ENVIRONMENTAL CATALYSTS AND OROFACIAL KINEMATICS OF EMERGENT CANONICAL SYLLABLES

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ABSTRACT

The vocalizations and jaw kinematics of 30 infants aged 6–8 months were recorded using a Motion Analysis System and audiovisual technologies. This study represents the first attempt to determine the effect of play environment on infants' rate of vocalization and jaw movement. Four play conditions were compared: watching videos, social interaction with an adult, playing alone with small toys, and playing alone with large toys. The fewest vocalizations and the least amount of spontaneous movement was observed when infants were watching videos and social interaction with an adult. Infants vocalized most when playing with large toys. The gross motor movement (e.g. waving, banging, shaking) naturally elicited by small toys was predicted to be the reason it educed fewer vocalizations than large toy play. This study was also the first to examine the kinematics of both vocalized and non-vocalized jaw movements from infants 6–8 months of age. Infants produced many spontaneous jaw movements without vocalization. When vocalizing, infants were not likely to move their jaw. This contradicts current theories that infants' canonical-stage vocalizations are jaw-dominant. Also, the onset of canonical babbling has been predicted to be driven by a change in oromotor skill. However, no differences were found in the jaw kinematics of infants who were canonical babbling versus those who were not. Results of the current study can inform both environmental and motor theories of infants' canonical babbling.

KEYWORDS: canonical babbling, vocalization, environment, jaw kinematics, infant speech, infant language

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CHAPTER 1: INTRODUCTION

A. Communication in the first year of life

a. Speech–language acquisition

Cognitive, sensory, and motor experiences in infancy form the foundation for successful speech communication. Even before birth, infants have regular experience with human speech. The fetus can hear the mother's speech through the low-pass filter of the womb by 25 weeks gestational age (GA) and can feel the vibrations of her speech even earlier (Busnel, Granier-Deferre, & Lecanuet, 1992). Extensive *in-utero* experience is a likely source of newborn infants' surprisingly advanced linguistic skills. Newborns can: distinguish their mother's voice from other females' voices (Spence & Freeman, 1996), recognize their native language from other languages (Mehler, Jusczyk, Lambertz, Halsted, Bertoncini, et al., 1988), and discriminate a story passage read to them during the last six weeks of intrauterine life from an unfamiliar passage (DeCasper & Spence, 1986). Newborns prefer the speech signal over spectrally- and temporally-similar non-speech sounds (Vouloumanos & Werker, 2004). Prenatal speech–language experience is frequent, multimodal, and highly salient.

Postnatally, infants not only hear and feel speech and language, but are able to see it expressed via the mouth, face, and body. The developing infant quickly uses this multimodal input to begin to make advanced generalizations. For example, by pairing auditory and visual patterns associated with speech production, infants as young as 2 months old can detect whether an auditory vowel corresponds to a visual articulating face (Bristow, Dehaene-Lambertz, Mattout, Soares, Gliga, et al., 2008; Patterson & Werker, 2003) and whether the voice belongs to a male or female (Bristow et al., 2008).

Young infants are able to separate elements of speech into linguistically-relevant categories from an early age as well (Hillenbrand, 1984; Kuhl, 1983). In the first month of life, infants can perform phonemic categorization (Eimas & Miller, 1980). That is, they make decisions about whether similar-sounding phonemes should be considered essentially the same (e.g. for English, /ɹ/ and /ɻ/) or different (e.g. for English, /p/ from /b/), based on rules of their native language. Throughout the first year, phonemic categorization of the native language gradually improves (Cheour, Ceponiene, Lehtokoski, Luuk, Allik, et al., 1998; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). Conversely, an infant's ability to categorize non-native phonemes sharply declines between 6 and 12 months (Cheour et al., 1998; Rivera-Gaxiola et al., 2005). In order to become efficient language perceivers and producers, infants must progressively become more attuned to the patterns of their native language and less attuned to non-native phonemic variation (called "Native Language Neural Commitment," Kuhl, 2004). This process occurs quickly—by 7.5 months, better native-language speech perception skills predict faster language development and better non-native speech perception skills predict slower language development (Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola, et al., 2008). By 11 months, good native speech sound discrimination predicts a larger receptive vocabulary, whereas non-native speech discrimination has become unassociated (Conboy, Sommerville, & Kuhl, 2008).

Infants learn not only the phonemes of language within the first year, but also pick up on linguistically-relevant sequences of phonemes. By 9 months, infants can distinguish frequently-occurring phonetic sequences in their language from infrequent sequences (Jusczyk, Luce, & Charles-Luce, 1994) and can quickly learn and generalize novel phonological patterns (Saffran & Thiessen, 2003). Recognizing the patterns of speech allows infants to parse words from long utterances and begin to form semantic and syntactic knowledge. By 7 months, they can efficiently segment words from continuous speech (Jusczyk, 1999). By 9 months, they can discriminate familiar from unfamiliar words (Vihman, Thierry, Lum, Keren-Portnoy, & Martin, 2007). Between 6 and 10 months, infants demonstrate word comprehension (Fagan, 2009; Fenson, Dale, Reznik, Bates, Thal, et al., 1994; Tincoff & Jusczyk, 1999). By 12 months, they have a substantial receptive vocabulary and demonstrate advanced abilities to process the grammatical patterns of entire sentences.

Infants are traditionally viewed as naïve and quite incapable of mature cognitive processes. However, these data on early language acquisition indicate that infants are proficient learners and even possess language-learning skills that are absent from the repertoire of children and adults. For example, unlike adults, infants can pick up on the grammatical patterns of an artificial language and apply these rules with novel words after only a few minutes of exposure (Gomez & Gerken, 1999). Infant language acquisition is not simply memorization of strings of sounds and words, but is instead an advanced cognitive skill unique to infancy. Over the first year, the strategies infants use to perform linguistic problem-solving change and evolve. Early in the first year, infants accomplish word segmentation primarily based on the statistical probability of the most common stress pattern of words (Jusczyk, 1999). By 11 months they use other cues instead, such as phonotactic and prosodic patterns (Johnson & Seidl, 2009; Jusczyk, 1999). Throughout the first year of life, infants use pattern detection, statistical probabilities, and advanced social skills to quickly learn whatever language they are exposed to, well before they speak it (Kuhl, 2004; Meltzoff, Kuhl, Movellan, & Sejnowski, 2009).

b. Speech–language production

The journey toward mature speech production begins *in-utero* as well. The human fetus responds to oral stimulation at 7.5 weeks GA (Fitzgerald & Windle, 1942) and produces jaw opening and tongue movement as early as 10–12 weeks GA (de Vries, Visser, & Prechtl, 1984; Hooker, 1952; Humphrey, 1964). Repetitive jaw open–close cycles are produced by 15 weeks GA (de Vries et al., 1984) and phonatory laryngeal postures (approximating vocal folds and open epiglottis with no swallowing) around 18 weeks GA (López Ramón y Cajal, 1996).

Some of these prenatal movements may prepare the infant to cry at birth. Crying is the first neonatal occurrence of vocal fold vibration coordinated with a respiratory pattern to support a sustained acoustic signal. Crying is also the infant's first communicative vocal signal. Parents can skillfully predict an infant's needs by distinguishing cry types from one another (e.g. hunger from pleasure from pain cries) (Corwin, Lester, & Golub, 1996). The communicative aspect of cry is then further reinforced by parents' contingent vocal responses to their infant's vocalizations.

Over the first year, infants gradually transition from producing reflexive vocal behaviors, such as crying or laughing, to producing cooing, babbling, and speech. The characteristics and stages of vocal development are consistent across many studies with participants from various socioeconomic, cultural, and linguistic backgrounds (Kent, 1984; Nathani, Ertmer, & Stark, 2006; Oller, Eilers, Neal, & Schwartz, 1999; Oller, 2000; Stoel-Gammon, 1992). First, all infants' vocalizations can be categorized as either non-protophonic or protophonic. Non-protophonic vocalizations include reflexive or vegetative sounds (e.g. cough, sneeze, burp) and fixed vocal signals (e.g. cry, laugh, moan). Protophonic vocalizations, on the other hand, are speech-like vocalizations unique to humans.

Infants' first protophones occur within the first two months of life and are referred to as *phonation*. During this stage, infants produce quasivowels with a modal voice and no articulatory posturing. They also produce glottal sounds, such as /h/, in isolation at this stage. By 4 months, infants produce quasivowels along with some movement of the vocal tract (e.g. lips, tongue), but do not produce any full consonants or full vowels. This stage is referred to as gooing or *primitive articulation*. Between 3 and 8 months, infants are in the *expansion* stage. They produce full adult-like vowels plus movement of the supraglottal vocal tract that is more consonant-like. This expansion stage is also referred to as *marginal babbling*. At this stage, infants begin to gain control of pitch and loudness parameters and introduce more prosodic variation into their vocalizations.

Between 5 and 10 months, infants begin to produce *canonical babbling* (Eilers, Oller, Levine, Basinger, Lynch, et al., 1993; Ejiri, 1998; Oller, 2000; Stark, 1980). Canonical syllables consist of at least one full vowel and one full consonant, with adult-like timing and rapid formant transitions. These syllables may occur in isolation or in reduplicated sequences (e.g. /bibi/, /dada/). Single syllables precede reduplicated syllables, but just barely—the mean age of onset of reduplicated canonical syllables is also 7 months (Fagan, 2009; van der Stelt & Koopmans-van Beinum, 1986). When an infant begins to produce canonical syllables, parents recognize the sudden transition to "speech" and can easily describe and repeat the vocalizations their infant produces (Oller, Eilers, & Basinger, 2001). They may even predict intent and assign meaning to the child's vocalizations (e.g. /mama/ is "mama") and report that their infant has begun to "talk".

By 11 months, infants produce *variegated babbling*, consisting of syllable sequences that contain either differing consonants or vowels (e.g. /bidi/, /baga/, /mumi/). First words, which have clear symbolic meaning and are usually nouns, are produced around 12 months (Marquis &

Shi, 2008). First words tend to have the same consonant inventory as the infant's babbling (Stoel-Gammon, 1992). Infants at this age also frequently use gestures to communicate and fill in for words or concepts as their verbal skills continue to develop (Bates, 1976; Greenfield & Smith, 1976; Iverson & Goldin-Meadow, 2005; Özçalışkan & Goldin-Meadow, 2005).

Recent research into the characteristics of infant vocalizations has highlighted some perhaps unintuitive truths about first-year pre-speech vocalizations. First, the onset of a new stage does not eliminate the occurrence of previous vocalization categories. For example, the onset of first words does not eliminate the occurrence of canonical babbling or even immature phonation (Nip, Green, & Marx, 2009). Instead, there is a great deal of overlap across each stage of vocal development (Nip et al., 2009). Secondly, infants' utterances do not increase substantially in length across the first year. Instead, infants progress from producing single vowels to consonant–vowel syllables, without an increase in the number of syllables per utterance (Fagan, 2009). In fact, most infant vocalizations in the second half of the first year of life are not multisyllabic (Fagan, 2009). This emphasizes that infant speech development does not require an increase in quantity, but instead a modest increase in complexity per utterance.

B. Canonical babbling

Of all the pre-speech vocalization stages of the first year of life, canonical babbling is certainly the most widely researched and easily recognized by adult listeners. Infants begin to produce canonical syllables between 5 and 10 months of age (mean and median 6.5–7 months) (Eilers et al., 1993; Ejiri, 1998; Fagan, 2009; Oller, 1980; Oller & Eilers, 1988; Stark, 1980), and this onset is stable cross-linguistically and across socio-economic statuses (Holmgren, Lindblom, Aurelius, Jalling, & Zetterstrom, 1986; Kent, 1984; Nathani et al., 2006; Oller, 2000; Oller &

Eilers, 1988; Oller et al., 1999; Stoel-Gammon, 1992). Canonical syllables are unique in that they are the infant's first production of adult-like speech. Canonical syllables consist of at least one full vowel and one full consonant with rapid formant transitions and adult-like timing of less than 500 milliseconds per syllable (Lynch et al., 1995; Oller, 2000).

Infants produce single canonical syllables first (e.g. "ba"), and then begin to produce the same syllables in reduplication ("baba") soon after (Fagan, 2009). Many changes occur around the age of onset of canonical babbling, and other vocal milestones of the first year of life may be best modeled when aligned by canonical or reduplicated babbling onset instead of by age (Fagan, 2009). During the month of reduplicated babble onset, there is a substantial increase in: the total number of CV syllables produced, the duration of vocal segments, the number of syllable repetitions per utterance, and number of utterances that contain repetition (Fagan, 2009). Interestingly, these significant trends decline after the month of reduplicated babbling onset and do not return until after first words are produced (Fagan, 2009).

Perhaps because canonical syllable onset and reduplicated syllable onset occur so closely in development (for both, mean = 7 months), the terms are often used synonymously or singly and in disregard of the other. Some studies of infant vocalization group marginal and canonical syllables together for analyses and consider these as distinct from reduplicated sequences (e.g. Fagan, 2009; Steeve, 2010). This is perhaps because only 10–30% of the syllables infants produce between 6 and 12 months are truly canonical (Oller, Eilers, Steffens, Lynch, & Urbano, 1994). Also, reduplicated syllables may be slightly more noticeable to the adult listener. Frequent reduplication, though salient, is time-limited in development. Following the onset of canonical babbling, there is a sharp increase in the number of repetitions per utterance (whether V or CV repetitions), which continues for a couple of months and then sharply declines before rising again at word onset (Fagan, 2009). Thus, the change that occurs and remains in the infant's repertoire is canonical, more so than reduplicated, syllable production.

The combination of the onset of mature canonical syllables and frequent repetitions of these syllables creates a prominent stage in early speech development. At the onset of canonical syllable production, parents are suddenly able to describe their infant's "talking" and can orthographically record and recall their infant's vocalizations (Oller et al., 1999, 2001). In fact, in studies of nearly 3500 infants, telephone interviews of infants' parents (untrained, and from all socioeconomic backgrounds) were found to be a highly reliable technique for determining whether or not an infant is in the canonical stage (Oller et al., 2001). Over 95% of infants were correctly identified by parents as producing either canonical or non-canonical speech, based on immediate laboratory follow-up (Oller et al., 1999). Also, over 93% of parents readily offered evidence of canonical babbling after simple open-ended questions such as 'What kinds of sounds does your baby make?' (Oller, Eilers, Neal, & Cobo-Lewis, 1998). Parent report of canonical babbling is often preferred over attempts from a clinician to elicit the behavior in a one-time situation, because infants are notoriously silent in an unfamiliar clinical environment and with unfamiliar people. Also, not only do infants vocalize more in the home than in the laboratory (Delack, 1978; Lynch, Oller, Steffens, Levine, Basinger, et al., 1995), but the vocalizations produced in the home tend to include higher proportions of speech-like syllables (Lewedag, Oller, & Lynch, 1994).

a. Predictive importance of canonical babbling

The production of canonical syllables is noteworthy not only because it is a prominent stage in speech development, accompanied by substantial changes in vocal behavior, but also because it is highly predictive of later speech–language performance. First, the characteristics of canonical babbling are continuous with those of early words. This relation emphasizes that canonical babbling truly is “pre-speech”. The canonical syllable consonant inventory predicts early word consonant inventory (Stoel-Gammon, 1985). Canonical babbling consonant characteristics (place, manner, vocalization length) also predict early word consonant characteristics (Stoel-Gammon, 1992). Even prosodic patterns in babbling carry over into first words (Chen & Kent, 2009; Locke, 1989). Thus, timely onset of canonical babbling with varied consonant inventory is a positive predictor of fruitful first words.

