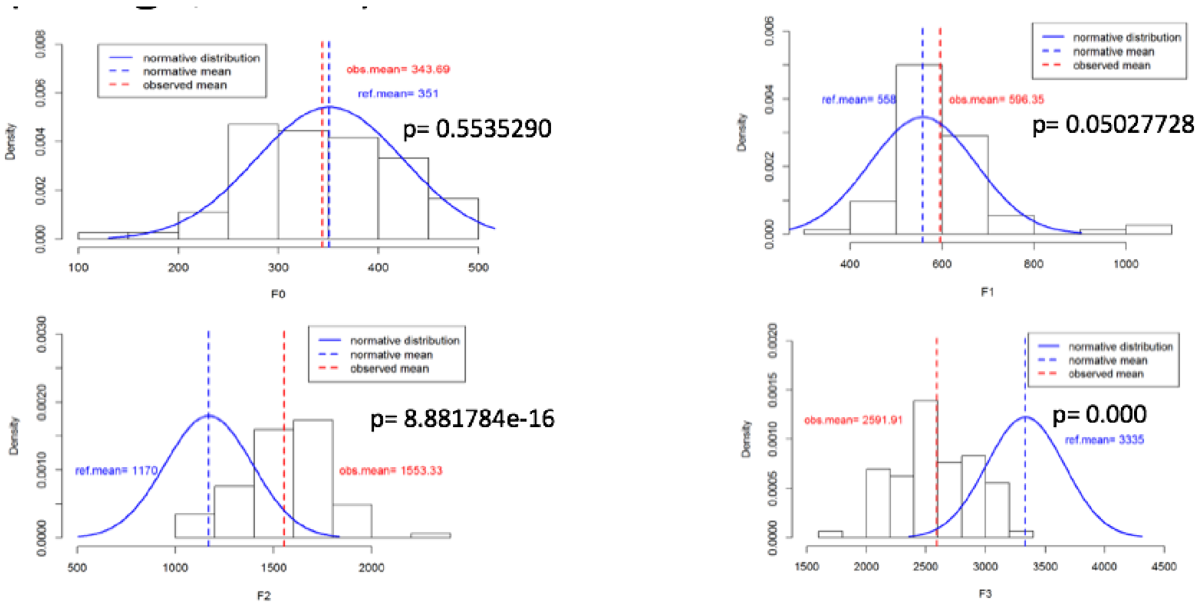
The observed Mean F0 for /u/ at 9-months was not significantly different than the normative mean (p= 0.066 from Table 10). The observed Mean F1 for /u/ at 9-months was significantly higher than the normative mean (p= 0.035 from Table 10). The observed Mean F2 for /u/ at 9-months was significantly higher than the normative mean (p= 4.885 e-15 from Table 10). The observed Mean F3 for /u/ at 9-months was significantly lower than the normative mean (p= 1.024e-09 from Table 10).

Figure 11: Histograms for /u/ Productions at 11-months vs 1-year Norms (Hodge, 1989)



The observed Mean F0 for /u/ at 11-months was significantly lower than the normative mean (p= 0.004 from Table 10). The observed Mean F1 for /u/ at 11-months was not significantly different from the normative mean (p= 0.402 from Table 10). The observed Mean F2 of /u/ at 11-months was not significantly different from the normative mean (p= 0.171 from Table 10). The observed Mean F3 of /u/ at 11-months was significantly lower than the normative mean (p= 0.000 from Table 10).

Figure 12: Histograms for /u/ Productions at 11-months vs 9-month Norms (Hodge, 1989)

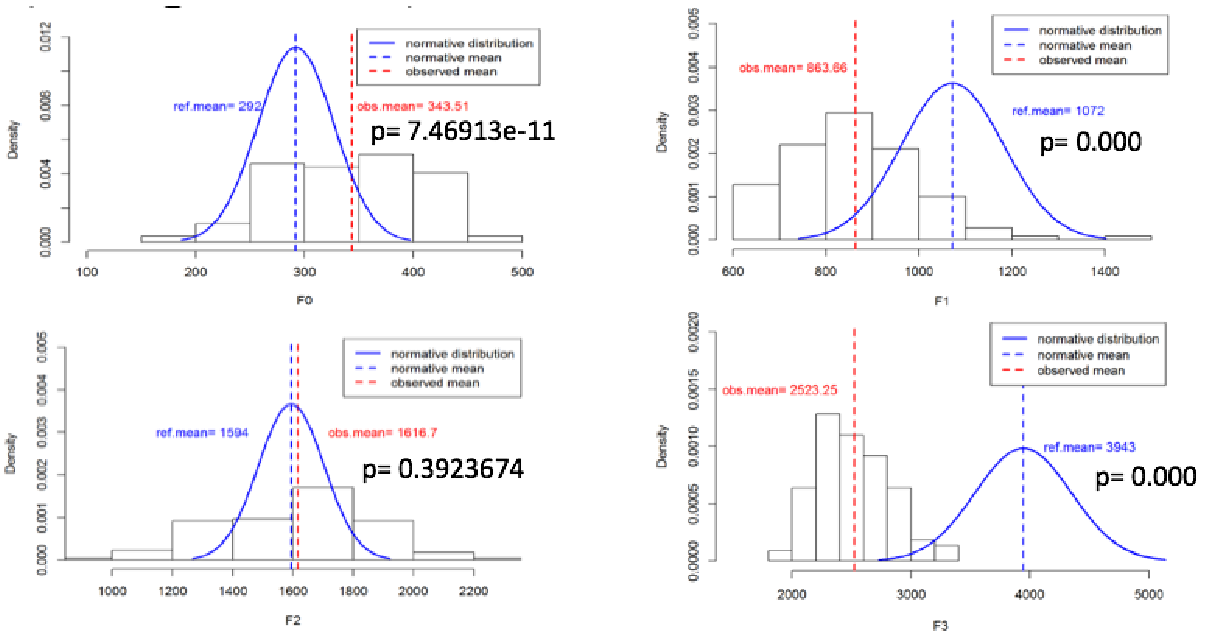


The comparison shown in Figure 11 takes into account the infant's hearing age during his 11-month recording, which would have been approximately 7-months. The observed Mean F0 for /u/ at 11-months was not significantly different from the 9-month normative mean (p= 0.554 from Table 10). The observed Mean F1 for /u/ was not significantly different from the 9-month normative mean (p= 0.050 from Table 10). The observed Mean F2 for /u/ at 11-months was significantly higher than the normative mean (p= 8.882e-16 from Table 10). The observed Mean F3 for /u/ at 11-months was significantly lower than the normative mean (p= 0.000 from Table 10).

Table 10: T-tests and Significance Level for /u/ Production Comparisons (Hodge, 1989)

Vowel	Comparison	Acoustic Measure	t-value	p-value
/u/	9-mos vs 9-mos norms	F0	-1.935	0.066
	9-mos vs 9-mos norms	F1	-2.245	0.035
	9-mos vs 9-mos norms	F2	1.877e+01	4.885e-15
	9-mos vs 9-mos norms	F3	1.009e+01	1.024e-09
	11-mos vs 1-yr norms	F0	3.021	0.004
	11-mos vs 1-yr norms	F1	-0.844	0.402
	11-mos vs 1-yr norms	F2	-1.383	0.171
	11-mos vs 1-yr norms	F3	19.922	0.000
	11-mos vs 9-mos norms	F0	0.595	0.554
	11-mos vs 9-mos norms	F1	-1.99	0.050
	11-mos vs 9-mos norms	F2	-1.036e+01	8.882e-16
	11-mos vs 9-mos norms	F3	13.656	0.000

Figure 13: Histograms for /a/ Productions at 11-months vs 1-year Norms (Hodge, 1989)



Observed acoustic measures for /a/ at 9-months of age could not be compared to normative /a/ acoustic measures because the infants in Hodge's (1989) study who were in the 7.7- to 9-month age group did not produce any /a/ tokens within the course of the study; therefore, /a/ comparisons can only be made between the infant's 11-month productions and Hodge's (1989) 1-year-old age group.

The observed Mean F0 for /a/ at 11-months was significantly higher than the normative mean (p= 7.469e-11 from Table 11). The observed Mean F1 for /a/ at 11-months was significantly lower than the normative mean (p= 0.000 from Table 11). The observed Mean F2 for /a/ at 11-months was not significantly different from the normative mean (p= 0.392 from Table 11). The observed Mean F3 for /a/ at 11-months was significantly lower than the normative mean (p= 0.000 from Table 11).