Delays and atypicality in canonical babbling onset predict speech–language delays or disorders as well. Age of onset of canonical babbling currently represents the earliest reliable linguistic predictor of speech–language impairment. Late onset of canonical babbling (after 10 months) has been shown to predict: smaller consonant inventory in the first year (Jensen, Bøggild-Andersen, Schmidt, Ankerhus, & Hansen, 1988), speech delay (Oller et al., 1998; Stark, Ansel, & Bond, 1988), expressive language delay (Jensen et al., 1988; Rvachew, Slawinski, Williams, & Green, 1999; Stoel-Gammon, 1992), receptive language delay (Jensen et al., 1988; Oller et al., 1998; Stoel-Gammon, 1989), and reading disability (Stark et al., 1988). Reduced phonetic inventory of pre-speech vocalizations in the first year predicts delays in speech development in the preschool and school-age years as well (Jensen et al., 1988; Lyytinen, Poikkeus, Leiwo, & Ahonen, 1996; Menyuk, Liebergott, & Schultz, 1986).

For over half of infants with delayed onset of canonical babbling, there is no earlier predictor—no diagnosed cognitive or medical problem, no noticeable atypical behavior—to indicate imminent delay in canonical babbling onset (Oller et al., 1999). Infant speech researchers predict that there is likely a core problem (or set of problems) that causes delays in canonical babbling onset (Oller et al., 1999; Davis & MacNeilage, 1995). Canonical syllable production is a complex motor and linguistic behavior that likely requires a set of developed skills in order to occur. These may include linguistic skills, social skills, auditory skills, sensorimotor and motor control skills, and requisite neuroanatomy and neurophysiology. Identifying these critical skills can help speech–language scientists develop assessment and therapeutic techniques to prevent delay. It can also provide insight into why typically-developing infants begin to babble in the first place. Why infants begin to produce canonical syllables at all or at any given moment is unknown (Locke, 1996).

b. Prerequisites of canonical babbling—the linguistic, social, and sensing brain

At least for the listening adult, syllable production is a linguistic activity. If speech and language are the goal, and canonical babbling is the first speech-like vocal behavior that infants produce, then the conclusion could be drawn that canonical babbling must have some sort of linguistic goal or purpose. Within the first year, infants are slowly becoming a product of their linguistic environment, so that by the age of onset of canonical babbling they are already language-tuned learners (Dehaene-Lambertz, Dehaene, Anton, Campagne, Ciuciu, et al., 2006). The infant’s brain is primed for speech–language acquisition (Kuhl, 2004, 2008). From birth to 6 months, synaptic density and connectivity increase both between and within hemispheres, in the temporal, parietal, and occipital regions (Homae, Hama, Watanabe, Otobe, Nakano, et al., 2010; Huttenlocher, 2002). Simultaneously, selective synaptic pruning is refining the infant’s brain, with noted decreases in connectivity observed in the frontal region (Homae et al., 2010). At less than 4 months of age, infants demonstrate structural interhemispheric asymmetries in the arcuate fasciculus and corticospinal tract, which are important language and sensorimotor structures

(Dubois, Hertz-Pannier, Cachia, Mangin, Le Bihan, et al., 2009). Three- and four-month-old infants also demonstrate functional lateralization for language, with increased left hemisphere responses to linguistic stimuli (Dehaene-Lambertz, Dehaene, Hertz-Pannier, 2002).

The classic perisylvian language areas are also primed at babbling onset. By 6 months, Broca's area shows response to speech, but not non-speech sounds, just as it does in the adult brain (Dehaene-Lambertz, et al., 2006; Imada, Zhang, Cheour, Taulu, Ahonen, et al., 2006). In adults, Broca's area is important for semantic processing (Heim, Eickhoff, & Amunts, 2008; Skipper, Goldin-Meadow, Nusbaum, & Small, 2007, 2009) and phonological and phonetic encoding and fluency (Fazio, Cantagallo, Craighero, D'Ausilio, Roy, et al., 2009; Heim et al., 2008; Papoutsi, Zwart, Jansma, Pickering, Bednar, et al., 2009; Paulesu, Frith, & Frackowiak, 1993). By 7 months, infants demonstrate increased responsiveness to speech compared to non-speech sounds in the bilateral posterior temporal lobe (Belin & Grosbras, 2010), which overlaps Wernicke's area (Binder, Frost, Hammeke, Cox, Rao, et al., 1997; Mesulam, 1998). Wernicke's area is typically thought to control speech processing and language comprehension in humans (Binder et al., 1997; Hein & Knight, 2008).

These demonstrated neural changes may be exactly what the brain and body need in order to begin producing adult-like syllables. The onset of canonical babbling may thus be driven by neural maturation. Conversely, the act of vocalizing and babbling may drive neural maturation as well. Whatever the relation, cognitive and linguistic maturation are predicted to act as catalysts for the attainment of advances in speech production (Kent, 1999; Nip et al., 2009).

The onset of canonical babbling may also or instead be driven by the abundance of social cues and feedback the infant receives. Language is a social activity, and social interaction can have a profound effect on children's speech–language development. Perhaps the most obvious necessity for social interaction is as a source of linguistic input for the infant to learn and imitate. There are many studies that indicate that the ability and proclivity to imitate occurs from very early in infancy. Even just a few hours after birth, infants spontaneously imitate the facial gestures of adults (Field, Woodson, Greenberg, & Cohen, 1982; Meltzoff & Moore, 1977). At as early as two weeks of age, the amount an infant vocalizes is positively related to the amount of speech the mother produces in the infant's presence (Jones & Moss, 1971). By 3 months, infants can imitate the intonation of the speech they hear (Rabson, Ueberman, & Ryalls, 1982). By 9 months, infants will attempt to reproduce vowels that are modeled for them (Goldstein & Schwade, 2008). Toward the end of the first year, infants are able to directly imitate their caregivers (Meltzoff et al., 2009).

Though the data seem clear, studies of early infant imitation should be approached with some caution. A common error made in imitation studies and subjective observations is to overlook that infant imitation can be masked by caregivers imitating the infant, rather than the other way around (Bjorklund, 2005; Jones, 2007). The parent may follow the lead of the infant's vocalizations by responding with a vocalization that approximates the infant's, but which maps onto the adult's native language, thus subsequently shaping the infant's vocalizations. This does not mean, however, that this type of imitation process is not still meaningful and helpful to the infant's linguistic development. Imitation is a crucial skill for speech–language learning (DeThorne, Johnson, Walder, & Mahurin-Smith, 2009), and some propose that infants learn the skill of imitating by being imitated (Jones, 2007; Smith & Breazeal, 2007). Parents may naturally take advantage of this helpful bidirectional process by both focusing on the vocalizations an infant produces and either imitating them, in order to teach imitation, or expanding on them, in order to drive speech progress.

Imitation and successful communication are dependent on turn-taking, and this is a skill infants learn early on as well. Universally, adults respond verbally to infants' vocalizations (Kaye & Fogel, 1980; Papoušek & Papoušek, 1989). By 3 months, infants are proficient at turn-taking (Ginsburg & Kilbourne, 1988) and the amount of vocalization an infant produces shifts from being predicted by the amount of maternal speech produced in the infant's presence to being predicted by the amount of maternal speech that *follows* the infant's vocalizations (Jones & Moss, 1971). Turn-taking may thus develop via repetitive contingent reinforcement. When the mother responds contingently and immediately to an infant's vocalization, the infant is more likely to produce another vocalization (Veneziano, 1988). Contingent parental vocalization affects not only the amount but also the quality and maturity of the infant's vocalizations. For three-month-olds, vocalizations produced after contingent feedback are more acoustically mature and speech-like than those produced with unpredictable feedback (Bloom, Russell, & Wassenberg, 1987; Goldstein, King, & West, 2003; Goldstein & Schwade, 2008). Infants are also more likely to match a target vocalization modeled for them than when vocal feedback is contingent, compared to noncontingent (Goldstein & Schwade, 2008).

Contingent reinforcement of infant vocalizations is encouraged as a treatment technique (American Speech–Language–Hearing Association, 2008; Rosetti, 2001). Unfortunately, though, the majority of research on the effectiveness of contingent reinforcement in infants younger than 12 months is limited to non-vocal motor behaviors. For example, infants can be trained to produce a target motor behavior with the arms, head, or legs when provided developmentally-appropriate contingent reinforcement, such as a turning mobile (Rovee-Collier, Sullivan, Enright, Lucas, & Fagen, 1980) or a colorful video (Alessandri, Sullivan, M.W., & Lexis, 1990).

The communicative turn-taking and regular vocal contingency that parents provide represents a small portion of a more broadly-important factor in infant development—parental responsivity. Infants are exposed to hours of language every day and are expected to listen, learn, and imitate accordingly. However, exposure alone may not be enough for language acquisition. Parental verbal responsivity is uniquely important to language learning, above and beyond total amount of language input (Tamis-LeMonda & Bornstein, 2002). A responsive parent is one who "changes their behavior in response to child change in ways that directly support and scaffold further development" (Warren & Brady, 2007). Responsive parents are verbally appropriate, prompt, and highly interactive (Tamis-LeMonda & Bornstein, 2002). Responsive parents also use teaching strategies such as modeling, expansion, recasting, and infant-directed speech (Warren & Brady, 2007).

Infants prefer infant-directed speech (aka "motherese") (Fernald & Kuhl, 1987), which tends to be slower, higher-pitched, prosodically exaggerated, directed, present-tense, and has shorter and more grammatically well-formed sentences (Fernald & Simon, 1984; Snow & Ferguson, 1977). Infant-directed speech also has exaggerated acoustic characteristics and creates distance in differentiation of both vowels and consonants (Burnham, Kitamura, & Vollmer-Conner, 2002; Kuhl, Andruski, Chistovich, Chistovich, Kozhevnikova, et al., 1997; Liu, Tsao, & Kuhl, 2007). Kinematically, infant-directed speech also has larger and slower mouth movements (Green, Wilson, Wang, & Moore, 2007). Infant-directed speech is associated with better speech discrimination performance in infants and may aid early language learning (Liu, Kuhl, & Tsao, 2003).

Opportunities for frequent and appropriate interactions, such as with infant-directed speech, may be compromised in infants who do not have responsive parents. On the extreme low end of parental responsivity, neglected children are known to be at high risk for expressive, receptive, and pragmatic language delays, likely because they receive minimal input and interaction (Coster & Cicchetti, 1993; Culp, Watkins, Lawrence, Letts, Kelly, et al., 1991).

Ultimately, infants will vocalize when it is stimulating or rewarding to them in some way. Kuhl (2007) proposes that one benefit of social interaction for language development may that the communicative partner is arousing the infant and maintaining his attention. When interacting with another person, the infant benefits from that person's eye gaze and bodily gestures such as pointing. Infants are particularly attentive to faces (Nelson, 2001) and quite sensitive to eye contact (Krentz & Corina, 2008). At 6 months of age, infants are highly tuned to speech–language input, particularly with associated emotional cues and regardless of linguistic content (Fernald, 1993). Future research should investigate what aspects of social interaction provide the greatest benefit to linguistic development and capitalize on those features.

Though it is the parent's job to provide speech examples in an interactive environment, the infant's own skills influence the type of stimulation he/she receives as well. Unfortunately, infants who have developmental disorders from birth are disadvantaged not only by their own inability to interact and communicate normally but also by the responses they receive from others. A child who does not communicate well from the start is more likely to receive atypical and less frequent communication from their caregivers. For example, at eight weeks, infants with Down syndrome are less communicative and lively than typically-developing infants, but their mothers interact with them just like they would with a typically-developing infant (Slonims & McConachie, 2006). By 20 weeks, however, mothers of infants with Down syndrome are less sensitive and more remote with their infants (Slonims & McConachie, 2006), and this is predicted to be the result of the lack of frequent reciprocal communication between infant and mother. Clearly, infant factors and environmental factors can have a detrimental reciprocal relation and are, together, crucial for developing normal linguistic skills.

Another requisite infant factor for typical onset of canonical babbling is hearing sensitivity. An infant must be able to hear the speech that is modeled for him or her in order to acquire it properly. Even a mild or temporary hearing loss can impact speech development. Infants who had otitis media at or before 6 months of age, and therefore experienced weeks to months of hearing loss, produce less mature speech at 18 months (Rvachew et al., 1999). The degree of hearing loss, age at hearing loss, and age at provision of amplification all matter. Deaf infants do not produce canonical syllables earlier than 11 months, and often not until age three (Eilers & Oller, 1994). Clearly, auditory input is required for canonical babbling to develop normally. Sometimes extra auditory input even propels the infant into earlier onset of babbling. Healthy preterm infants often babble early (Eilers et al., 1993), even though preterm infants have no other advantages in major cognitive or motor milestones.

Though hearing, social interaction, and adequate linguistic input all affect the age of onset of canonical babbling, none of these factors alone is enough to secure the onset of syllabic productions. There are many hearing infants who are delayed in canonical babbling and speech onset. There are also many infants who have perfectly attentive and responsive parents who provide them with an abundance of linguistic input to imitate, who are also delayed in canonical babbling and speech onset.

For infants at the age of onset of canonical babbling, syllable production may not be as "social" or as "linguistic" a behavior as often assumed. Around 6 months, more than at older or younger ages, infants are particularly unlikely to directly mimic the vocalizations of adults (Jones, 2007) and do not tend to direct their vocalizations toward others (Fay, 1967; Furrow, 1984). In fact, between 5 and 9 months, but not by the time they are 12 months, infants vocalize more when they are alone than when an adult is interacting with them (Delack, 1978; Jones & Moss, 1971; Locke, 2004). Social, linguistic, and auditory factors are all important in the onset of canonical babbling, but clearly are not the only, or perhaps primary, factors in the onset of canonical syllable production.

c. Prerequisite of canonical babbling—oromotor development

There are several populations of infants for whom delayed canonical babbling is expected well before it occurs. These include infants with Down Syndrome (Lynch et al., 1995), cerebral palsy (Levin, 1999), and premature infants with very low birthweight (Jensen et al., 1988; Jennische & Sedin, 1999; Rvachew, Creighton, Feldman, & Sauve, 2005) or history of bronchopulmonary dysplasia (BPD) (Rvachew et al., 2005). One characteristic all these infants have in common is general motor delays. Preterm infants with extended history of respiratory therapy, such as those with RDS, have been recently shown to have atypical oromotor coordination and development (Poore, Barlow, Wang, & Lee, 2008). Also, typically-developing infants who are tracheostimized during part or all of the babbling period, and thus do not get the practice with babbling vocalizations and typical laryngeal movements end up with speech delays that persist past decannulation (Kertoy, Guest, & Quart, 1999; Locke & Pearson, 1990).

In general, infants with almost any motor delay or reduced opportunity for vocal tract movements are at risk for having speech–language delays (American Speech–Language–Hearing Association, 2008; Goffman, 2010). Canonical babbling fundamentally requires orofacial movement, and at least some, if not many infants may be delayed in canonical babbling because they are delayed in development of oromotor coordination.

i. Infant orofacial kinematics

In order to achieve mature syllabic production, infants must combine a novel respiratory pattern (quick inspiration with extended expiration and sustained subglottal pressure), appropriately-timed vocal fold vibration, and quick and precise oral articulation. By 7 months, infants demonstrate the requisite respiratory, phonatory, and oromotor control behaviors via their ability to produce canonical syllables. However, little is known about the trajectory or features of kinematic development that lead an infant to this stage.

Most available orofacial kinematic data is on older infants. Data from infants one to two years of age indicates that jaw control matures faster than lip control, and that infant vocalizations tend to be jaw-dominant (Moore, 2004; Green & Nip, 2010). Jaw speed increases and plateaus earlier than lip speed (Nip et al., 2009) and jaw spatiotemporal coordination increases comparatively quickly (Green, Moore, & Reilly, 2002; Steeve, 2010). The lips, however, move as a coupled unit and are not well coordinated with the jaw (Green et al., 2002; 2005; Nip et al., 2009; Green & Nip, 2010). In general, coordinated jaw movements for speech occur before both coordinated lip or tongue movements (Green, Moore, Higashikawa, & Steeve, 2000; Green et al., 2002; Kent, 1999; MacNeilage, Davis, Kinney, & Matyear 2000).

There are few studies available on orofacial kinematics of infants younger than 12 months old. Results from one study indicate that from 9 to 12 months, lip and jaw opening and closing speeds tend to increase (Nip et al., 2009). Jaw speed increases from about 27 mm/s at 9 months to about 32 mm/s at 12 months (Nip et al., 2009). Lip speed increases from about 37 mm/s at 9 months to ~50 mm/s at 12 months (Nip et al., 2009). However, this trajectory has not been aligned with vocal milestone achievement.

For infants younger than 9 months, very little is known about their oral kinematic development. Most of what is known about young infants' vocal development comes from acoustics studies. For example, compared to adults, infants' vocalizations have a higher fundamental frequency, are more nasalized, have a more variable quality, and have greater distance between vowel formants (see Voperian & Kent, 2007 for review). Aerodynamic studies have also contributed some. For example, by 6 months, infants demonstrate adequate velopharyngeal competency for pre-speech behaviors (Thom, Hoit, Hixon, & Smith, 2006). It is not known, however, what lip, tongue, or jaw skills infants must have in order to begin producing speech behaviors.

Both theoretically and practically, a major challenge of studying pre-speech vocal development is that it requires the researcher to make the choice of how to categorize (or not categorize) which orofacial behaviors should count as "pre-speech". Well over half the movements young infants make with their lips and jaw are actually non-vocalized; these movements are referred to as "spontaneous" oromotor behaviors or "jaw wags" (Meier, McGarvin, Zakia, & Willerman, 1997; Nip et al., 2009). The total number of spontaneous oromotor behaviors increases with age from 1 to 12 months (Green & Wilson, 2006). Thus, silent jaw movements increase in frequency even once the infant has begun to produce canonical syllables, variegated babbling, and first words.

Spontaneous/silent oral movements have traditionally been considered babble precursors (Meier et al., 1997; MacNeilage, 1998; Thelen, 1991), and there are several good reasons for that. First, infants tend to treat any silent lip and jaw movements that adults produce as equivalent to vocalized ones. For example, infants will mimic with "mamama" when an adult produces modeled silent lipsmacks (Meier et al., 1997). Infants also produce silent jaw wags within the same utterances as phonated speech (Meier et al., 1997). Though silent jaw movements and lip smacks to the adult are not viewed as communicative, this may not matter to the infant. Canonical syllables and vocalizations actually do not seem to be considered primarily “communicative” by infants between 5 and 9 months old, anyway. Between these ages, infants vocalize more alone than with an adult (Delack, 1978; Jones & Moss, 1971) and more when their mother is silent than when she’s communicating and interacting with the infant (Lin & Green, 2009). If vocalized and canonical syllables aren’t communicative for the infant, then it is possible that the infants consider these movements as essentially the “same” as non-vocalized versions. To the infant, voicing may simply be an added feature or variant of a type of general behavior. For example, infants may conceptualize these behaviors, grouped together, as ‘moving the mouth’.

Silent lip and jaw movements also follow kinematic developmental trajectories that align with and would be expected for pre-speech vocalizations. For example, coupling between the upper and lower lip increases and movement duration decreases for silent spontaneous oral behaviors around the age of typical onset of canonical syllable production (Green & Wilson, 2006). These kinematic characteristics would presumably improve syllable production. Also, at 5 months, which is right before the age of onset of canonical syllable production, there is a huge increase in the number of spontaneous movements produced (Green & Wilson, 2006). This evidence indicates the potential facilitatory role of silent spontaneous jaw movement in the onset of canonical syllables.

Despite the similarities between silent jaw movement and jaw movement accompanied by phonation, there are also some notable differences. For example, infants tend to produce silent jaw wags with greater mean cycles per utterance (= 2) than phonated syllables (= 1) (Meier et al., 1997). Also, deaf infants produce silent jaw wags just as often as hearing children do, though deaf infants do not produce as many phonated jaw movements (Meier et al., 1997). These minor differences between phonated and non-phonated jaw motion in young infants could be due to the increased task demands of producing laryngeal and oral behaviors simultaneously. However, studies of older infants indicate no kinematic differences between non-vocalized and vocalized lip and jaw movements at 18 months of age (Nip et al., 2009). It is not until well into the second year that infants again begin to kinematically differentiate phonated from non-phonated lip and jaw movements, with non-phonated movements tending to be slower in speed and with lesser vertical jaw displacement (Nip et al., 2009; Steeve & Moore, 2009).

Particularly for the youngest infants, it is reasonable to measure pre-speech oromotor skills by examining both phonated and non-phonated lip and jaw movements. A more debatable issue, though, is whether oromotor skills for sucking and chewing should also be considered precursors or adjunct to the oromotor skills required for early speech. Some of the evidence motivating the idea that sucking, chewing, and speech are related in motor control includes observations of continuity between early feeding disorders and later speech–language delays (Adams-Chapman, 2006; Ballantyne, Frisk, & Green, 2006). The premise is that foundational problems of oromotor dyscoordination may be primary reasons for delays in both feeding and speech behaviors. Some predict that early training of sucking skills in infants who exhibit oromotor dyscoordination will impact later oromotor control for speech–language development and ameliorate some speech–language delay (Barlow & Estep, 2006).

Though vocal and feeding oral behaviors may be predictive of one another and potentially share common underlying neural circuitry, the kinematic profiles of the behaviors become increasingly distinct throughout development. For infants 9–22 months of age, jaw kinematics for speech and feeding tasks are notably different (Steeve, Moore, Green, Reilly, & Ruark McMurtrey, 2008; Steeve & Moore, 2009; Steeve, 2010; Wilson, Green, Yunusova, & Moore, 2008). This evidence is used to argue that there are fundamental task differences between the two: chewing requires an occlusal point and greater occlusal force from the jaw, the behaviors have different goals, respiratory patterns are different, and phonation is required for speech but not for sucking or chewing (Tremblay, Houle, & Ostry, 2008; Wilson et al., 2008). Some argue that the development of speech and feeding behaviors is parallel rather than successive (Steeve, et al., 2008). However, ultimately, kinematic differences and performance differences observed in older infants cannot be presumed to be characteristic of what is happening with younger infants. Suck and chew may initially have more overlapping control than they do later in development, and results from 1- and 2-year-olds cannot be extrapolated to early infancy. Just as spontaneous lip and jaw movements seem to be more alike than different early in infancy, then spread apart in behavioral and kinematic patterns, sucking and chewing may too become increasingly distinct with age.

ii. Infant orofacial anatomy

Another reason for the protracted course of speech development may be the infant's immature anatomy. Compared to adults, vocal tract anatomical differences in infants include: proportionately small mandible, shorter oral cavity, more anterior tongue body, gently-sloping oropharyngeal channel, closer velum and epiglottis, higher larynx, and circular-shaped lips (Kent & Voperian, 1995; Smith, Goffman, & Stark, 1995). Adult humans have round tongues that are capable of various deformational shapes. The infant tongue, however, it comparatively flat and broad, which limits the range of movement to mostly protrusion and retrusion (Takemoto, 2001;

Toure & Vacher, 2006). As a primary articulator, the tongue of the infant would thus certainly limit articulatory success for both vowels and consonants.

Across the first year of life, infants experience rapid growth of the muscles, bones, and soft tissue. Though male–female differences in growth patterns and rates will emerge later in life, there is generally no significant sexual dimorphism in the first 12 months of life (Vorperian, Kent, Lindstrom, Kalina, Gentry, et al., 2005). In the first 18 months of life, both male and female infants experience the most rapid change of vocal tract size/structure than any other period in development (Voperian et al., 2005). By 18 months, vocal tract structures are between 55% and 80% of their projected adult size (Voperian et al., 2005). The growth pattern in the first year is in both the horizontal and vertical dimensions, equally (Voperian et al., 2005). Some structures mature considerably faster than others, though. The fastest-growing structures include the hard palate length and maxillary lip thickness; the slowest-developing changes include laryngeal descent, hyoid descent, and tongue length (Voperian et al., 2005). Clearly, infants are not just scaled-down versions of adults. Instead they must deal with constantly-changing proportional relations among anatomical structures (Auluck, Mudera, Hunt, & Lewis, 2005).

Conversely, the use of vocal tract structures for phonation and babbling behaviors may not wait for adequate anatomical maturity, but may instead actually drive anatomical development. Craniofacial development, both prenatally and in infancy, is predicted to be driven in part by mechanical forces and use (Bosma, 1975; Moss, 1997). Thus, babbling behaviors may support maturation of motor-fiber composition of muscles required for efficient speech production. Examples from vocal tract anatomy in children and adults support this hypothesis. For example, the vocal folds of young adults with cerebral palsy have been found to have abnormal mucosal structure, which is likely due to lack of mechanical stimulation from vocalization (Sato, Nakashima, Nonaka, & Harabuchi, 2008).

iii. Principles of oromotor control

The slower lip and jaw speeds, lesser articulatory displacement, increased variability, and poor general timing and coordination characteristic of infant oromotor behavior result from both anatomical and neurophysiological immaturity of infants. In addition to muscular and motor unit immaturity, slower oromotor speed in infancy may be due to underdevelopment of corticomotoneuronal efferents (Müller & Hömberg, 1992). Underdeveloped myelin and smaller axon diameters would lead to decreased nerve conduction speed in infancy. Throughout infancy and childhood, the sensorimotor cortex matures and myelination increases (Dubois, Benders, Borradori-Tolsa, Cachia, Lazeyras, et al., 2008; Hermoye, Saint-Martin, Cosnard, Lee, Kim, et al., 2006; Paus, Zijdenbos, Worsley, Collins, Blumenthal, et al., 2001), lifting these production constraints. Infants' motor control systems are underdeveloped compared to the adult, as well. Limits in motor control processing may lead to slower lip and jaw velocities of early speech movements (Green & Nip, 2010; Smith & Goffman, 2004; Thelen, 1991).

Limited practice and performance of the behavior could also lead to slower performance time and certainly increased kinematic spatiotemporal variability. The use of vocal tract structures is known to drive neurophysiological maturation. Spontaneous movement supports, and may be required for, sensorimotor pathway formation and refinement (Fields & Nelson, 1992; Kalb & Hockfield, 1992). The spontaneous jaw and lip movements that young infants perform—with peak rate of performance immediately preceding the onset of mature canonical syllables—could certainly support the onset of canonical babbling.

New stages of speech production are expected to result from repeated attempts and subsequent practice of the target behavior in order to ensure learning and attainment (Smith, 2006). Dynamic Systems Theory models, which are nonlinear and iterative, suggest that the onset of a new level of skill is preceded not only by an increase in repeated attempts at the behavior, but an increase in variability of motor performance (Smith & Thelen, 2003; Thelen, 1995). For example, a period of regression in jaw motor control could predict the impending onset of a new level of mature jaw behavior. The lack of longitudinal studies of speech motor control in the first two years of life, however, makes it impossible to know whether this principle applies to speech development in infancy. Speech scientists tend to predict that speech motor development is generally a nonlinear process (Goffman, 2010; Green & Nip, 2010; Smith & Zelaznik, 2004; Thelen, 1991; van Lieshout, 2004). Support for this view comes from evidence of speech learning in older children and adults (Goffman, 2010). There is also some evidence of a regression in lip and jaw motor control for infants at 2 years of age, which is predicted to correspond with the "word spurt" (Green et al., 2000). Whether or not variability is required in order to learn a new motor skill continues to be debated (Green & Nip, 2010).

d. What is canonical babbling?

If not for the goal of communication, what could motivate the infant to produce mature canonical syllables so suddenly and at a frequent reduplicated rate? Some suggest that babbling is actually a *stereotypic motor behavior*, characterized by repetitive rhythmic oscillations (Davis & MacNeilage, 1995; Meier et al., 1997; Thelen, 1991). This is likely motivated by the fact that the onset of canonical babbling is closely followed by a sharp increase in reduplicated babbling (Fagan, 2009; Oller, 2000). When canonical syllables are being produced in reduplication, they resemble the characteristic repeated cycles and consistent spatiotemporal patterning of stereotypy that occurs with other body parts (Thelen, 1991). In fact, the onset of canonical and reduplicated babbling is curiously tied with a simultaneous sharp increase in arm stereotypy, also called ‘arm waving’ or ‘hand banging’ (Ejiri, 1998; Iverson, 2005; Iverson & Fagan, 2004; Locke, Bekken, McMinn-Larson, & Wein, 1995; Thelen, 1981), even though canonical babbling onset has not been tied to changes in any other major motor milestones. This peak in rhythmic arm stereotypy at the onset of canonical babbling holds true regardless of the infant’s age (Ejiri, 1998; Iverson, 2005; Iverson & Fagan, 2004) and is not accompanied by an increase in repetitive rhythmic movement of any other body part, including the legs (Ejiri, 1998; Iverson, 2005), head, torso, and feet (Iverson, 2005). Rhythmic motor stereotypy is common in infants and occurs with body parts other than the hands and mouth (Thelen, 1979, 1981). Around the age of onset of canonical babbling, most spontaneous movements are actually produced by the legs (Piek & Carman, 1994). Therefore, it is interesting that the hands and mouth would produce stereotypic rhythmic behaviors together and in exclusion of other body parts.

One explanation for the co-occurrence may be that peaks in the two behaviors happen to occur at the same time developmentally and then simply entrain to one another when produced. Infants 6–12 months old produce rhythmic arm stereotypy at 2.5–3.5 Hz (Ejiri, 1998; Petitto, Holowka, Sergio, Levy, & Ostry, 2004; Petitto, Holowka, Sergio, & Ostry, 2001; Thelen, 1979); vocal babbling occurs at about 3 Hz as well (Dolata, Davis, & MacNeilage, 2008). This may make circumstantial entrainment quite possible. It is important to note, however, that these two behaviors occur together regardless of development of other cognitive and motor skills—they can both be delayed (e.g., in infant siblings of children with autism [Iverson & Wozniak, 2007] and in children with Down syndrome [Cobo-Lewis, Oller, Lynch, & Levine, 1996]) or even early-occurring (e.g., in preterm infants, [Eilers et al., 1993]). This suggests that rhythmic arm stereotypy and canonical babbling may *together* represent a common unidentified skill or stage in development. It also or instead may suggest that the production of one behavior is actually facilitating the production of the other behavior (Ejiri & Masataka, 2001; Iverson & Thelen, 1999).