Table 11: T-tests and Significance Level for /a/ Production Comparisons (Hodge, 1989)

Vowel	Comparison	Acoustic Measure	t-value	p-value
/a/	11-mos vs 1-yr norms	F0	-7.232e+00	7.469e-11
	11-mos vs 1-yr norms	F1	11.929	0.000
	11-mos vs 1-yr norms	F2	-0.859	0.392
	11-mos vs 1-yr norms	F3	29.287	0.000

Statistical Analysis of Vowel Type and Age Effect

Using the average acoustic measures from the two undergraduate research assistants, ANOVA was used to analyze vowel type and age effect with Tukey HSD post hoc comparisons conducted for significant results. The ANOVA model fit on the acoustic measurements with vowel type and age showed that generally, vowel type and the interaction between vowel and age was significant, while the main effect of age was insignificant. ANOVA tables will be reported by acoustic measure (Tables 12, 14, 16, and 18). Figures 13-16 provide a visual description of the vowel interaction and changes over time based on each acoustic measure. Tukey HSD tables will be reported following the ANOVA results for each acoustic measure.

Table 12: Mean F0 ANOVA

F0 Variables	F-value	Pr(>F)
Vowel	39.28	(<) 2e-16***
Age	0.361	0.548
Vowel & Age	4.582	0.011*
Significance codes: 0 *** 0.01 *		

Figure 14: Vowel Interaction Plot for F0 Values

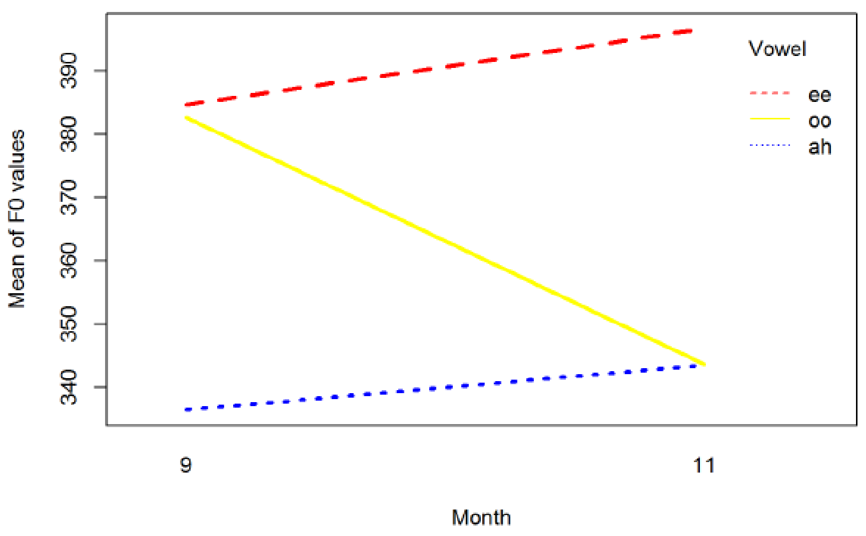


Table 13: Mean F0 Vowel Tukey-HSD

Vowel Comparison	Age (in months)	p adj
/i/-/a/	9	0.000
/u/-/a/	9	0.024
/u/-/i/	9	0.999
/i/-/a/	11	0.000
/u/-/a/	11	1.000
/u/-/i/	11	0.000

Table 13 shows that, at 9-months, the infant's Mean F0 of /a/ was significantly different than his Mean F0 of /i/ and /u/, but his Mean F0s of /i/ and /u/ were not significantly different from one another. At 11-months, the infant's Mean F0 of /i/ was significantly different than his Mean F0 for /a/ and /u/, but his Mean F0s of /u/ and /a/ were not significantly different from one another.

Table 14: Mean F1 ANOVA

F1 Variables	F-value	Pr(>F)
Vowel	207.565	(<) 2e-16***
Age	0.220	0.639
Vowel & Age	1.859	0.157
Significance codes: 0 ***		

Figure 15: Vowel Interaction Plot for F1 Values

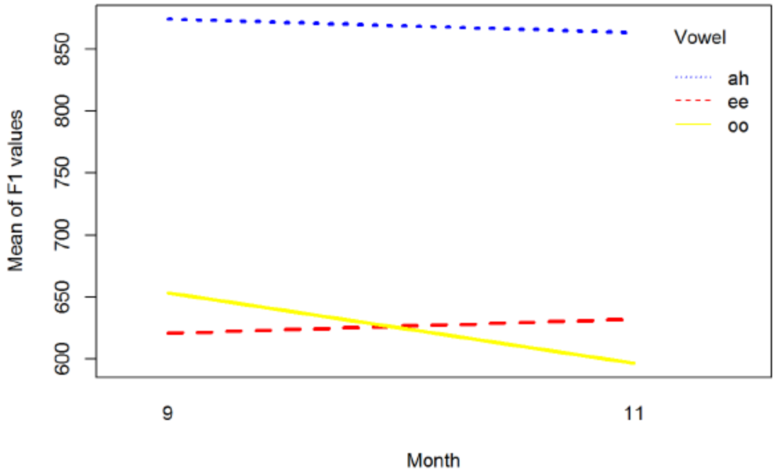


Table 15: Mean F1 Vowel Tukey-HSD

Vowel Comparison	Age (in months)	p adj
/i/-/a/	9	0.000
/u/-/a/	9	0.000
/u/-/i/	9	0.891
/i/-/a/	11	0.000
/u/-/a/	11	0.000
/u/-/i/	11	0.431

Table 15 shows that, at both 9-and 11-months, the infant's Mean F1 of /a/ was significantly different than his Mean F1 of /i/ and /u/, but his Mean F1s of /u/ and /i/ were not significantly different from one another.

Table 16: Mean F2 ANOVA

F2 Variables	F-value	Pr(>F)
Vowel	19.972	4.162e-09***
Age	1.042	0.307
Vowel & Age	6.055	0.003**
Significance codes: 0 *** 0.001 **		

Figure 16: Vowel Interaction Plot for F2 Values

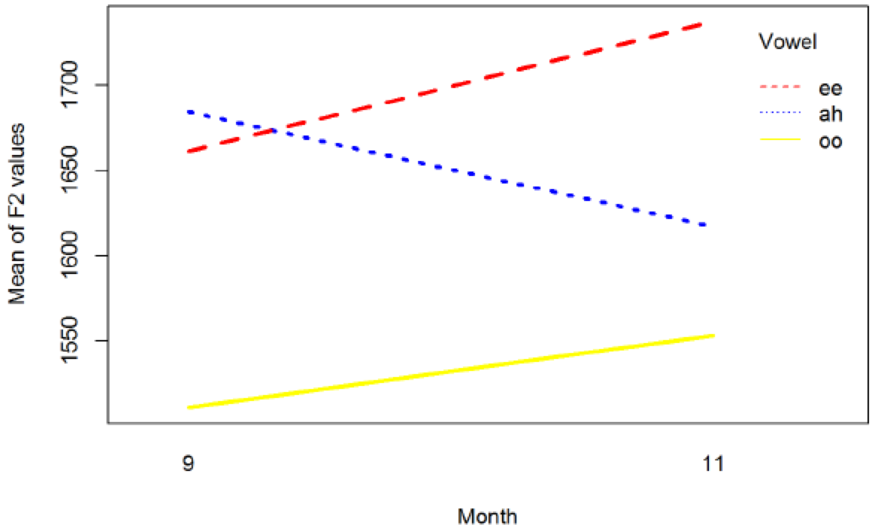


Table 17: Mean F2 Vowel Tukey-HSD

Vowel Comparison	Age (in months)	p adj
/i/-/a/	9	0.977
/u/-/a/	9	0.010
/u/-/i/	9	0.031
/i/-/a/	11	0.000
/u/-/a/	11	0.414
/u/-/i/	11	0.000

Table 17 shows that, at 9-months, the infant's Mean F2 of /u/ was significantly different than his Mean F2 of /a/ and /i/, but his Mean F2s of /i/ and /a/ were not significantly different from one another. At 11-months, the infant's Mean F2 of /i/ was significantly different than his Mean F2 of /a/ and /u/, but his Mean F2s of /u/ and /a/ were not significantly different from one another.