Some suggest that the onset of babbling is supported by the developmental onset of motor stereotypy in general (MacNeilage, 1998; Meier et al., 1997; Thelen, 1991). Rhythmic oscillations of the mandible could provide a convenient 'frame' on which vocalization and syllabic speech can be produced (Davis & MacNeilage, 1995). Frame–Content Theory suggests just that. With jaw stereotypy as the frame and vocalizations providing content, the mandible leads the tongue, lips, and soft palate in positioning of vocalizations in young infants (Davis & MacNeilage, 1995). Support for the Frame–Content Theory comes from observations that most infant vocalizations are led by the jaw and that place of articulation tends to assimilate across consonant and vowel. Labial consonants tend to occur with front vowels (/mama/) and dorsal consonants tend to occur with back vowels (/kuku/). Additional consistency in infant babbling is observed cross-linguistically, indicating that there are certain combinations and types of syllables that infants tend to produce at the age of onset of canonical babbling. For example, canonical syllables tend to include corner vowels (Locke, 1983) and voiced labial and alveolar stops (Kent & Miolo, 2004).

Though Frame–Content Theory and the conceptualization of canonical babbling as a class of motor stereotypy are reasonable, they remain debatable theories. The onset of canonical syllables is required for speech development. However, the *reduplication* of canonical syllables may not be. Instead, reduplication may occur because of the infant's tendency toward stereotypy at this stage. Rhythmic canonical syllable reduplication may be a result of a particular stage of motor control, during which the tendency toward stereotypy is high. This coming together of stages with the onset of canonical syllable production may not be essential, but helpful by providing the infants practice with mature multisyllabic vocalizations. These multisyllabic vocalizations may then gradually take on increasing levels of linguistic relevancy via social reinforcement and cognitive and linguistic maturation and provide the foundation upon which speech is built. Conversely, syllable reduplication may not even be a type of stereotypy at all—after all, multisyllabic utterances are required for speech, and the infant may simply be imitating and executing multisyllabicity. Stereotypy is expected to have a fairly consistent spatiotemporal patterning. However, no evidence of consistent spatiotemporal patterning has been found in the silent jaw oscillations of infants around the age of onset of canonical babbling (Green & Wilson, 2006).

e. Why do infants babble?

In addition to a lack of understanding of what canonical syllables are to the infant and why infants begin to produce canonical syllables, there is also a lack of understanding of why infants produce canonical syllables *at any given moment*. The circumstances in which babies babble have not been carefully studied (Locke, 2004). In fact, a lot of time and effort is spent attempting to elicit vocalizations from infants younger than 12 months of age. Infants are notoriously silent in laboratory environments (Lewedag et al., 1994; Nathani & Stark, 1996). Infants also generally can not be expected to cooperate with any given activity more than 15 minutes maximum and sometimes as little as 3 minutes (Aslin & Fiser, 2005). Thus, the techniques that scientists use to elicit vocalizations from infants must be productive and efficient.

Infant speech–language researchers often spend an hour or more attempting to elicit vocalizations from young infants, switching from activity to activity (Fagan, 2009; Steeve & Moore, 2009; Steeve & Price, 2010). Within that hour, the researcher may use any or all of the following techniques: solo play with various toys, playing with experimenter, playing with mother, watching videos, use of contingent reinforcement and modeling paradigms by the experimenter or mother, among others (Fagan, 2009; Nathani & Stark, 1996; Oller et al., 1994; Stark, Bernstein, & Demorest, 1993; Steeve & Moore, 2009; Steeve & Price, 2010). These activities, all generally referred to as "play", are generally poorly described and the rate of vocalizations across techniques remains unreported.

A fundamental problem with many of these "play" interactions is that infants at the age of onset of canonical babbling do not tend to vocalize in the presence of adults and in social situations (Jones & Moss, 1971; Locke, 2004; Lin & Green, 2009; Delack, 1978). Yet, social interaction remains a primary technique for eliciting infant vocalizations, regardless of the infant's age or developmental stage. Videos are also used regularly, with the assumption that consistency of input from infant to infant will lend to purity of the elicited behavior. However, those who have used videos to elicit vocalizations mention that the technique tends to encourage silence and listening, rather than vocalizing behavior (Steeve & Moore, 2009).

Based on strong pilot data from our lab (Poore, 2010) and brief allusions from the literature (e.g. Oller et al., 1994; Steeve & Moore, 2009), allowing the infant to play with toys alone, without adult interaction, is superior to any type of video or live social interaction. This is true even when the social interaction includes modeling and strict contingent reinforcement paradigms (Poore, 2010). Also noteworthy is that the pilot data from Poore (2010) demonstrates a slight effect of the *type* of toy used for eliciting vocalizations. At the age of onset of canonical babbling, infants produce an increased amount of arm stereotypy (Ejiri, 1998; Iverson, 2005; Iverson & Fagan, 2004; Locke et al., 1995; Thelen, 1981). When given a toy that affords arm waving (grippable, lightweight, and is not easily dropped), infants this age *will* wave their arms—almost incessantly (Iverson, 2005; Iverson & Fagan, 2004; Poore, 2010). Unfortunately, however, large, fast arm waving appears to interfere with the rate of vocalization (Poore, 2010). This may be because the gross motor movements that are being afforded by these specific toys reduce the likelihood of simultaneous vocalization. This is also seen anecdotally with other gross motor behaviors. Infant–toddler speech–pathologists often note that a cessation of vocal development and decrease in frequency of vocalizations often occurs when infants first begin to walk.

C. Research questions

a. Specific Aim #1

Pilot data for this study indicated that the activity provided to the infant during data collection has a substantial impact on the amount of vocalization the infant produces. Social interaction and videos tended to elicit fewer vocalizations per minute than leaving the infant alone with toys. Also, small toys that afford maximal motor movement with the hands and arms tended to elicit fewer vocalizations than large toys that the infant could not easily shake or wave. Thus, a goal of this study was to systematically vary and document the environmental circumstances used to elicit vocalizations from infants. The first aim was designed to determine whether there are differences between the number of jaw open–close cycles produced or protophonic vocalizations produced by infants (6–8 months of age) across different play conditions that vary by opportunity for movement, audio stimulation, visual stimulation, and social interaction. Measurements parameters included: protophonic vocalizations per minute, jaw cycles per minute, and protophonic jaw cycles per minute.

It was hypothesized that large toys that could not easily be shaken or waved would elicit the most protophonic vocalizations and protophonic jaw cycles, followed by small shakable toys, followed by social interaction, and last video play conditions. The toy and social conditions were predicted to elicit the same number of jaw open–close cycles, while the video condition was predicted to elicit the fewest jaw open–close cycles. The null hypothesis would be satisfied with no differences in protophonic vocalizations per minute, jaw cycles per minute, or protophonic jaw cycles per minute among conditions.

b. Specific Aim #2

Oral kinematic parameters of infant vocalizations before 9 months of age have not been studied. It is not known what oromotor skills infants may be lacking before the onset of canonical syllable production, or what skills may allow them to begin to babble. Given that canonical syllable production is predicted to be dependent on mature oromotor skills (e.g. Moore, 2004; Oller, 2000), jaw movement skills in particular (Davis & MacNeilage, 1995, MacNeilage, 1998), this is clearly an area in need of inquiry.

When examining the difference between marginal and canonical syllables, the most-often cited difference is a change in acoustic spatiotemporal variables (Oller, 2000). The change in acoustic timing parameters and targeted vocal tract resonances must be achieved by changes in kinematic spatiotemporal parameters. With this study, the temporal kinematics of jaw behavior were compared across infants who have and infants who have not achieved canonical syllable production. The second aim was designed to determine whether there are kinematic differences between the jaw open–close cycles produced by babbling vs. non-babbling infants (6–8 months of age). Measurement parameters included: opening velocity (mm/sec), closing velocity (mm/sec), cycle frequency (Hz), protophonic vocalizations per minute, jaw cycles per minute, and protophonic jaw cycles per minute.

It was hypothesized that infants who had begun to produce canonical syllables would have faster opening and closing velocities, greater cycle frequency, more protophonic vocalizations, and more jaw cycles per minute. The null hypothesis would be satisfied with no differences between groups among the jaw kinematic parameters.

CHAPTER 2: METHODS

A. Participants

a. Recruitment and eligibility

Recruitment procedures, informed consent, and data collection procedures and methods for the current study were approved by the University of Kansas Human Subjects Committee, Lawrence, Kansas. Infants were recruited via emailed letter to families whose names had appeared in local birth announcements. Interested families replied to the primary investigator by phone or email to determine eligibility and schedule participation.

Eligibility to participate was determined by confirming that the infant was: 24–35 weeks old (6–8 months), from a Midwest monolingual American English household, full-term at birth (> 37 wks GA), currently healthy, and with no history of major medical illness (including vision, hearing, physical, or neurological impairments) nor diagnosed cognitive or motor disorder.

Once the infant arrived for his/her scheduled appointment, additional data were collected in order to verify eligibility for inclusion in the study. The parent completed the Ages and Stages 6-month (24–28 weeks) or 8-month (29–35 weeks) Questionnaire (ASQ), based on the infant's age at time of study. Additional inclusion criteria included: scores within normal ranges of the Ages and Stages test areas (Communication, Gross Motor, Fine Motor, Problem Solving, Personal–Social) and weight, length, and head circumference within the 5th–95th percentile (Centers for Disease Control and Prevention Infant Growth Charts, 2001).

The parents were asked to describe the infant's vocalizations and expand upon the information provided in the ASQ questionnaire. The parent's responses allowed the investigator to confirm whether or not the infant had begun to produce canonical syllables. Evidence from Oller et al. (1999, 2001) indicates that verbal interviews of parents are over 98% accurate for determining whether or not an infant is producing canonical syllables. Infants who were reported to produce canonical syllables daily were classified as typically-developing "**Canonical Babblers (CB)**". Infants who had never produced canonical syllables or had produced only a few canonical syllables ever were classified as typically-developing "**Non-babblers (NB)**".

Of all parents who were contacted by email to request participation in the study, approximately 65% responded that they were interested in participating in the study. Of all parents who participated in the initial email-based screening, only one parent had an infant who was excluded from the study due to their infant's premature birth status. All other infants (n = 30) who were brought into the laboratory for participation met all criteria for study inclusion.

b. Sample description

A power analysis was run to determine an adequate sample size. A sample size of n = 30 was estimated using Statistical Analysis Software (SAS 9.2, SAS Institute 2002–2008) for a design with two groups (NB, CB) and four conditions (LargePlay, SmallPlay, Social, Video) and medium effect size.

Thirty infants (12 female:18 male) were stratified across test ages ranging from 6 to 8 months and included 9 non-babblers (NB) and 21 babblers (CB). Participant demographics are shown in Table 1.

ID	BirthDate	TestDate	Age(d)	Age(m)	CBStatus	Sex
M20	7/6/10	1/6/11	184	6	CB	M
M30	**8/24/10**	**2/26/11**	**186**	**6**	**NB**	**M**
M11	**5/25/10**	**12/3/10**	**192**	**6**	**NB**	**M**
M19	**5/29/10**	**12/11/10**	**196**	**6**	**NB**	**F**
M01	**4/26/10**	**11/10/10**	**198**	**6**	**NB**	**F**
M27	**7/25/10**	**2/9/11**	**199**	**6**	**NB**	**M**
M26	7/24/10	2/9/11	200	6	CB	M
M21	**6/21/10**	**1/8/11**	**201**	**6**	**NB**	**M**
M23	6/18/10	1/10/11	206	6	CB	F
M24	**6/18/10**	**1/10/11**	**206**	**6**	**NB**	**M**
M10	5/7/10	11/30/10	207	6	CB	M
M28	**7/9/10**	**2/12/11**	**218**	**7**	**NB**	**F**
M22	6/3/10	1/9/11	220	7	CB	M
M29	7/7/10	2/14/11	222	7	CB	M
M18	**4/29/10**	**12/10/10**	**225**	**7**	**NB**	**F**
M25	5/30/10	1/12/11	227	7	CB	F
M05	3/31/10	11/14/10	228	7	CB	M
M06	4/1/10	11/15/10	228	7	CB	F
M09	3/22/10	11/18/10	241	7	CB	F
M16	4/9/10	12/9/10	244	8	CB	M
M04	3/10/10	11/14/10	249	8	CB	M
M07	3/12/10	11/18/10	251	8	CB	F
M08	3/1/10	11/18/10	262	8	CB	M
M17	3/22/10	12/9/10	262	8	CB	F
M02	2/23/10	11/14/10	264	8	CB	M
M13	3/11/10	12/4/10	268	8	CB	F
M03	2/18/10	11/14/10	269	8	CB	M
M12	3/9/10	12/4/10	270	8	CB	M
M15	3/13/10	12/8/10	270	8	CB	F
M14	3/9/10	12/7/10	273	8	CB	M

Table 1: Participants

B. Testing procedures

a. Participant preparation

Upon arrival at the laboratory for testing, the study methods and equipment were explained to the parent(s) and consent for participation was obtained. During this time, the tester(s) talked and played with the infant to familiarize him/her with the new adults.

In preparation for infrared digital video capture of mandibular movements (Motion Analysis Corporation, Santa Rosa, CA, USA), a low-mass plastic reference marker array was attached to the infant's midline forehead at the hairline with double-sided medical adhesive tape (Figure 1, left). This reference array consisted of four 4-mm reflective spherical markers fixed to a solid plastic square. The markers were spaced several millimeters from one another to create three unique triangular spatial planes (x-, y-, and z-dimensions). This reference array was used to accurately track three-dimensional positioning of the infant's head during vocal play and toy manipulation as well as derive independent movement trajectories of a separate 4-mm reflective marker placed off-midline on the mandibular edge (Figure 1, left).

The infant was also instrumented with an accelerometer, which was embedded within a polyester fiber–Spandex medical band. The medical band was wrapped around the infant's neck so that the accelerometer's flat base was stabilized against the infant's skin at the level of the larynx (Figure 1, right). The accelerometer allowed for measurement of reactive tissue force in the area of the right thyroid lamina associated with vocal fold medialization and fundamental frequency during vocalization, grunts, and cough. By virtue of the placement and sensor design, the accelerometer was not sensitive to environmental sounds (e.g., other talkers, toys banging on table surface, etc.). Thus, the accelerometer signal was used in conjunction with an acoustic signal to aid identification of vocalization onset and offset.

Figure 1: Head block array and jaw marker (left); Jaw marker and laryngeal accelerometer (right)

b. Testing environment

The infant was secured in an upright position in a modified high chair with a custom hardwood work tray attached. The high chair was placed at the center of a 10’ × 10’ recording suite that houses the array of infrared digital (4 M pixel) motion capture cameras (Motion Analysis Corp., Santa Rosa, CA, USA), digital video, and cardioid microphones. The perimeter of the suite was lined with dark curtains. Within the recording space, the infant could see only the highchair s/he was sitting in, a blank black TV screen, and the illuminated diode array faces of five motion capture cameras, which were partially disguised with black covers. (*See Figure 2: Testing Environment*)

The parent sat in the motion capture suite, off to the right and behind the infant. The infant knew the parent was there, and could see him/her with a 45° head turn. However, secure with that knowledge, very few infants ever looked at their parent during the 16-minute data collection session. The purpose of the parent's presence was to make the infant feel safe and secure, but without distracting or interfering with the infant. The parent was instructed to remain motionless and quiet and not talk to or make eye contact with their infant, nor touch the infant or toys. Based on pilot data for this study, the parent's presence allowed for more natural and lengthier data-collection sessions. The possibility that the infant may not be able to be left alone without anxiety or increased likelihood of crying was expected—between 6 and 12 months of age, maternal attachment and avoidance of strangers increases (Bowlby, 1969).

Figure 2a: Infant's test chair and custom work/play surface.

Figure 2b: Infrared motion capture suite with camera array aimed at infant's 3D work space.

c. Data acquisition

Kinematic data was collected using a video motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) included five Eagle-4.0 Mpixel digital real-time infrared cameras, programmed to sample at 119.88 frames/second, shutter speed at 1000/sec, and tracking parameters set with maximum speed to 30 mm/frame. The five two-dimensional camera views were translated into a three-dimensional (3D) space by an MS-WIN7 x64bit workstation specially configured with a high-speed solid-state disk drive to handle the massive multichannel data stream. Markers were tracked with .15 mm resolution. Two acoustic, one accelerometer, and one SVGA video data stream were digitized in parallel through a National Instruments USB 6218 DAC (16-bit). Real time data acquisition, synchronization, and display of all motion capture and biological signals was accomplished with Cortex™ software version 2.0.2.917 (Motion Analysis Corporation, Santa Rosa, CA, USA). One acoustic data stream was synchronized into Cortex and sampled via a Sony cardioid directional microphone ("Microphone B") hanging approximately six inches above the infant's head. This acoustic data stream was used to align kinematic data within Cortex. The second acoustic data stream was sampled using a lapel microphone ("Microphone A") attached to the infant's chair, approximately 6 inches from the mouth and at shoulder level. Data from this microphone was sampled directly into the computer sound card. Kinematic, acoustic, and accelerometer signals were digitized at 12 kHz/channel at 16-bit vertical resolution (+/– 2.5V).

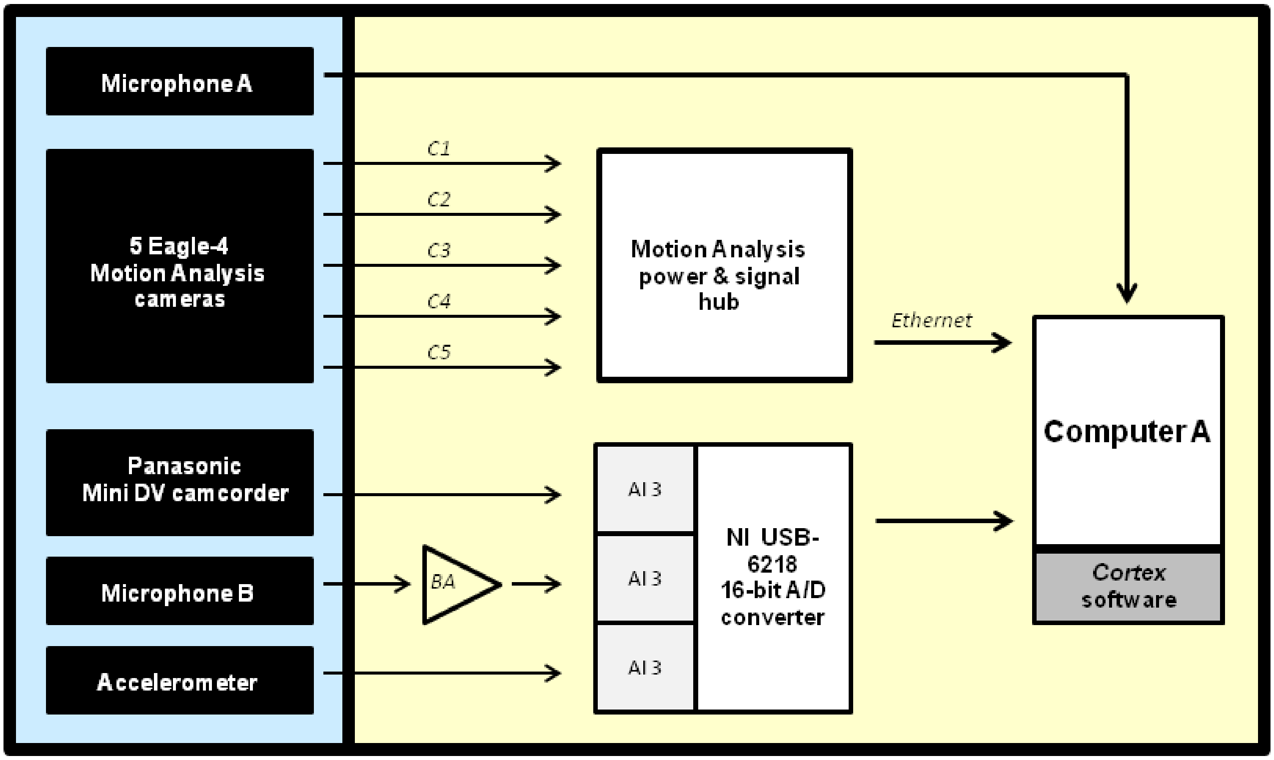

Figure 3: Data Acquisition Chart

d. Test session and conditions

Once instrumented and secured into their high chair, each infant participated in four successive test conditions, each four minutes in length. The order of test conditions was randomized and presented consecutively, for a total of 16 minutes of data collection. The test conditions were as follows:

- **"LargePlay":** The infant was provided an opportunity to play with seven toys that were difficult to grasp with one hand. Four were sound-producing (e.g. squeaky toy) and three were noiseless. The toys were between 9 cm minimum and 34 cm maximum circumference. These toys could be picked up and manipulated by the infant using both hands, but did not afford rapid play movements such as waving or shaking (Figure 4). All toys were presented at the same time. If the infant dropped a toy, it was ignored.

- **"SmallPlay":** The infant was provided an opportunity to play with seven toys that were easily grasped with one hand at the minimum circumference ("grip radius", .5 to 1.5 cm). Four were sound-producing (e.g. rattle) and three were noiseless. These toys were easily picked up and manipulated by the infant and tended to afford rapid play movements (e.g. waving, banging, shaking) in infants this age (Figure 4). At the developmental onset of canonical babbling, infants produce frequent arm stereotypy compared to earlier and later developmental stages and tend to shake, wave, and bang any toys that allow this type of motion (*pilot data*; Ejiri, 1998; Iverson, 2005; Iverson & Fagan, 2004; Locke et al., 1995; Thelen, 1981). All toys were presented at the same time. If the infant dropped a toy, it was ignored.
- **"Social":** The infant was not provided any toys to touch. Instead, the experimenter sat next to the infant and held the toys and used modeling and contingent reinforcement of vocalizations in order to attempt to elicit vocalizations from the infant. The social condition contained the following activities in counterbalanced order (Figure 4).
  - *Duck puppet, 60 seconds* = Experimenter says "/kae/, /kae/, /kae/" and moves puppet's mouth to match. Experimenter repeats "/kae/, /kae/, /kae/" with puppet mouth movement as soon as the infant produces a protophonic vocalization or after eight seconds—whichever comes first.

    - *Frog puppet, 60 seconds* = Experimenter says "/b^/, / b^/, / b^/" and moves puppet's mouth to match. Experimenter repeats "/b^/, / b^/, / b^/" and puppet mouth movement as soon as the infant produces a protophonic vocalization or after eight seconds—whichever comes first.
    - *Telephone, 60 seconds* = Experimenter holds telephone to ear and says "hi". Experimenter puts telephone to infant's ear and holds it there for four seconds. Experimenter brings phone back to own ear and repeats "hi".
    - *Peek-a-boo, 60 seconds* = Experimenter holds tray in front of face for six seconds, then removes tray so infant can see her face and says "boo". Experimenter then returns tray to occlude face and holds it there until the infant produces a protophonic vocalization or after six seconds—whichever comes first—before removing and saying "boo" again.
- **"Video":** The infant was not provided any toys to touch. Instead, the infant viewed a series of videos on a Samsung 25" ×35" LED graphics monitor at eye level, seven feet in front of the infant. The videos included clips of inanimate objects (e.g. spinning top, bubbles, moving train) obtained from Baby Einstein™ videos. Thirteen-second video clips with music and sound effects were alternated with seven-second silent video clips, with presentation order counterbalanced across infants. The sound was played at a moderate level (approximately 55 dB SPL).

Figure 4: Test Conditions—LargePlay, SmallPlay, Social

If the infant started to cry during any condition, data collection for that condition was stopped, the parent was allowed to calm the infant, and the next condition was started. The condition during which the baby became fussy was resumed at the end of the other testing conditions for however much time was left in that condition, unless there was less than 30 seconds remaining for that condition). For some infants, testing could not be resumed because the infant did not calm down once s/he started crying.

C. Analysis procedures

a. Data post-processing and analysis

Video, acoustic, accelerometer, and kinematic data streams were analyzed using the Cortex™ Software version 2.0.2.917 (Motion Analysis Corp., Santa Rosa, CA, USA) and custom coded peak-picking software (MatLAB v.9) coded by Joan Wang, MSEE in the Communication Neuroscience Laboratory.

The Cortex™ Software was used to identify markers and low-pass filter (Butterworth f_c @ 10 Hz) all marker paths (*see Figure 5*). The Cortex™ Software was also used to switch from data references on three planes of movement (x, y, z) to one—the Euclidian distance between the lowest head marker (at forehead) and right paramedian jaw marker. This head-referenced jaw movement trajectory more accurately captured infants' mandibular motion than referencing to a real-world plane of motion because infants regularly turned their head from upright while exploring their environement. The CNL MatLAB and LabVIEW coded peak picking software was used to automatically identify all peaks within a jaw movement trajectory. A jaw movement peak (cycle) was defined as any displacement of at least 2 mm plus any adjacent return toward baseline position within 1 second or less, from the initiation to termination of this displacement (Figure 6).

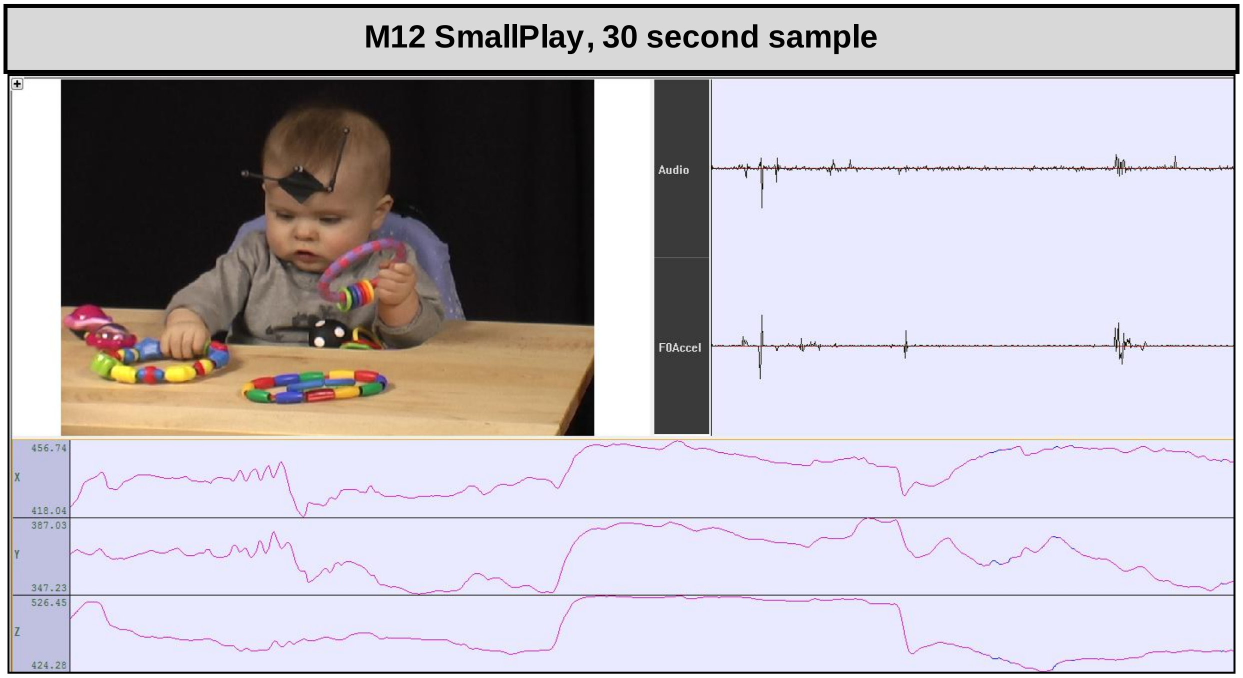

Figure 5a: Cortex™ Software: top left = video stream; top right = audio and accelerometer streams; bottom = raw jaw marker data, planes x (left–right), y (up– down), and z (front–back) relative to the head marker.

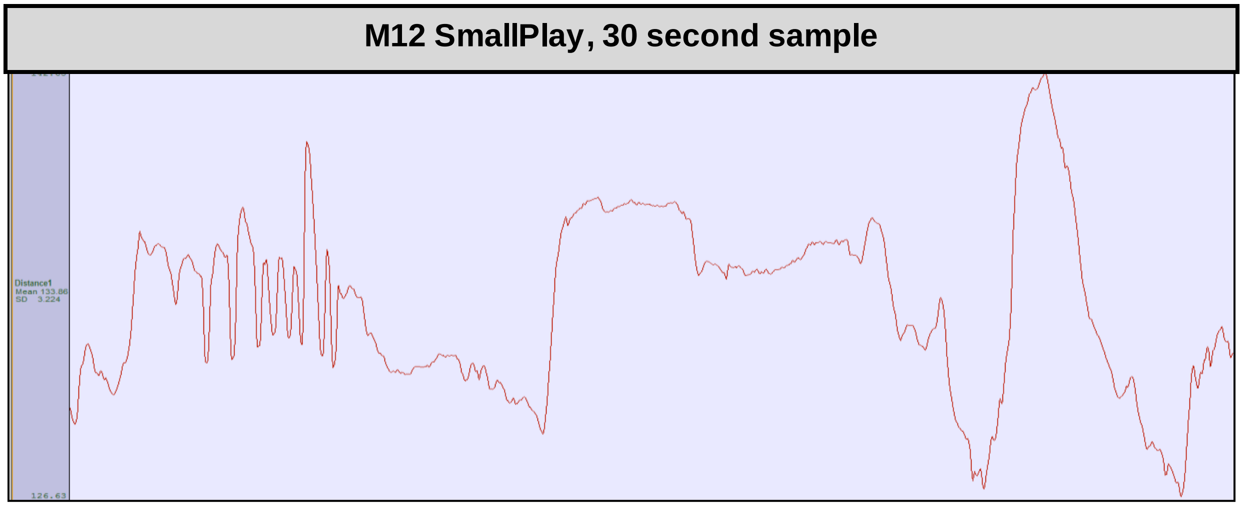

Figure 5b: Cortex™ Software: Euclidean jaw movement trajectory referenced to the head block array