Table 18: Mean F3 ANOVA

F3 Variables	F-value	Pr(>F)
Vowel	367.653	< 2e-16***
Age	2.832	0.093 .
Vowel & Age	4.585	0.011*
Significance codes: 0 *** 0.01 * 0.05 .		

Table 19: Mean F3 Age Tukey-HSD

Month	p adj
11-months-- 9-months	0.096

Table 19 shows the effect of age on Mean F3 values was not found to be significant.

Figure 17: Vowel Interaction Plot for F3 Values

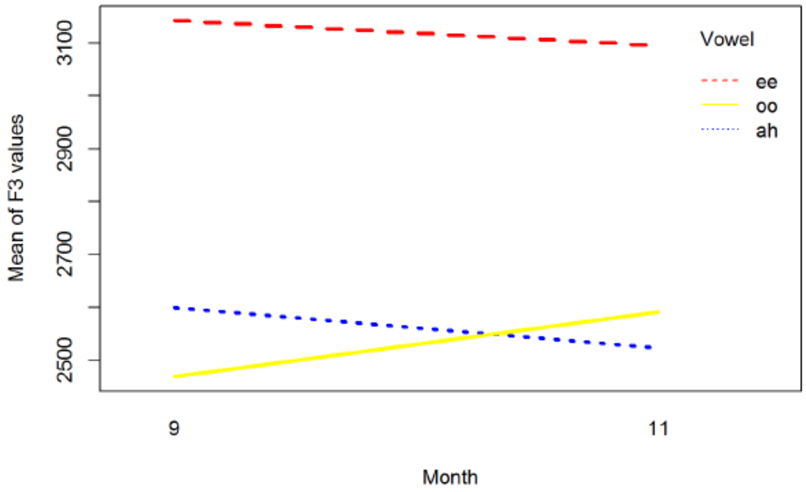


Table 20: Mean F3 Vowel Tukey-HSD

Vowel Comparison	Age (in months)	p adj
/i/-/a/	9	0.000
/u/-/a/	9	0.181
/u/-/i/	9	0.000
/i/-/a/	11	0.000
/u/-/a/	11	0.433
/u/-/i/	11	0.000

Table 20 shows that, at 9-months, the infant's Mean F3 of /i/ was significantly different than his Mean F3 of /a/ and /u/, but his Mean F3s of /u/ and /a/ were not significantly different from each other. At 11-months, the infant's Mean F3 of /i/ was significantly different than his Mean F3 of /a/ and /u/, but his Mean F3s of /u/ and /a/ were not significantly different from one another.

Association Between Time of Day and Communication Partner

There are multiple levels to the communication partner component of this study because the recordings represent a naturalistic home environment. For simplicity, the levels are aggregated as follows: 1) alone (alone or family members in background), 2) mom (communication with mom no matter if other family members are in background), 3) more than mom (communication is with mom and other family members), and 4) without mom (communication with dad or brother).

Table 21: Number of Occurrences Based on Communication Partner and Time of Day

Time of Day	Alone	Mom	More Than Mom	Without Mom
Early	40	88	69	0
Mid	50	90	44	0
Late	50	88	38	14

Because the instances when the infant communicated without mom (with dad or brother) occurred only in the evenings (Late), this set was eliminated, and a Chi-square test was performed on the remaining data. A p-value of 0.0297 indicated a significant association between the time of day and the communication partner.

Table 22: Percentage of Tokens Based on Communication Partner

Time of Day	Alone	Mom	More Than Mom
Early	0.29	0.33	0.46
Mid	0.36	0.34	0.29
Late	0.36	0.33	0.25

Table 22 demonstrates that the infant had a constant probability of communication with only “Mom” throughout the day (proportion 0.33, 0.33, 0.34), while communication with “More Than Mom” occurred most likely in the early time of day (proportion 0.46).

Table 23: Percentage of Occurrences Based on Time of Day

Time of Day	Alone	Mom	More Than Mom
Early	0.20	0.45	0.35
Mid	0.27	0.49	0.24
Late	0.28	0.50	0.22

Table 23 shows that when compared to the Mid and Late times, the infant has a relatively low probability of being alone in the early portion of the day, which most likely contributes to the infant’s high probability of communication with mom and other family members in the early time of day.

Communication Partner as Covariate on Acoustic Measures

Communication partner was added into the acoustic measures ANOVA model and a backward model selection revealed no significant association between communication partner and acoustic measures, with the exception of Mean F2.

Table 24: Mean F2 ANOVA (including communication partner)

F2 Variables	F-value	Pr(>F)
Vowel	21.633	8.89e-10***
Age	0.621	0.431
Communication Partner	3.027	0.029*
Vowel & Age	5.815	0.003**

Significance codes: 0 *** 0.001 ** 0.01 *

Table 24 shows the Mean F2 ANOVA identified an association between “communication partner” and Mean F2 values. Because “communication partner” was found to be associated with Mean F2 values, a Tukey test was conducted.

Table 25: Mean F2 Communication Partner Tukey-HSD

Communication Partner	p adj
mom-alone	0.966
more than mom-alone	0.552
without mom-alone	0.020
more than mom-mom	0.727
without mom-mom	0.027
without mom-more than mom	0.085

In summary, statistical analyses demonstrated that for Mean F0 measures, vowel type and the vowel/age interaction influenced Mean F0 values. For Mean F1 measures, only the vowel type influenced the value. For Mean F2 measures, vowel type, age, and communication partner influenced the value--specifically, mom influenced Mean F2 values. For Mean F3 measures, vowel type, the vowel/age interaction, and age influenced the value; however, the Tukey test revealed that age effect was insignificant for Mean F3.

CHAPTER 5

DISCUSSION

The goal of this investigation was to measure the acoustic properties of an infant hearing aid user's productions of /a/, /i/, and /u/ in the natural home environment over the course of two months. The following questions were explored:

1) How does the infant hearing-aid user's acoustic measures of target vowel productions (/a/, /i/, and /u/) compare to infants with typical hearing?

2) How does the infant hearing-aid user's target vowel productions change between recording one (9-months-old) and recording two (11-months-old)?

3) How does time of day and/or communication partner influence the acoustic measures of the infant hearing aid user's target vowel productions?

Acoustic Measures of Target Vowel Productions Compared to Norms

The infant's 9-month F1 and F2 values fall within the normative range when compared to Kent and Murray's (1982) 9-month normative F1 and F2 values (Figures 5 and 6). The infant's F1 values fall near the lower end of the norms (92.58% are in the normative range), which indicates that the infant's tongue is <u>higher</u> in the oral cavity than his NH peers. The infant's F2 values also fall in the lower end of the normative range (84.72% are in the normative range), which indicates that the subject's tongue is more <u>retracted</u> toward the back of the oral cavity than his NH peers. These results are similar to McGowan et al.'s (2008) findings which suggested that F1 values of DHH 1-year-olds were slightly lower than their NH peers, and F2 values of DHH 1-year-olds were significantly lower than their NH peers.

Through statistical analysis, this study demonstrated that vowel type has a significant effect on acoustic measures (Tables 12, 14, 16, & 18), which would be expected as formant frequencies are an acoustic measure of the vocal tract. In order to produce different vowel sounds, one must configure the vocal tract differently for each vowel. If the configuration is different, the acoustic measurement would of course be expected to be different as well. Therefore, comparisons of acoustic measures made with only data that is collapsed across all vowels, may be different than comparisons of acoustic measures made at the vowel level.

When comparing the observed 9-month acoustic measures (collapsed across vowels) with the collapsed normative measures reported by Kent and Murray (1982), the infant falls within normal limits—albeit the lower end of normal. However, when comparing the observed 9-month acoustic measures with Hodge's (1989) measures (which were reported by vowel type), the infant's productions deviate from the normal range in some instances. Specific information about the infant's deviance from the normative acoustic measurements can be derived when comparing acoustic measures of like vowels.

/a/ Productions

Due to lack of reported acoustic measures for /a/ productions of NH 9-month-olds, comparisons were only made between the infant's 11-month /a/ productions and 1-year norms (Figure 13; Table 11). At 11-months, the infant's /a/ productions can be described as having pitch (F0) that is significantly higher than 1-year-old NH peers. F1 was significantly lower than 1-year normative values, indicating that his tongue was placed higher in the oral cavity than his NH peers. His tongue advancement (F2) was not significantly different from NH peers, however, his F3 was significantly lower than 1-year norms—approximately 1420Hz lower.