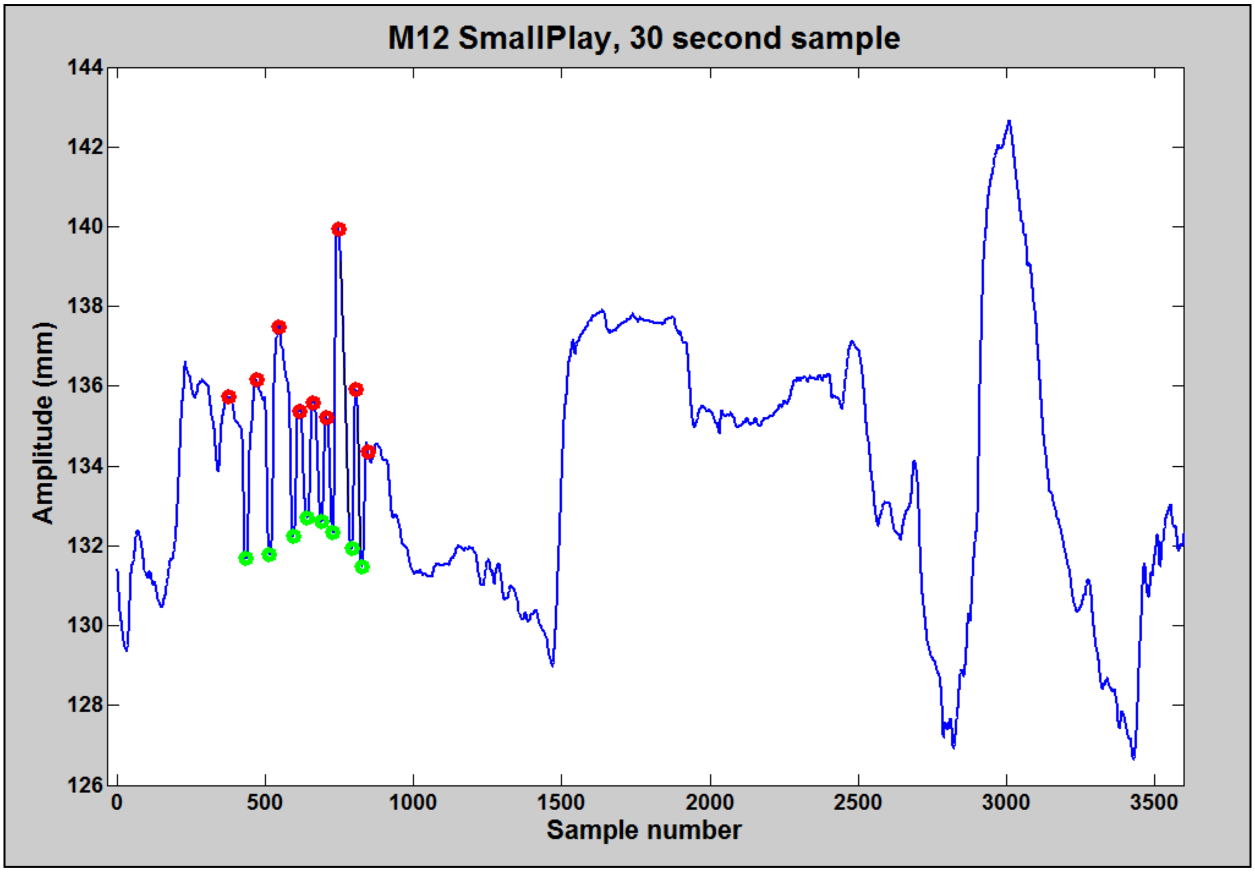

Figure 6: CNL MatLAB and LabVIEW Peak-Picking Program: red dots index jaw cycle peaks; green dots index jaw cycle valleys; amplitude (mm) is distance from head block array; sample number is on a time scale of 119.88 samples per second.

Once the jaw cycles were identified, Cortex™ Software was used to align video, acoustic, accelerometer, and kinematic data for the categorization of cycles. First, any cycle that was produced with concurrent oral obstruction (e.g. finger or toy in mouth) was coded. Then, cycles were categorized as either vocalized or silent. Vocalized cycles were audible from the acoustic stream and characterized by the presence of either an acoustic waveform, vocal fold motion data from the laryngeal accelerometer, or most-often both, overlapping with the kinematic jaw cycle.

Once the vocalized jaw cycles were identified, they were separated into one of three categories: non-protophonic, vowel/marginal, or canonical. Non-protophonic vocalizations included whines, sighs, squeals, grunts, cry, or giggle. Vowel/marginal vocalizations included quasivowels, vowels, quasivowels with movement of the supraglottal vocal tract, and marginal syllables. Canonical vocalizations included full canonical syllables. Protophonic vocalizations (vowel/marginal or canonical) that were *not* associated with a jaw cycle were also identified and counted. Previous research suggests that adult listeners are highly skilled at identifying canonical vs. non-canonical syllables (Oller, 2001). Inter-rater reliability was performed by having a KU speech pathology graduate student categorize a random sample containing 10% of the jaw cycles categorized by the first author. The student identified 93% of the cycles in the same category as did the first author. This 93% inter-rater reliability was judged sufficient to accept the method of categorization of cycles.

All jaw cycles (silent, non-protophonic, vowel/marginal, and canonical) were then analyzed using MatLAB and LabVIEW for the following parameters: jaw closing velocity (mm/sec), jaw opening velocity (mm/sec), and jaw cycle frequency (Hz).

b. Statistical analysis

For the current study, it was essential to recognize the hierarchical nature of the data; observations of outcome variables were repeatedly measured under different conditions (level-1), which were nested within subjects (level-2) and groups (level-3). When nested data are analyzed without regard to interdependency within a setting, Type I error is inflated leading to unwarranted rejection of the null hypothesis (Dorman, 2009; Hedges, 2007). Thus, general mixed modeling, which accounts for lack of independence among observations, was used for analysis. This approach expands general linear modeling, such as repeated measures analysis of variance (RM ANOVA), by supporting more variations in specifying the covariance structure of the repeated measures (Raudenbush & Bryk, 2002). The compound symmetry (CS) covariance structure of the repeated measures yielded smaller Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) than did the unstructured (UN), first-order autoregressive (AR), and variance component (VC) covariance structures, and thus was chosen for the current mixed model. For parameter estimation, maximum likelihood method, which accommodates the observations missing at random, (Little, 1987) was used. Statistical significance of model parameters were determined at 0.05 alpha level. All analyses were conducted using SAS 9.2 (SAS Institute, 2002–2008).

For each of the outcome variables, a mixed model was fitted in order to examine the group (level-3, NB vs. CB) effect as well as condition (level-1) effect (Figure 7). Infants' age and gender were also included into the model as covariates to account for differences in these factors and to thereby further increase power to detect significant effects. For opening velocity, closing jaw velocity, and cycle frequency, the presence of an object in the infant's mouth ("oral obstruction") was also incorporated as a covariate, due to exploratory analyses indicating an effect of oral obstruction on jaw kinematic parameters. When the group or condition effect was significant, adjusted means were pair-wise compared using a Bonferroni-corrected p-value.

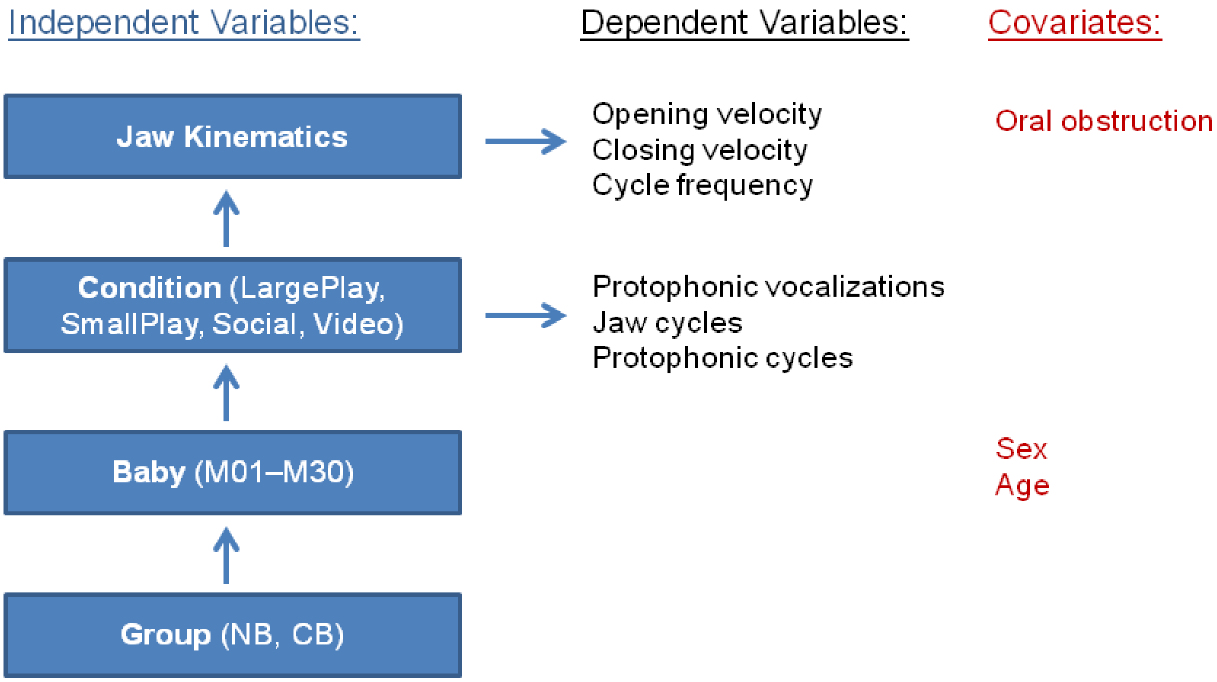

Figure 7: Statistical Mixed Model

CHAPTER 3: RESULTS

A. Condition results, Specific Aim #1

After controlling for infant sex and age, a significant trend was observed for the number of protophonic vocalizations produced in each condition [$F(3,83) = 183.72$, $p < .0001$], Cohen's $f = 2.51$ (*large*). Given the significant condition effect, adjusted means were pairwise compared. Pairwise comparisons after a Bonferroni adjustment among each of the conditions resulted in $p < .0001$ for each comparison. LargePlay elicited the most protophonic vocalizations, followed by SmallPlay, Social, and Video. The following table provides the estimated mean and standard error for the number of protophonic vocalizations per minute in each condition:

Protophonic vocalizations / minute		
Condition	*M*	*SE*
LargePlay	4.76	.63
SmallPlay	3.00	.63
Social	1.79	.64
Video	.73	.64

Table 2: Condition results: protophonic vocalizations per minute

After controlling for infant sex and age, a significant trend was observed for the number of jaw cycles produced in each condition [$F(3,75) = 265.74$, $p < .0001$], Cohen's $f = 3.17$ (*large*). Given the significant condition effect, adjusted means were pairwise compared. Pairwise comparisons after a Bonferroni adjustment among each of the conditions resulted in $p < .0001$ for every comparison *except* Social compared to Video. SmallPlay elicited the most jaw cycles, followed by LargePlay, then Social and Video. The following table provides the estimated mean and standard error for the number of jaw cycles per minute in each condition:

Jaw cycles / minute		
Condition	*M*	*SE*
LargePlay	9.19	1.28
SmallPlay	10.68	1.28
Social	2.72	1.31
Video	2.14	1.31

Table 3: Condition results: jaw cycles per minute

After controlling for infant sex and age, a significant trend was observed for the number of protophonic jaw cycles produced in each condition [$F(3,72) = 85.35$, $p < .0001$], Cohen's $f = 1.82$ (*large*). Given the significant condition effect, adjusted means were pairwise compared. Pairwise comparisons after a Bonferroni adjustment among each of the conditions resulted in $p < .0001$ for every comparison *except* Social compared to each SmallPlay and Video. LargePlay elicited the most jaw cycles, followed by SmallPlay, then Social and Video. The following table provides the estimated mean and standard error for the number of protophonic jaw cycles per minute in each condition:

Protophonic jaw cycles / minute		
Condition	*M*	*SE*
LargePlay	1.47	.23
SmallPlay	.52	.23
Social	.19	.24
Video	.00	.24

Table 4: Condition results: protophonic jaw cycles per minute

After controlling for infant sex, age, and oral obstruction no significant trend was observed for jaw closing velocity among conditions [$F(3,70) = 1.98$, $p = .13$]. The following table provides the estimated mean and standard error for the jaw closing velocities (mm/sec) per cycle per condition:

Jaw closing velocity (mm/sec)		
Condition	*M*	*SE*
LargePlay	32.14	1.87
SmallPlay	32.71	1.79
Social	34.13	2.15
Video	29.56	2.14

Table 5: Condition results: jaw closing velocity

After controlling for infant sex, age, and oral obstruction a significant trend was observed for jaw opening velocity among conditions [$F(3,70) = 3.82$, $p = .01$]. However, pairwise comparisons after a Bonferroni adjustment among each of the conditions resulted in $p = .01$ for *only* SmallPlay compared to Video. All other comparisons resulted in $p > .30$. SmallPlay elicited the greatest opening velocity, compared to Video, and LargePlay and Social fell in between. The following table provides the estimated mean and standard error for jaw opening velocities (mm/sec) per cycle per condition:

Jaw opening velocity (mm/sec)		
Condition	*M*	*SE*
LargePlay	27.07	1.55
SmallPlay	29.20	1.48
Social	27.30	1.77
Video	24.79	1.76

Table 6: Condition results: jaw opening velocity

After controlling for infant sex and age, a significant trend was observed for the frequency (Hz) of jaw cycles produced in each condition [$F(3,70) = 10.42$, $p < .0001$], Cohen's f

= .62 (*medium*). Given the significant condition effect, adjusted means were pairwise compared. Pairwise comparisons after a Bonferroni adjustment among each of the conditions resulted in $p < .0001$ for LargePlay compared to SmallPlay, and SmallPlay compared to Video. SmallPlay elicited a greater cycle frequency than each LargePlay and Video. All other comparisons resulted in $p > .10$. The following table provides the estimated mean and standard error for jaw cycle frequency (Hz) per cycle per condition:

Jaw cycle frequency (Hz)		
Condition	*M*	*SE*
LargePlay	1.77	.08
SmallPlay	1.96	.08
Social	1.80	.09
Video	1.64	.09

Table 7: Condition results: jaw cycle frequency

B. Group results, Specific Aim #2

After controlling for infant sex and age, no significant trend was observed between NB and CB groups and the number of protophonic vocalizations produced [$F(1,26) = .10$, $p = .76$]. The following table provides the estimated mean and standard error for the number of protophonic vocalizations per minute produced by each the NB and CB groups:

Protophonic vocalizations / minute		
Group	*M*	*SE*
NB	2.34	1.17
CB	2.79	.66

Table 8: Group results: protophonic vocalizations per minute

After controlling for infant sex and age, no significant trend was observed between NB and CB groups and the number of jaw cycles produced [$F(1,24) = .03$, $p = .86$]. The following table provides the estimated mean and standard error for the number of jaw cycles per minute produced by each the NB and CB groups:

Jaw cycles / minute		
Group	*M*	*SE*
NB	5.92	2.41
CB	6.45	1.39

Table 9: Group results: jaw cycles per minute

After controlling for infant sex and age, no significant trend was observed between NB and CB groups and the number of protophonic jaw cycles produced [$F(1,24) = .32$, $p = .58$]. The following table provides the estimated mean and standard error for the number of protophonic jaw cycles per minute produced by each the NB and CB groups:

Protophonic jaw cycles / minute		
Group	*M*	*SE*
NB	.38	.25
CB	.69	.43

Table 10: Group results: protophonic jaw cycles per minute

Note, however, that though this metric did not reach significance, of the total 140 protophonic jaw cycles produced, only 10 (7%) came from NB babies. Yet, there was no difference in either number of protophonic vocalizations nor number of jaw cycles per group, indicating that protophonic vocalizations *with* jaw displacement is a behavior produced primarily by CB infants. Though the great majority of protophonic jaw cycles were from CB babies, this measure was not significant in part because these protophonic jaw cycles were produced entirely by *five* of the total 21 CB infants. These five infants were all 8 months of age. The plot below shows the number of protophonic jaw cycles per infant, by age:

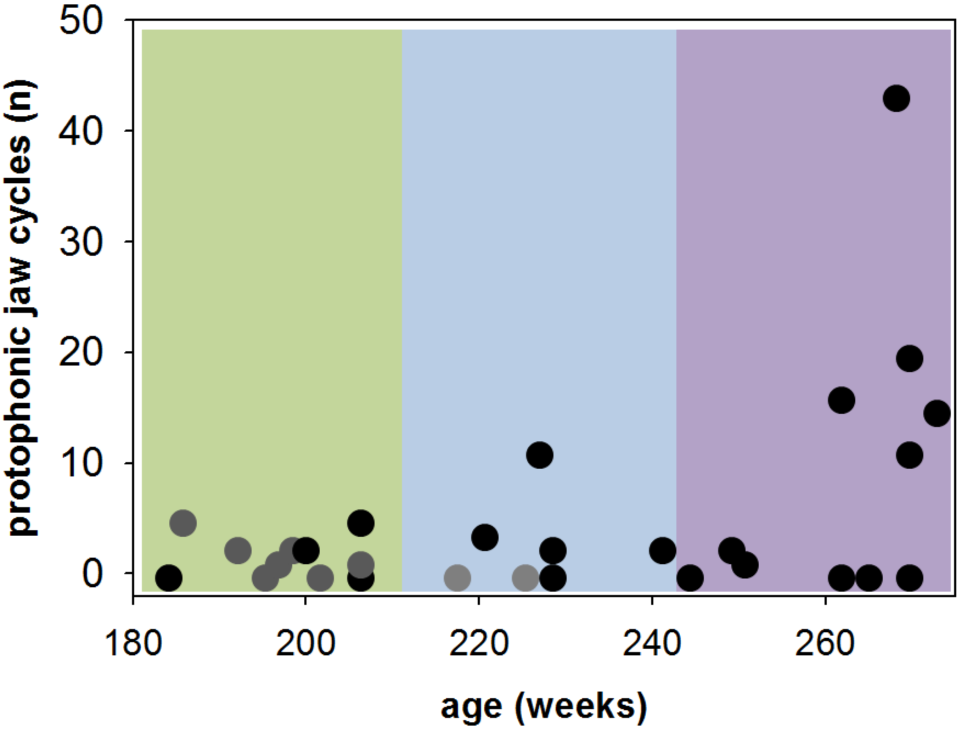

Figure 8: Protophonic jaw cycles by age. Green = 6-month-old infants, Blue = 7-month-old infants, Purple = 8-month-old infants; Black circles = CB; Gray circles = NB

After controlling for infant sex, age, and oral obstruction, no significant trend was observed between NB and CB groups and the closing velocity of jaw cycles produced [*F*(1,24) = .14, *p* = .71]. The following table provides the estimated mean and standard error for the closing velocity of jaw cycles produced by each the NB and CB groups:

Jaw closing velocity (mm/sec)		
Group	*M*	*SE*
NB	32.88	3.19
CB	31.40	1.81

Table 11: Group results: jaw closing velocity

After controlling for infant sex, age, and oral obstruction, no significant trend was observed between NB and CB groups and the opening velocity of jaw cycles produced [$F(1,24) = .44$, $p = .52$]. The following table provides the estimated mean and standard error for the opening velocity of jaw cycles produced by each the NB and CB groups:

Jaw opening velocity (mm/sec)		
Group	*M*	*SE*
NB	26.03	2.64
CB	28.15	1.50

Table 12: Group results: jaw opening velocity

The following frequency histograms given in Figures 9 and 10 show the distribution of jaw opening and closing velocity (mm/sec) data, for all babies, across all conditions, before corrected for the covariates sex, age, and oral obstruction.

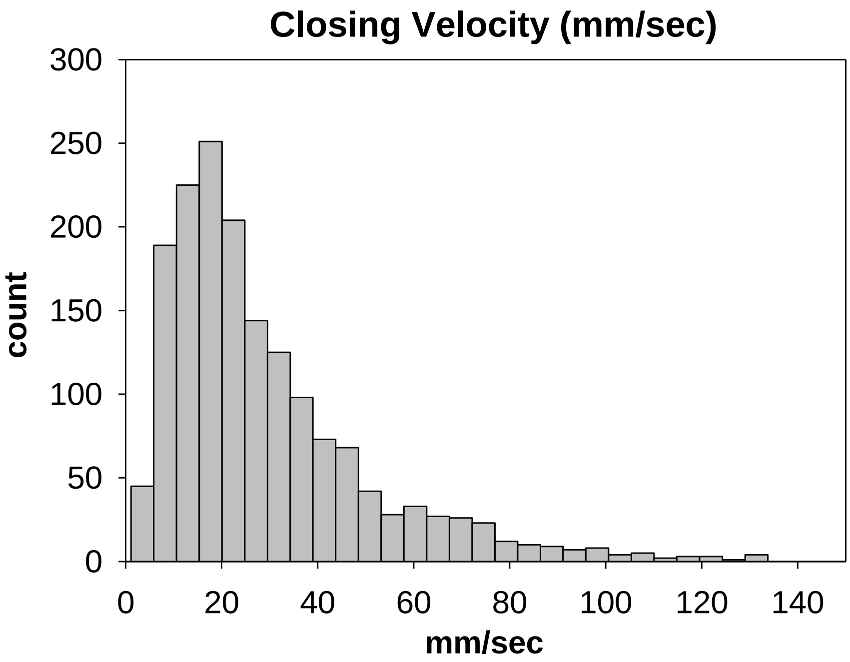

Figure 9: Closing velocity (mm/sec) of jaw cycles for all infants

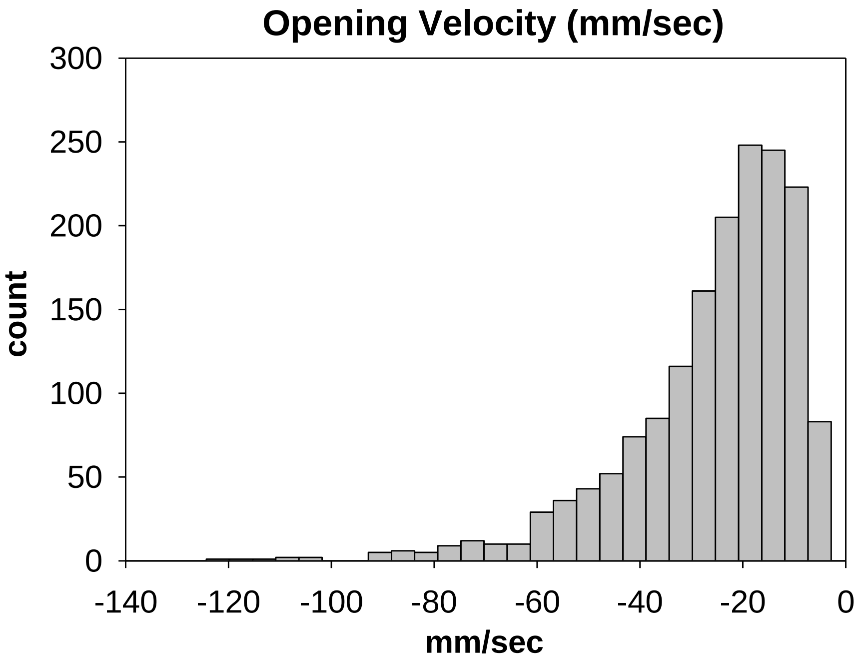

Figure 10: Opening velocity (mm/sec) of jaw cycles for all infants

After controlling for infant sex, age, and oral obstruction, no significant trend was observed between NB and CB groups and the frequency of jaw cycles produced [$F(1,24) = .04$, $p = .84$]. The following table provides the estimated mean and standard error for the frequency of jaw cycles produced by each the NB and CB groups:

Jaw cycle frequency (Hz)		
Group	*M*	*SE*
NB	1.80	.14
CB	1.80	.08

Table 13: Group results: jaw cycle frequency

The following frequency histogram given in Figures 11 shows the distribution of jaw cycle frequency (Hz) data, for all babies, across all conditions, before corrected for the covariates sex, age, and oral obstruction.

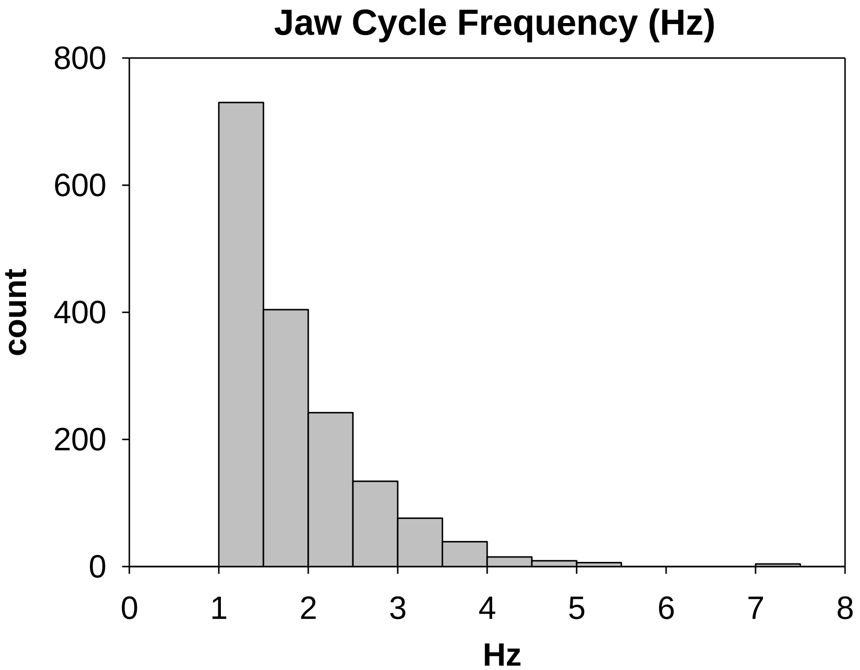

Figure 11: Cycle frequency (Hz) of jaw cycles for all infants

C. Covariate results

The covariates sex, age, and oral obstruction were taken into account for statistical analyses of group and condition effects. The following results are for each of the covariates accounted for.

A significant trend was observed in infant sex and the number of protophonic vocalizations produced [$F(1,26) = 5.19$, $p < .05$], Cohen's $f = .39$ (*medium*). Females produced more protophonic vocalizations than males. The following table provides the estimated mean and standard error for the number of protophonic vocalizations per minute produced by each females and males:

Protophonic vocalizations / minute		
Sex	*M*	*SE*
Females	2.86	.86
Males	1.55	.34

Table 14: Protophonic vocalizations per minute by sex

No significant trends were observed in infant sex for number of jaw cycles produced, number of protophonic jaw cycles produced, jaw opening velocity, jaw closing velocity, or jaw cycle frequency.

Likewise, no significant trends were observed in infant age across any measured parameters, including number of jaw cycles produced, number of protophonic vocalizations produced, number of protophonic jaw cycles produced, jaw opening velocity, jaw closing velocity, or jaw cycle frequency.

There was a significant trend observed in oral obstruction and jaw closing velocity [$F(1,24) = 53.16$, $p < .0001$], Cohen's $f = 1.42$ (*large*), and opening velocity [$F(1,24) = 27.02$, p

< .0001], Cohen's *f* = .34 (*medium*). There was not a significant trend observed in oral obstruction and jaw cycle frequency $F(1,24) = 6.07$, $p = .02$. The following table provides the number of jaw cycles with and without oral obstruction, along with the estimated mean and standard error for closing velocity, opening velocity, and cycle frequency:

Jaw cycles with oral obstruction							
	N	Closing velocity (mm/sec)		Opening velocity (mm/sec)		Cycle Frequency (Hz)	
		M	*SE*	*M*	*SE*	*M*	*SE*
No oral obstruction	1311	27.06	.55	-24.51	.48	1.85	.02
Oral obstruction	359	38.89	1.46	-31.61	1.06	1.87	.03

Table 15: Oral obstruction and jaw cycle kinematics

Since the frequency across jaw cycles with and without oral obstruction remains nearly constant, it is presumed that the increased jaw amplitude with intraoral obstruction reflects kinematic adaptation through a rescaling of opening/closing velocity in order to maintain cycle frequency. This metric required attention as a covariate, because of the large amount of oral obstruction in many of the conditions. For each of the conditions, the percentage of cycles with oral obstruction was: LargePlay, 22%; SmallPlay, 27%; Social, 16%; Video, 10%.

D. Exploratory results

Follow-up analyses were performed to more closely examine the jaw cycles infants were producing. Jaw cycles were divided into four categories: silent, non-protophonic, vowel/marginal, and canonical (*see Results: Data post-processing and Analysis for descriptions*). Comparisons of cycle type were not included in the statistical model due to a lack of adequate data across each category. Thus, the following results should be considered preliminary and can inform future studies but cannot be generalized.

Only CB infants produced canonical syllables. Of the 43 canonical syllables produced, 35 were from one 8-month-old female infant. Vowel/marginal syllables were from 18 infants' data, both CB and NB, but NB babies only produced 10 total marginal/vowel syllables with jaw movement (protophonic jaw cycles). Thus, only 10 total marginal/vowel syllables from NB babies were analyzable for the kinematic parameters of velocity and frequency. All other marginal/vowel syllables came from CB babies. Non-protophonic cycles were from 11 infants' data. All infants produced silent jaw cycles.

All four cycle types were produced in all four conditions, LargePlay, SmallPlay, Social, and Video. Table 16 provides the total number of protophonic cycles, then the number of protophonic cycles in each condition. Table 17 summarizes jaw closing velocity, opening velocity, and cycle frequency across each cycle type.

Cycle Type	*N*	LargePlay	SmallPlay	Social	Video
Canonical	**43**	36	3	3	1
Vowel/marginal	**97**	38	39	14	6
Non-protophonic	**48**	30	3	9	6
Silent	**1482**	397	609	243	233

Table 16: Protophonic vocalization type across conditions

		Closing velocity (mm/sec)		Opening velocity (mm/sec)		Cycle Frequency (Hz)	
Cycle Type	*N*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Canonical	**43**	43.62	3.60	-25.35	1.66	1.64	.05
Vowel/marginal	**97**	39.65	2.51	-34.50	1.98	2.11	.08
Non-protophonic	**48**	25.92	1.91	-28.58	1.91	1.69	.09
Silent	**1482**	28.66	.57	-25.42	.47	1.85	.02

Table 17: Protophonic cycle type kinematics

CHAPTER 4: DISCUSSION

A. Environmental catalysts of emergent canonical syllables

a. Infant jaw movement and vocalizations while watching videos

Infants produced the fewest number of protophonic vocalizations, jaw cycles, and protophonic jaw cycles per minute while watching videos. This effect was significant when compared to playing with either large or small toys. For comparison to the Social condition, the effect reached significance in the measure of protophonic vocalizations per minute, but did not reach significance for jaw cycles or protophonic jaw cycles per minute.