There are a number of factors that could have influenced the infant's F0 during /a/ productions. One possibility for the significantly higher pitch (F0) may be due to high tongue height (lower F1 values). Typically, /a/ is produced by placing the tongue in a low position in the oral cavity. The infant's significantly higher F0 may have been the result of the higher tongue placement, as the tongue may have caused the larynx to raise with the tongue, thus producing a higher pitch. The fact that the infant's F0 was not significantly different than norms for /i/ and /u/ productions, despite deviation of F1, F2, and F3 values from norms, indicates that high tongue height would be unlikely to be the sole reason for the infant's high F0 during /a/ productions. However, it could be a contributing factor.

At 11-months, the infant's F2 for /a/ productions was not significantly different from normative values, indicating his tongue advancement was similar to NH peers. Considering the infant demonstrated measurable improvement in tongue advancement placement for /u/ productions from recording one (9-months) to recording two (11-months), it is plausible that the infant also improved tongue advancement placement for /a/ productions as well. However, because 9-month normative F2 values are not available to compare to 9-month observed F2 values, it is difficult to confidently conclude that the infant improved tongue advancement for /a/ within the timeframe of the study. It is equally possible that the infant's tongue advancement placement for /a/ productions was similar to NH peers at 9-months as well.

The infant's 11-month F3 values for /a/ productions were significantly lower than NH 1-year-olds by approximately 1,420Hz. Very little is known about F3 values, particularly in infants. F3 may be related to tongue tenseness and lip rounding (Kent & Read, 2002; Small, 2016), however, the correlated articulatory-acoustic relationship between F3 values and tongue tenseness/lip rounding has not been definitively established. Therefore, F3 values are reported and patterns of F3 change over time will be discussed, however, articulatory-acoustic correlation for F3 measures discussion is limited.

/i/ Productions

At 9-months, the infant's /i/ productions can be described as having pitch (F0) within normative 9-month values, with F1, F2, and F3 significantly different (lower) from normative values. This finding translates to tongue height (F1) that is higher than NH peers, tongue retracted (F2) further toward the back of the oral cavity than NH peers, and a significantly lower F3 (3142.4Hz) than NH peers (4538Hz)—approximately 1396Hz lower (Figure 7; Table 9).

At 11-months, the infant's pitch (F0) during /i/ productions remained similar to NH 1-year-olds. F1 was significantly higher than 1-year norms, and F2 was significantly lower. The infant's tongue was higher (F1) in the oral cavity than NH peers at 9-months; however, at 11-months, his tongue was lower (F1) in the oral cavity than NH 1-year-olds. At 11-months, his tongue remained more retracted (F2) than his NH peers (same tongue advancement trend he exhibited at 9-months). His F3 values were significantly lower than NH peers by approximately 1297Hz (Figure 8; Table 9).

In order to determine if the infant's hearing age impacted his /i/ productions, a comparison was made of the infant's 11-month productions to the Hodge (1989) 7.7 to 9-month norms (Figure 9; Table 9). The infant's hearing age fell within the 7.7 to 9-month norms at the 11-month recording. At 11-months, the infant's pitch (F0) of /i/ productions was not significantly different than the 9-month norms, but his F1, F2, and F3 were significantly different. The infant's F1 at 11-months indicated slight improvement as his F1 value was 11.74Hz closer to 9-month norms (hearing age peers) than he was during the 9-month recording. His F2 at 11-months indicated further deviation from the normative range, as his 11-month F2 value was 76Hz further (lower) from 9-month norms (hearing aid peers) than he was during the 9-month recording. His F3 at 11-months indicated a slight improvement as his F3 was 47Hz closer to 9-month norms (hearing age peers) than he was during the 9-month recording. These findings translate to a tongue placement that was higher (F1) and more retracted (F2) than hearing age peers, and F3 values that were significantly lower than NH 9-month-olds (hearing age peers).

Based on the results of the comparisons, a few /i/ production trends were noted. First, the infant's pitch (F0/source measure) at both 9-and 11-months was not impacted even though there were significantly deviant vocal tract measures (F1, F2, F3). Second, at 9-months, the infant's F1, F2, and F3 measures were all significantly lower than 9-month norms. However, this trend did not continue across recordings, as the infant's 11-month F1 was higher in value than NH peers (F2 and F3 remained lower). The change in /i/ F1 from 9-months to 11-months is surprising as it would be expected that his F1 values would either deviate lower than norms or approach norms, but not "overshoot" norms to the opposite end of deviation. Further study is needed to understand developmental deviation patterns of infant acoustic measures over time.

Another /i/ production trend observed was that the infant's F3 values differed significantly from normative values at both 9-months and 11-months. While his F3 values cannot be translated into an articulatory-acoustic correlation, the F3 pattern of change over time can be examined. His F3 at 9-months was approximately 1400Hz lower than 9-month norms, and his F3 at 11-months was approximately 1297Hz lower than 1-year norms. This finding indicates that the infant demonstrated a slight "closing of the gap" as his 11-month F3 values were approximately 103Hz closer to the NH peers (1-year norms) than he was at 9-months (9-month norms).

/u/ Productions

At 9-months, the infant's /u/ productions can be described as having pitch (F0) within normative 9-month values, with F1, F2, and F3 significantly different from normative values. This finding translates to tongue height (F1) that is lower than NH peers, tongue protruded (F2) further toward the front of the oral cavity than NH peers, and a significantly lower F3 (2468.83Hz) than NH peers (3335Hz)—approximately 866Hz lower (Figure 10; Table 10).

At 11-months, the infant's pitch (F0), F1, and F2 values during /u/ productions were all similar to NH peers, while F3 remained significantly lower—approximately 1297Hz (Figure 11; Table 10).

Even though the infant's 11-month /u/ productions fell in the normative range of NH peers for all acoustic measures except F3, a comparison was made of the infant's 11-month productions to the Hodge (1989) 7.7 to 9-month norms in order to examine the infant's /u/ productions compared to his hearing age peers (Figure 12; Table 10). At 11-months, the infant's pitch (F0) of /u/ productions was not significantly different than the 9-month norms, but his F1, F2, and F3 were significantly different. The infant's F1 at 11-months indicated slight improvement as his F1 value was 57Hz closer to 9-month norms (hearing age peers) than he was during the 9-month recording. His F2 at 11-months indicated further deviation from the normative range, as his 11-month F2 value was 42Hz further (higher) from 9-month norms (hearing aid peers) than he was during the 9-month recording. His F3 at 11-months indicated further deviation from the normative range, as his F3 was 123Hz further (lower) from 9-month norms (hearing age peers) than he was during the 9-month recording. These findings translate to a tongue placement that was lower (F1) and more protruded (F2) than 9-month hearing age peers, and F3 values that were significantly lower than NH 9-month-olds (hearing age peers).

Based on the results of the comparisons, a few /u/ production trends were noted. First, the infant's pitch (F0/source measure) at both 9-and 11-months did not deviate from normative values regardless of whether the vocal tract measures were similar to normative values or significantly deviant. A similar trend was observed for the infant's /i/ productions. This finding indicates that F0 measures may be independent of F1, F2, and F3 measures. Considering the source-filter theory, this finding would be expected. While vocal tract configuration may impact perceptual pitch, the measurable change in overall F0 value may not be significant. Further study on the impact of vocal tract configuration on infant F0 values is needed.

Another trend noted in the infant's /u/ productions over time was that F1 and F2 measures were higher than NH peers, while F3 measures were lower than NH peers across 9-month comparisons. A trend of lowered F2 values for vowel productions of DHH infants has been reported and replicated (McGowan et al, 2008; Baudonck et al., 2011); so, it is surprising that the infant's /u/ F2 values were found to be consistently higher than the normative F2 values. A plausible explanation for why the infant might have had a higher F2 than the normative F2 values for /u/ productions (and a lower F2 for /i/ and /a/ productions) is vowel neutralization. One characteristic of deviant speech productions is that they lack the distinguishing features necessary for a listener to discern the produced speech sound. Verhoeven et al. (2016) reported vowel reduction to schwa in subjects with hearing impairment. The direction of deviation toward schwa (mid-central vowel) would depend on the vowel type. Because vowels are produced with a variety of vocal tract configurations, it is important to report acoustic measures by vowel type in order to accurately examine and describe the direction of deviance from normative values. Although lowered F2 values occur in DHH infant vowel production, it cannot be overgeneralized as a trend for all vowel productions. Perhaps a more precise description of DHH infant vowel productions might be deviation in F2 values and the direction of F2 deviation is based on vowel type (e.g., lower F2 for front vowels, higher F2 for back vowels). Further study is needed to explore F2 variations in both typically developing infants and infant special populations.

The infant's F3 values for /u/ differed significantly from normative values at both 9-months and 11-months. A significantly lower F3 value from normative data across all comparisons was a trend found in this investigation for all three target vowels (/a/, /i/, and /u/). Again, the infant's /u/ F3 values cannot be translated into an articulatory-acoustic correlation, however, the /u/ F3 pattern of change over time was examined. The infant's F3 at 9-months was approximately 866Hz lower than 9-month norms, and his F3 at 11-months was approximately 894Hz lower than 1-year norms. This finding indicates that the infant potentially demonstrated further deviation from the normative values, as his 11-month F3 values were approximately 28Hz further (lower) from NH peers (1-year norms) than he was at 9-months (9-month norms). It is interesting that at 11-months, the infant approached 1-year norms for all /u/ acoustic measures (F0, F1, F2) except F3—which further deviated from the normative range. More studies on F3 acoustic measures are needed in order to further understand the articulatory-acoustic correlation of F3 in infant speech development.

Acoustic Changes from Recording One (9-mos) to Recording Two (11-mos)

Statistical analyses revealed that only vowel type influenced F1 values (Figure 15; Tables 14-15). F1 is represented schematically in the vowel quadrilateral and is associated with tongue height. The vowel quadrilateral will frame the context of discussing vowel interaction patterns within acoustic measures in this section. At both 9-months and 11-months of age, the subject's average Mean F1 when producing /a/ was statistically different than the Mean F1 values of /i/ and /u/. This pattern is reasonable when considering the vowel quadrilateral: /a/ is produced with a low tongue height and /i/ and /u/ are produced with a high tongue height. In addition to tongue height correlation, F1 has been reported to reflect speed and efficiency of speech (Hodge, 1989). The consistent F1 pattern from recording one (9-months) to recording two (11-months) may be reflective of the infant's age-appropriate mastery of tongue height or it may be reflective of the level of difficulty the subject has when producing one vowel over another.

While F1 may characterize economy of speech, F2 measures potentially serve as an early predictor of speech intelligibility (Hodge, 1989), and are associated with tongue advancement. The ANOVA used in this study demonstrated that Mean F2 values for vowels (/a/, /i/, and /u/) were all statistically different from one another at both 9-months and 11-months, which may support Hodge's (1989) theory (Figure 16; Tables 16-17). This finding suggests that the infant used three measurably different vocal tract configurations in order to produce the three target vowels. Perhaps vowel distinction for listeners, or speech intelligibility, is influenced most by tongue advancement (F2).

Although the ANOVA did not identify an association between F2 and age, the Tukey-HSD identified an association between the subject's Mean F2 for /i/ and age (Figure 16; Tables 16-17). At 9-months, the subject's Mean F2 of /u/ was statistically different than his Mean F2 values for /a/ and /i/. This grouping pattern was not expected based on the vowel quadrilateral: /a/ and /u/ are both back vowels, while /i/ is a front vowel. At 11-months, the subject's Mean F2 of /i/ productions was statistically different than his Mean F2 values for /a/ and /u/, which is the expected pattern based on the vowel quadrilateral as it reflects a significant difference in Mean F2 (tongue advancement) for /i/ which is a front vowel, and similarities between the two back vowels /a/ and /u/. Perhaps the pattern reversal of /i/ from recording one (9-months) to recording two (11-months) may be the reason for the Tukey test identifying an association to age for /i/ only.

Statistical analysis demonstrated that vowel type and the vowel/age interaction influenced Mean F0 values (Figure 14; Tables 12 & 13). Although F0 values are not represented schematically in the vowel quadrilateral, it may be interesting to explore F0 vowel interaction trends in the context of the vowel quadrilateral. At 9-months the subject’s pitch when producing /a/ was significantly different than his pitch when producing /i/ and /u/. This pattern is reasonable when examining this grouping in the context of the vowel quadrilateral: /a/ is produced with a low tongue height, while /i/ and /u/ are produced with a high tongue height. The tongue height can potentially explain the difference in pitch; however, it is unlikely to be the only contributing factor. At 11 months, the subject’s pitch when producing /i/ was statistically different than his pitch when producing /a/ and /u/. Although seemingly contradictory, this pattern is also reasonable when considering the vowel quadrilateral: /a/ and /u/ are back vowels, while /i/ is a front vowel. This time, perhaps tongue advancement (F2) potentially impacted Mean F0. No definitive conclusions can be drawn from this comparison. Further studies on the acoustic measurements of typically developing prelinguistic infants are needed in order to explore not only normative acoustic measures, but also to examine the ebb and flow of normative developmental patterns.

When examining pitch, another factor to consider is the high variability of pitch in infant vocalizations (Kent & Read, 2002). The standard deviation of F0 (SDF0) refers to the overall stability of the vocal fold vibrations (Wang et al., 2017). During early childhood, children have weak control over the stability of vocal cord vibrations, which is a possible explanation for relatively high SDF0. While SDF0 may be high when compared to adults, Hodge (1989) reported that within an age level, F0 had the least measurement error out of all of the acoustic measures, and the current investigation found the same pattern. The lack of published acoustic measures of typically developing infants makes it difficult to identify what is deviant and what is "deviantly normal" developmentally.

For Mean F3 measures, the ANOVA demonstrated that vowel type, age, and the interaction between vowel and age were all significant for Mean F3 values; however, the Tukey test revealed the age effect was insignificant for Mean F3 (Figure 17; Tables 18-20). While F3 is not represented in the vowel quadrilateral schematic, it may be interesting to discuss F3 trends within that context. Overall, Mean F3 values are significantly lower than normative Mean F3 values for all target vowels at both 9-months of age and 11-months of age, with deviations as far as 1000Hz lower than the norm. When examining the pattern of change for the vowels, the subject's Mean F3 for /i/ was significantly different than his Mean F3 for /a/ and /u/ at both 9-months and 11-months. When considering this grouping in the context of the vowel quadrilateral, /a/ and /u/ are both back vowels and /i/ is a front vowel. This grouping suggests that Mean F3 is potentially related to Mean F2 (tongue advancement) more than it is related to Mean F1 (tongue height).

If Mean F3 is related to lip protrusion (Small, 2016), it would be expected that Mean F3 for all vowels (/a/, /i/, and /u/) would be significantly different than one another, as /u/ is produced with rounded/protruded lips, /i/ is produced with spread lips, and /a/ is produced with relatively lax lips. If Mean F3 is related to tongue tenseness (Small, 2016), it is expected that Mean F3 of /a/ would be significantly different from the Mean F3 values of /i/ and /u/, as /a/ is produced with a low lax tongue, /i/ is produced with a high tense tongue, and /u/ is produced with a low tense tongue. The subject's Mean F3 pattern did not follow either of the expected trends which would support the articulatory-acoustic correlation of Mean F3 and lip protrusion or tongue tenseness. Very limited published F3 data exists particularly for infant vowel vocalizations. More research is needed to understand the articulatory-acoustic relationship of Mean F3 values—particularly in typically developing prelinguistic infants.

Effect of Time of Day/Environment/Communication Partner

There was a significant association between time of day and the communication partners (Tables 21-23). Communication with "only mom" occurred throughout the entire day, communication with "mom and other family members" occurred mostly in the early portion of the day, and communication with "other family members without mom" occurred in the late portion of the day. This finding is most likely reflective of communication opportunities in the home environment. Mom is the primary caregiver and is with the infant all day, so it would be expected that the data would reflect a constant probability of communication with mom throughout the day. Dad works away from the home during the day, so his interactions were limited to the late portion of the day as reflected by the analysis. The infant's older brother was also home with the infant and mom all day; however, his brother is not always directly interacting with him. The analysis suggests that the infant's interactions with both his mom and brother occur most likely in the early portion of the day.

One of the most surprising and interesting findings from this study was that statistical analysis of communication partner effect on acoustic measures demonstrated that mom had a significant influence on the subject's Mean F2 values (Tables 24-25). When framing this finding in the context of articulatory-acoustic correlation, this finding suggests that mom influenced the infant's tongue advancement (Small, 2016; Kent & Read, 2002) and speech intelligibility (Hodge, 1989). Family training is not only an important component of AV therapy, but also

ASHA recommended best practice for DHH newborn therapy (NYS Department of Health, 2007). According to ASHA's clinical practice guidelines (based on NYS Department of Health, 2007), recommendations for family training are currently made based on Level C Evidence (limited evidence) and Level D2 Evidence (consensus panel opinion not based on findings from a systematic review). The effect of mom on Mean F2 values demonstrated in this study may provide measurable, objective support for recommending family training as a crucial component of DHH infant therapy.

Limitations

Five main limitations of this study are highlighted. First, this is a single case investigation and therefore, limited generalizations can be made based on the study's findings. However, many of the findings in this single case replicate findings in the current literature. The in-depth analysis adds to the literature base and demands future investigation.

Second, the normative data used in the comparisons of this investigation were derived from the limited published normative data that exists for the infant's age group. The Kent and Murray (1982) study included 21 typically hearing 9-month-old infants; and the Hodge (1989) study included 15 typically hearing 7.7 to 9-month-old infants and 20 typically hearing 1-year-old infants. Considering the normative data was derived from studies with small sample sizes, the results of this investigation should be interpreted with caution.

Third, a potential methodological limitation may be the fact that the identification and classification of vowels was performed by only one coder—the lead researcher. Therefore, the initial coding system of classifying vowel productions as /a/, /i/, or /u/ could be described as perceptually subjective. Designing a more systematic method of classifying vowels involving other trained coders may result in increased reliability of vowel classification methods.

Fourth, an additional methodological limitation was the creation of the communication partner coding scheme after listening to the two home recordings in their entirety. This post-hoc creation can lead to ambiguity. For example, during acoustic analysis, a target vowel was identified and a description of communication partners was listed based on the voices identified in the recording. A communication partner description might be written as “with mom (brother in background).” Based on this description an interpretation was later made as to whether the interaction was with “mom” only or “mom and brother.” A clinical setting, as opposed to a home setting, might provide more controlled conditions from which to design a more precise coding scheme; however, using the controlled conditions of a clinical setting would not provide information about the infant’s vocalizations in the natural home environment. In future studies, the development of strict definitions of what constitutes a communication partner “category” apriori might be beneficial.

Finally, the fifth limitation of the study was poor reliability of Mean F0 measures between undergraduate research assistants. Ultimately, “MC”’s data set was chosen for comparisons made to normative data because it more closely matched those values. It is possible that the “true” observed Mean F0 values were more deviant from the norm F0 values than was demonstrated in this study. The fact that observed Mean F0 values were close to norm values for most of the vowels may be due to using only one research assistant’s data set. Infant Mean F0 values have been reported in the literature as highly variable by nature (Kent & Read, 2002; Wang et al., 2017). Perhaps the highly-varied nature of Mean F0 values in the infant population contributed to the discrepancy between coders. Another possibility could be variability within the Praat F0 algorithm itself. Coder technique differences as a possibility for Mean F0 variation is an unlikely explanation because if cursor/highlight precision was a factor in value discrepancy, it would be expected that all of the acoustic measures would have been affected instead of just Mean F0. However, it is possible that Praat's Mean F0 algorithm may be more sensitive to exact cursor/highlight placement than the other acoustic measures, which may have been a reason for the discrepancy between coders.

CHAPTER 6

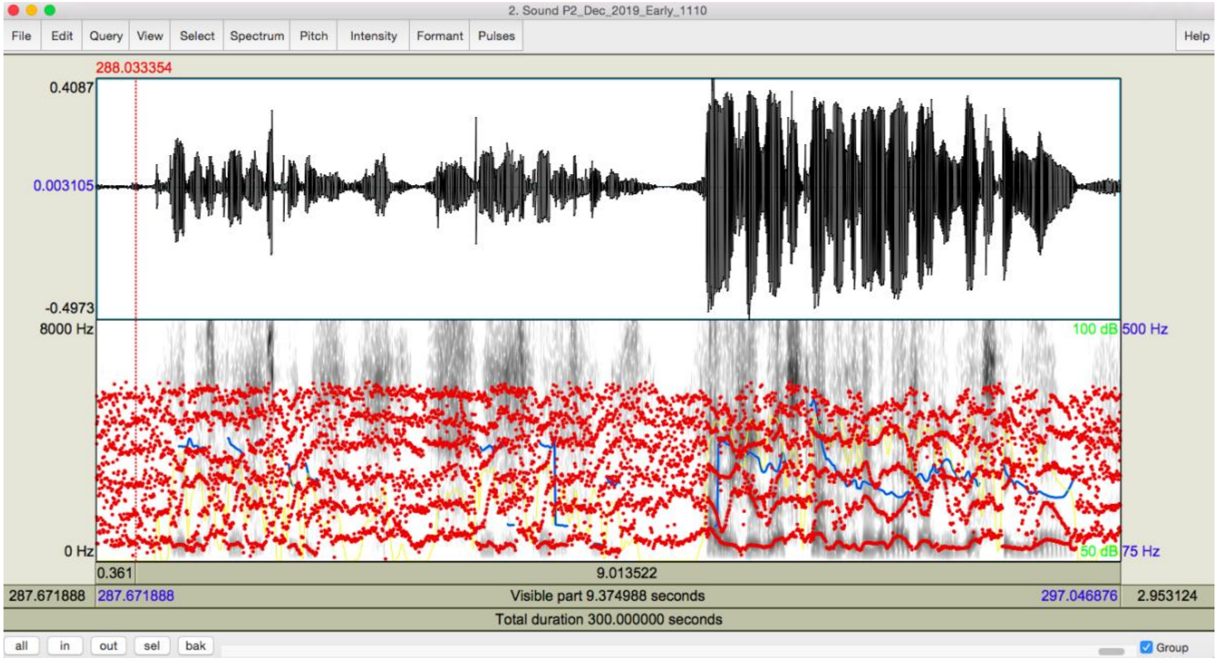
EXPLORATORY THEMES

Three additional topics were explored in this study in order to identify areas for future study. While a comprehensive literature review and thorough discussion of these themes is outside of the scope and purpose of this study, a brief discussion of each theme and pilot results are presented.

Parentese

Infant-directed speech, more commonly known as “motherese” or “parentese,” is described in the literature as “a unique acoustic signature characterized by a higher fundamental frequency (pitch), exaggerated intonation contours, and a slower tempo” (Fernald & Simon, 1984: Grieser & Kuhl, 1988; Stern, Spieker, Barnett & Mackain, 1983).

Figure 18: Parentese Speech on Left vs Adult-Directed Speech on Right



The exaggerated contours, slower tempo, and higher fundamental frequency characteristics of parentese may go beyond infant attention-getting strategies or infant preferences. The exaggerated articulations of vowels, for example, enhance and magnify the distinctive features that distinguish them (Kuhl et al., 1997). The exaggerated prosody of parentese may contribute to the development of such skills as pitch and temporal order discrimination, and auditory pattern recognition—skills that are "prelinguistic" in the most fundamental sense (Fernald & Simon, 1984).

From a neuroimaging perspective, when newborn babies hear a sentence, more activity is observed in the right mid superior temporal gyrus (STG) than in the left mid STG (Skiede & Friederici, 2016). Given that, in adults, the right mid STG is known to support prosodic processing, this finding indicates that newborn babies not only are sensitive to phonological information but also are equally, or perhaps even more, sensitive to suprasegmental (prosodic) acoustic information in a sentence. The sensitivity of infants to prosody may not only play a role in parental bonding, but may also form the basis for learning how to segment the auditory stream into words, according to the specifics of the target language (Skiede & Friederici, 2016).

A recent study conducted with NH infants indicated that parentese speech in 1:1 contexts is positively correlated with both concurrent speech and later word productions (Ramirez-Esparza et al., 2014). This finding in conjunction with the importance of audibility to speech production suggests that the manner in which parents interact with DHH infants and young children can significantly impact the development of speech. Given that this finding related to the use of parentese was conducted with typically hearing infants, there is a need to further explore the use of parentese and its relationship to speech production of DHH infants.

Event-related potential (ERP) work suggests that, at 6 months of age, infants only recognize words that have previously been accentuated (that is, marked as acoustically prominent by increasing sound pressure and frequency), but not if they have merely been repeated (Skiede & Friederici, 2016). The same literature suggests that not until 12 months of age do infants no longer rely on accentuation to detect phonological word forms. These findings indicate that DHH infants may require parentese delivery of speech for longer periods of time in order to account for their hearing age.

This exploratory theme examined the fundamental frequency (pitch) of the mother's voice when speaking to her infant son. The researcher coded three samples of parentese and three samples of adult-directed (AD) speech from both recording one (infant age 9-months) and recording two (infant age 11-months). The three values of parentese F0 were averaged and the three values AD speech F0 were averaged. The results are listed in the table below.

Table 26: Parentese Acoustic Measures from Recording One to Recording Two

9-month Mean Length	3.79 sec	11-month Mean Length	2.15 sec
9-month Mean Parentese F0	244.70Hz	11-month Mean Parentese F0	264.16Hz
9-month Mean AD F0	255.58Hz	11-months Mean AD F0	209.43Hz

As expected, during recording two (infant age 11-months), the mother's AD speech F0 was 54.74 Hz lower than her parentese F0. Unexpectedly, however, during recording one, the mother's AD speech F0 was 10.88 Hz higher than her parentese F0. It is interesting to note that, perceptually, her 9-month infant-directed speech was coded as parentese, but acoustically it did not measure that way, as her AD speech had a higher F0 than her parentese speech. The mother's AD speech in the 9-month recording was 46.15Hz higher than her AD speech in recording two, and her parentese speech in recording one was 19.46Hz lower than her parentese speech in recording two.

Wang et al. (2018) examined whether infants with hearing aids showed a listening preference for parentese speech over AD speech, similar to the preferences established with their NH peers. The study demonstrated that older infants (mean chronological age of 17.57 months) listened longer to both parentese speech and AD speech relative to silence; however, neither infants with HAs nor infants with NH showed a listening preference for parentese speech over AD speech. When looking at younger infants (mean chronological age 9.86 months) both infants with HAs and infants with NH showed a listening preference for parentese speech and AD speech relative to silence; in addition, both groups preferred listening to parentese speech over AD speech.

The infant participant in this study falls into the younger infant category based on the classification system used by Wang et al. (2018). It may be coincidental that the infant produced more vowel tokens in recording two when the mother's parentese F0 was measurably higher. This finding may also be explained by other factors such as a small parentese recording sample, age, experience in AV therapy, etc. One clinical implication that can be made from the results is the use of acoustic measures as a possible training tool for families of DHH infants. Future studies could explore if there is an ideal parentese pitch range for both NH and DHH infants.

Canonical Babble

Canonical babble, a vocalization containing a minimum of a consonant and a vowel, is a precursor to first words and emerges in NH children between 7-and 10-months of age (Oller, 1980; Stark, 1980). The onset of canonical babbling is typically delayed in DHH infants, and when it occurs, the utterances differ in duration and timing (Kent et al., 1987; Oller & Eilers, 1988; Oller et al., 1985). The infant hearing aid user in this study falls within the age range (7 to 10-months) where it would be expected to hear the infant producing canonical babble. The infant did not produce any repetitive canonical babble in the timeframe of this study, and the CV syllables he produced did not meet the criteria of a true canonical syllable as defined by Oller (1980), which requires the formant transition between consonant-vowel to be less than 120ms. However, the CV syllables he produced were documented in order to track quantity of canonical babble attempts and to take a phonetic inventory over the course of the study.

Table 27: Canonical Babble 9-months vs 11-months

9-month Canonical Attempts	9	11-month Canonical Attempts	23
Average CV Formant Transition Length	294.752 ms	Average CV Formant Transition Length	271.848 ms

The infant increased CV syllable production by 14 tokens from recording one (9-months) to recording two (11-months). Consonant-vowel formant transition decreased by 22.90ms from recording one (9-months) to recording two (11-months) which demonstrates slight improvement in consonant-vowel formant transition time. However, the results are indicative that the infant CV syllable productions were marginal productions, not meeting the criteria for well-formed, adult-like canonical syllables.

At 9-months, the infant’s consonant inventory within CV contexts included: /dw/, /b/, /m/, /w/; and his vowel inventory used in CV contexts included: /ɛ/ (as in “exercise”), /u/, /i/, /æ/ (as in “apple”), and /eɪ/ (as in “bay”).

Table 28: 9-Month-Old Infant Hearing Aid User CV Consonant Inventory

Consonant	Number of Uses in CV Contexts
/dw/	1
/b/	5
/m/	1
/w/	2

Table 29: 9-Month-Old Infant Hearing Aid User CV Vowel Inventory

Vowel	Number of Uses in CV Contexts
/ɛ/	1
/u/	2
/i/	1
/æ/	4
/eɪ/	1

At 11-months, the infant's consonant inventory within CV contexts included: /d/, /b/, /m/, /w/, /g/; and his vowel inventory used in CV contexts included: /a/, /u/, /i/, /æ/ (as in "apple"), and /eɪ/ (as in "bay"). The infant's consonant inventory in CV contexts increased by one token ("g") within the timeframe of the study. For vowel productions used within CV contexts, the infant used the same number of vowel tokens as he did when he was 9-months-old; however, at 11-months of age, /ɛ/ was not present in his CV context vowel inventory, and /a/ was a new addition to his CV context vowel repertoire at 11-months.

Table 30: 11-Month-Old Infant Hearing Aid User CV Consonant Inventory

Consonant	Number of Uses in CV Contexts
/d/	2
/b/	2
/m/	1
/w/	17
/g/	1

Table 31: 11-Month-Old Infant Hearing Aid User CV Vowel Inventory

Vowel	Number of Uses in CV Contexts
/a/	4
/u/	3
/i/	10
/æ/	2
/eɪ/	4

Future studies could compare CV consonant and vowel inventories between DHH infants and NH infants, as well as explore the average developmental time frame both NH infants and DHH infants require in order to achieve CV formant transition times indicative of a true canonical syllable.

Ingressive Vocalizations

Normal phonation requires positive driving pressure that is generated below the level of the glottis (Titze, 1994), and is produced using exhaled air. In contrast, ingressive phonation, or voice produced on inhaled air, involves driving pressure generated above the level of the glottis (Harrison et al., 1992). Ingressive (or inspiratory) vocalizations have been documented in both normal (Grau et al., 1995) and pathological voices (Fiz et al., 1993; Colton & Casper, 1996).

Robb et al. (2001) examined adult ingressive vocalizations of /a/, /i/, and /u/ and demonstrated the F0 of inspiratory phonation was significantly higher than normal phonation. Grau et al. (1995) reported inspiratory cries of infants were significantly shorter in duration and higher in F0 in comparison to egressive cries.

While both adult and infant ingressive vocalizations have been shown in studies to measure higher F0 than egressive vocalizations, one major difference between the two populations is the concept of adult volitional production versus infant reflexive production. One possible explanation of the reflexive nature of infant ingressive vocalizations relates to developmental changes in the sequential timing of muscle activity innervating the laryngeal and lower respiratory systems. Specifically, electromyographic (EMG) results performed with adults have shown that the posterior cricoarytenoid (PCA, a vocal fold abductor) "activates" prior to diaphragmatic and intercostal muscles during quiet breathing (Brancatisano et al., 1984; Strohl et al., 1980). The early activation of the PCA serves to stiffen the upper airway during inspiration, thereby helping to avoid airway obstruction. However, EMG results on newborns has shown this sequential process to be inconsistent (Eichenwald et al., 1992).

Another interpretation is related to the configuration of the infant vocal tract. Between 4- and 6-months of age, considerable remolding of the infant's vocal tract occurs. Thus, beginning at 4- to 6-months of age one might predict a decrease in instances of inspiratory cry phonation. Kent (1982) suggested that the early remodeling of the vocal tract is a product of both the infants' natural biological predisposition as well as their actual use of the vocal tract. Therefore, the infrequent or frequent and/or prolonged use of inspiratory phonation may be a determinant in the ultimate configuration of the infant's vocal tract anatomy.

Harrison (1991), Martinez (1991), Ruggins and Milner (1993), all reported findings that infants who died of upper airway obstruction, namely Sudden Infant Death Syndrome (SIDS), displayed subtly different laryngeal anatomy compared to same-age non-SIDS infants. Perhaps even more compelling is the finding that the majority of SIDS cases occur during a median age of 3-to 4-months (Peterson, 1989; Sasaki et al., 1977), the precise time period during which the infant's vocal tract is undergoing reconfiguration (Grau et al., 1995).

Based on the combined perspectives of both interpretations, it would be reasonable to expect that the infant hearing aid user in this study would reduce inspiratory vocalizations from recording one (9-months) to recording two (11-months) most likely due to developmental changes and neuromuscular maturity.

Table 32: Ingressive Vocalizations 9-months vs 11-months

9-month Ingressive Vocalizations	30	11-month Ingressive Vocalizations	4
9-month Mean Ingressive Vocalization Length	0.288 sec	11-month Mean Ingressive Vocalization Length	0.908 sec

The data reflects the expected result, that the infant reduced the number of ingressive vocalizations by 26 tokens from recording one (9-months) to recording two (11-months). It is interesting to note that while the number of ingressive tokens decreased over time, the mean length of ingressive vocalizations increased with age. It is also interesting to note that mom reported the infant did not produce ingressive vocalizations in the home environment. Her report discrepancy may be due to a lack of understanding of what an ingressive vocalization is and/or what it sounds like. It could also be due to the fact that ingressive vocalizations are present in both pathologic and normal voices; therefore, the presence of occasional ingressive vocalizations in her son's repertoire did not appear to mom as pathologic in nature.

No acoustic measures were performed on the infant's ingressive vocalizations in this theme, however, differences can be observed visually in a side-by-side comparison of spectrogram figures.

Figure 19: Infant /a/ Ingressive Vocalization

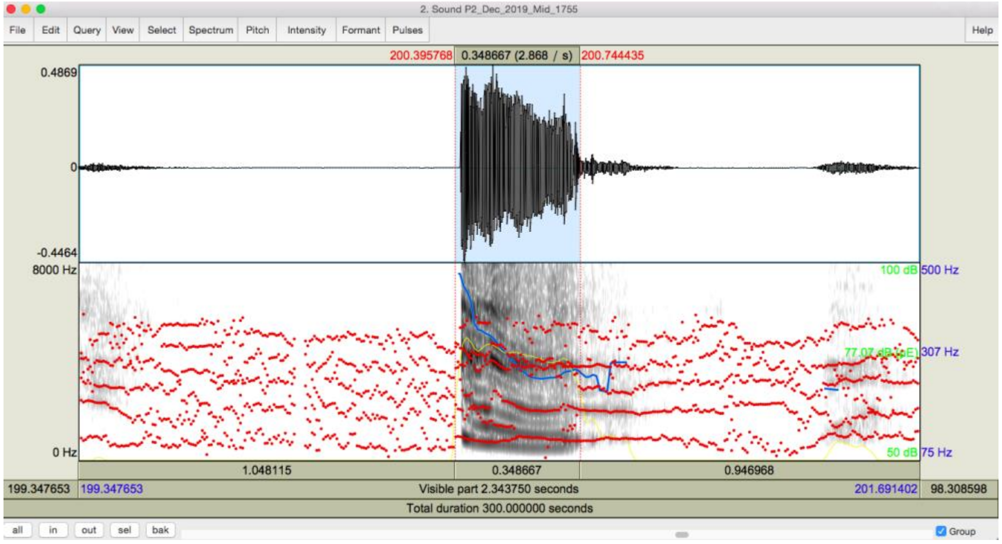
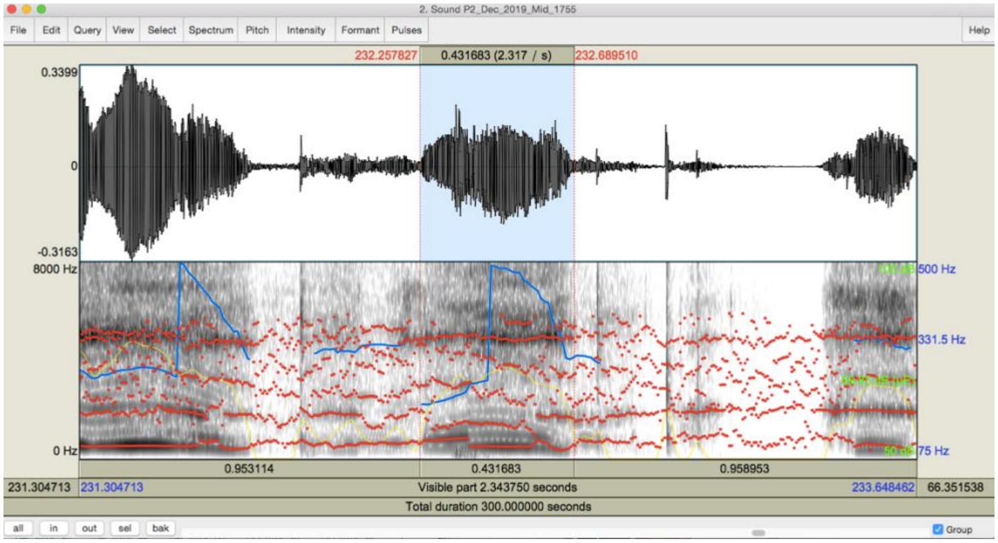


Figure 20: Infant /a/ Egressive Vocalization



Future studies could focus on measuring not only number of ingressive vocalization tokens, but also formant frequency values of ingressive vocalizations for typically developing infants, as well as special populations such as DHH infants and infants with cleft palates. The acoustic measures may provide information about vocal tract development that could potentially be used as part of a diagnostic tool for SIDS and other vocal tract developmental disorders.

CHAPTER 7

CONCLUSIONS

This investigation examined vowel productions (/a/, /i/, and /u/) of an infant hearing aid user in his home environment over a two-month period. Statistical analysis demonstrated that vowel type had a significant impact on acoustic measures. Unlike comparing collapsed acoustic measures across all vowels, comparing acoustic measures of like vowels may provide more specific information about articulatory-acoustic correlations and direction of deviation from normative values. The infant's F1 and F2 deviation patterns identified in this investigation were variable both across vowels and time (age), which makes it difficult to identify and discuss any generalized trends. F2 values that are lower than normative values have been reported and replicated as a general trend in the DHH infant literature. While lowered F2 values occur, a more precise description of this trend may be that F2 values are deviant from normative values, and the direction of F2 deviation is based on vowel type. One trend that was prevalent across all vowels and all comparisons in this study was that infant's F3 measures were significantly lower than norms. However, the lack of F3 articulatory-acoustic correlation knowledge limits meaningful use of this finding.

ANOVA and Tukey-HSD tests identified an association between the infant's F2 values and communication partner, indicating mom significantly impacted the infant's F2 measures. This finding provides objective, measurable support for the importance of including family training as a component of DHH infant treatment plans.

Acoustic analysis of vowels could be an extremely useful clinical tool to provide objective measurements pertaining to speech development in the prelinguistic infant population. In addition to tracking speech production progress, inferences about anatomical vocal tract development can also be derived from acoustic measures. Due to the considerable remolding of an infant's vocal tract during the prelinguistic stage (approximately 4-to 6-months of age), documented formant frequencies could be used to not only aid in identifying atypical speech patterns, but also atypical respiratory system development. More acoustic analysis studies of typically-developing infants are needed in order to make confident statements about speech development patterns from which to compare special infant populations.

LENA technology allows for unobtrusive access to the home environment. Advances in recording technology have reduced many of the limiting factors of early acoustic studies, particularly the issue of small vocal output during recording for infant populations. The recordings obtained from LENA can be used in a variety of ways such as documenting consonant/vowel inventory, acoustic analysis, use of family training strategies in the home and quality of family training in the home. With the rise of teletherapy practice, acoustic measures obtained from home recordings may be a valuable part of dynamic assessment and goal progress-tracking efforts in the future.

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