Clearly, video stimuli encourage silence and stillness in infants 6–8 months of age. An initial hypothesis of this study was that infants may be attending to the sounds of the video and listening rather than producing sound themselves. Because of this prediction, our study design incorporated silent videos in an attempt to ameliorate this potential effect. Over 35% of the video clips played to infants contained seven seconds of continuous silence. Based on pilot data, this was as much silence as could be incorporated into the condition without the video clips becoming too boring to the infant, whereby the infant would become fussy and be unwilling to participate. Nonetheless, even with these silent videos a large effect of non-elicitation of infant vocalizations was still found. Thus, auditory stimulation is unlikely to be the reason videos induce silence.

The non-participatory effect of videos is somewhat intuitive to those with experience watching young children view television and movies. The television is truly an easy “babysitter,” because it causes the child to become still and silent. This effect may be why so many parents and caregivers use the television. By just 3 months of age, 40% of infants have regularly watch television or videos, and by 24 months 90% of children regularly watch television and videos (Zimmerman, Christakis, & Meltzoff, 2007).

Despite the stillness and quietness that is induced in infants while watching videos, infant researchers still incorporate videos into their studies in order to elicit infant vocal and motor behaviors (e.g., Pierce, Conant, Hazin, Stoner, & Desmond, 2011), though some have noted that videos do not work very well to elicit playful behaviors or vocalization (Steeve & Moore, 2009). Other researchers have found that when using animated toys and video clips as reinforcers, the animated toys elicit significantly more contingent responses from the infants than the video clips (Karzon & Banerjee, 2010). Not only do videos reduce infant output, but other researchers have found that infants also do not learn well from videos. Infants from 12–24 months of age learn words only from live interaction, not videos (DeLoache, Chiong, Sherman, Islam, Vanderborght, et al., 2010; Richert, Robb, Fender, & Wartella, 2010).

An obvious benefit of digital media is that it can be easily controlled and manipulated, which serves well for many research studies attempting to carefully manipulate and control input to infants. However, this study is the first to demonstrate just how substantially stifling videos can be to infant vocal and oromotor output. Thus, any advantages of the manipulability or consistency that videos provide is likely to be outweighed by the drawbacks of suppressing infants' behaviors. Videos temporarily turn an infant who moves, vocalizes, and explores his or her own skills and environment into a motionless being.

b. Infant jaw movement and vocalizations during social play

Infants produced significantly more protophonic vocalizations and jaw cycles during social play with an adult compared to watching videos. However, infants produced significantly *fewer* protophonic vocalizations, jaw cycles, and protophonic jaw cycles per minute during social play with an adult compared to individual play with large toys. Infants also produced significantly fewer protophonic vocalizations and jaw cycles per minute during social play with an adult compared to individual play with small toys. Thus, having an adult play with a 6- to 8-month-old infant is less stifling to vocal and oromotor output than videos, but still more stifling than allowing the infant to play alone with toys.

It is important to note that the Social play condition used in the current study used both age-appropriate modeling and contingent reinforcement of vocalization—both techniques which have been suggested as appropriate for teaching and eliciting vocalizations from infants and toddlers (American Speech–Language–Hearing Association, 2008; Rosetti, 2001). However, research on the effectiveness of contingent reinforcement in infants younger than 12 months has been limited to non-vocal and non-oral motor behaviors. Infants will contingently move their arms, head, or legs to elicit a desirable result such as a moving toy or colorful video (Alessandri, Sullivan, & Lexis, 1990; Rovee-Collier, Sullivan, Enright, Lucas, & Fagan, 1980). Clearly this paradigm is not ideal within the realm of eliciting vocalization in young infants.

Change is the hallmark for infants from 6 to 12 months, and extending through two years. Play routines that are appropriate for encouraging vocalizations from older infants simply may not work for an infant as young as 6 months old. Other studies have demonstrated that, specifically at the age of onset of canonical babbling, infants do not produce high rates of vocalization in the presence of adults or in social situations (Jones & Moss, 1971; Locke, 2004; Lin & Green, 2009; Delack, 1978). Around 6 months, more so than at older or younger ages, infants are particularly unlikely to directly mimic the vocalizations of adults (Jones, 2007) and do not tend to direct their vocalizations toward others (Fay, 1967; Furrow, 1984). Between 5 and

9 months, infants vocalize more when they are alone (Delack, 1978; Jones & Moss, 1971). Also, when the mother is present, infants this age vocalize more when the mother is silent than when she is vocalizing and interacting with the infant (Lin & Green, 2009).

At the age of onset of canonical babbling, infants may be particularly attentive to adults—so much so that it reduces their own vocal and motor output. Infants may be mesmerized by adults' faces and eye contact, both which have been shown in previous research to be particularly stimulating and intriguing to infants (Krentz & Corina, 2008; Nelson, 2001). Even though during the moment of interaction infants have reduced vocal and motor output, this does not suggest that adult interaction with infants has a negative impact on the infant. The learning that takes place when an infant watches an adult communicate and respond to him or her is, on a greater time scale, a very beneficial experience for the infant. Parental responsivity has been shown to be quite beneficial to communication development across infancy and early childhood (Tamis-LeMonda & Bornstein, 2002; Warren & Brady, 2007), and infants learn language by listening to adult examples. Kuhl (2007) suggests that, because infants are so attentive to faces and eye contact, an adult's social interaction with the infant is particularly beneficial to language development indeed because the adult is so good at arousing the infant and maintaining his or her attention. This unwavering attention would then act to the benefit of the linguistic signal being modeled during the vocal interaction.

Another possible hypothesis for why infants 6–8 months are particularly silent in the company of an adult is that infants this age do not treat protophonic vocalizations as primarily communicative. To the infant, vocalizations may more closely resemble other playful motor behaviors such as waving the arms or banging toys on a tray. To an adult, vocal communication increases or only occurs when a communicative partner is present. To the infant, however, a communication partner may not be an environmental requisite of vocalization at all. The infant certainly knows that vocalization *can* be used to elicit attention from the parent, which they learn during cry and vocal attention-seeking interactions. This communication function of vocalization, however, may not be primary to the infant. The infant may instead use vocalization primarily for the function of play and self-stimulation, or may not have any intent behind his or her vocalizations at all.

c. Infant jaw movement and vocalizations during individual play with toys

Allowing an infant to play with toys alone elicits more protophonic vocalizations, more jaw cycles, and more protophonic jaw cycles per minute than either social play with an adult or watching videos. However, not all toys elicit the same type and amount of movement and vocalization from the infant.

At the age of onset of canonical babbling, infants produce substantially more arm stereotypy than at any other stage of development (Ejiri, 1998; Iverson, 2005; Iverson & Fagan, 2004; Locke et al., 1995; Thelen, 1981). When given toys that afford arm stereotypy, such as rattles, keys, or other items that have a narrow surface for gripping, infants will hold and wave or bang these items almost incessantly (Iverson, 2005; Iverson & Fagan, 2004). Pilot data for the current study indicated that, though arm stereotypy and canonical syllable production both increase at the same time developmentally, they are rarely produced *simultaneously*. Thus, toys that have a small grip radius and afford gross motor arm movements (SmallPlay) were included in a condition distinct from toys that have a larger grip radius and can be picked up but not easily waved or banged with a single hand (LargePlay).

The results of this study show that, though both SmallPlay and LargePlay elicited generally high vocalization rates, LargePlay elicited significantly more protophonic vocalizations and protophonic jaw cycles per minute than SmallPlay. We predict that this is because arm waving and gross motor movements are not conducive to simultaneous vocalization. If the infant is moving his or her arms and engaging that musculature and motor control system, he or she may be less likely to engage the respiratory and phonatory musculature and control system required to produce a playful vocalization. This effect of a gross motor behavior reducing vocal motor output has been seen anecdotally in other scenarios, as well. For example, infant–toddler speech pathologists often note a slowing of vocal development and decrease in frequency of vocalizations when an infant first begins walking.

Interestingly, the results of this study are in direct conflict with a previous study indicating that in the month of onset of canonical babbling, canonical syllables are more likely to occur with arm stereotypy than without (Iverson & Fagan, 2004). Instead, we found arm stereotypy to be particularly stifling to protophonic vocalization rate—and the infants in the current study are all very near or within the month of onset of canonical babbling. Looking at canonical syllables specifically, there was no preference for production during the SmallPlay condition at all. In fact, the overwhelming majority of canonical syllables (84%) were produced during the LargePlay condition, and SmallPlay elicited the same number of canonical syllables as the Social condition (both 7%), with the Video condition eliciting the fewest (2%).

Though LargePlay elicited the most protophonic vocalizations, it did not elicit more jaw movement cycles than SmallPlay. The SmallPlay condition actually elicited significantly *more* jaw cycles per minute than the LargePlay condition. Thus, though LargePlay is best for eliciting vocalizations, SmallPlay is best for eliciting jaw movement in general. We hypothesize that the increase in rate of jaw movements during the SmallPlay condition is due to the overall increased amount of bodily movement. Increased large-amplitude and fast movements of the arms may carry over into control of the jaw and influence it to move a bit more, even slightly. Note that in this study, jaw movement had to be only 2 mm in order to be counted as a “jaw cycle.” Thus, tiny movements during the SmallPlay condition were included in the cycle count. Ultimately, wagging the jaw by a few millimeters takes considerably less effort than simultaneously engaging the respiratory and laryngeal musculature required to produce a protophonic vocalization, which may be why the gross motor arm movements increase the rate of jaw movement but not the rate of vocalization.

The SmallPlay condition also elicited significantly greater jaw opening velocities (mm/sec) than the Video condition, and greater, but not significantly greater, jaw opening velocities than either LargePlay or Social. The frequency of jaw cycles was also significantly higher in the SmallPlay condition compared to either LargePlay or Video. These additional differences in jaw kinematics between SmallPlay and the other play conditions are also likely due to the increase in overall amount and amplitude of motor movements that occur during the SmallPlay condition when the infant is waving, shaking, and banging toys.

B. Orofacial kinematics and protophonic vocalizations of emergent canonical babblers

a. Amount of vocal and oromotor output at canonical babbling onset

Most adults would not consider silent jaw movements to be pre-speech behaviors. However, silent jaw oscillations are often considered precursors to canonical syllables and, to the infant, not necessarily part of a distinct behavioral category (Meier et al., 1997; MacNeilage, 1998; Thelen, 1991). Previous studies have found that the total number of jaw movements increases during the first year and predict that these behaviors are helpful in honing the infant's oral kinematic skills (Green & Wilson, 2006). In fact, at 5 months there is a substantial increase in the number of jaw cycles produced, which is predicted to be preparatory for the onset of canonical syllable production (Green & Wilson, 2006). However, the current study found no significant difference in the number of jaw cycles produced between either NB and CB infants or among the tested age range of 6 to 8 months. This suggests that while infants may gradually produce more jaw cycles during the first year with a marked peak around 5 months, the absolute number of jaw cycles produced does not differentiate infants' ability to produce canonical syllables and is thus unlikely to be particularly influential in the onset of canonical syllables.

This study also found no significant difference between NB and CB infants and the number of protophonic vocalizations produced per minute or protophonic jaw cycles produced per minute. This result is consistent with data from a recent study (Fagan, 2009) that reported that infants do not demonstrate an increase in the number of syllables per utterance over the first year of life. Thus, the onset of canonical babbling is marked by an increase in vocalization complexity but not necessarily the quantity of vocalizations.

b. Orofacial kinematics and the onset of canonical babbling

Acoustic studies of canonical versus marginal syllables have found that canonical syllables are distinct from marginal in that they have rapid formant transitions and adult-like timing of less than 500 milliseconds per syllable (Lynch et al., 1995; Oller, 2000). This change in acoustic timing parameters and transitions between targeted vocal tract resonances must be achieved by changes in kinematic spatiotemporal parameters. Researchers have predicted that the onset in canonical syllable production requires some maturation of oromotor skills (Moore, 2004; Oller, 2000), mandibular control in particular (Davis & MacNeilage, 1995; MacNeilage, 1998). It is already known that jaw speed and spatiotemporal coordination attain more mature rates sooner in development than the lips or tongue (Green, Moore & Reilly, 2002; Nip et al., 2009; Steeve, 2010) and that vocalizations of infants from 9–24 months of age tend to be jaw-dominant (Green & Nip, 2010). Thus, because the jaw seems to be the primary articulator in infant vocalizations, one hypothesis for the current study was that gains in oral kinematic maturity should be demonstrated by gains in jaw kinematics as infants attain new milestones such as the onset of canonical babbling. In older infants, this is the case. For example, high jaw speed is correlated with higher performance on speech–language tests among children 9 to 21 months of age (Nip, Green, & Marx, 2011).

Despite the predictions and evidence from older infants, the current study of infants 6–8 months of age found no differences in jaw opening velocity, jaw closing velocity, or jaw cycle frequency across infants' age or canonical babbling status. Jaw kinematics were within the expected range, based on previous studies of older infants (Nip, et al., 2009) and studies of silent jaw motion in infants (Green & Wilson, 2006). Several explanations follow for the lack of jaw kinematic differences between babbling groups and across ages.

First, age may not be a significant predictor of jaw kinematics in the current study because infants are at a semi-plateau in their development of jaw velocity and cycle frequency at this age. Or more likely, age may not be significant because the age range (6 to 8 months) is simply too small to see a developmental effect. Other studies have demonstrated age-related differences in jaw velocity, but sample over a wider age range. For example, jaw speed has been found to increase slightly, due to growth and neural maturation, from about 27 mm/s at 9 months to about 32 mm/s at just 12 months (Nip et al., 2009). However, this result came from a wider age range than the current study and is still even a small difference. Nonetheless, age was not expected to be a particularly strong predictor in this study.

The fact that infants who are producing canonical syllables, and thus able to demonstrate precise and quick articulatory transitions, yet do not in general move their mouths any more quickly than non-babbling infants was surprising. One reason for this may be that, at a time of transition such as the onset of canonical syllables, infants are still learning this new kinematic skill and thus have quite variable motor performance. All repeated attempts at a behavior, including both accurate and inaccurate attempts, may support learning and attainment of a new oromotor skill because they help refine the spatiotemporal parameters of the behavior (Smith, 2006). Dynamic Systems Theory models suggest that the onset of a new level of skill is preceded not only by an increase in repeated attempts at the behavior, but an increase in variability of motor performance as well (Smith & Thelen, 2003; Thelen, 1995). Based on evidence from older children, many speech scientists predict that speech motor development is nonlinear and marked by substantial amounts of variability, particularly at times of transition to attainment of a new skill (Goffman, 2010; Green & Nip, 2010; Smith & Zelaznik, 2004; Thelen, 1991; van Lieshout, 2004). All of the “inaccurate,” possibly slower-velocity and slower-frequency jaw behaviors infants produce when newly canonical babbling may obscure the “accurate” speedier jaw movements, and thus have made the appearance of significant results impossible to detect in the current study, when examining all the infants’ jaw behaviors as a whole.

Another reason for the lack of significant differences in jaw velocity and cycle frequency between NB and CB babies may be that overall increases in jaw velocity and jaw cycle frequency could actually occur *once* an infant begins to produce canonical syllables, rather than *in order for* the infant to begin producing canonical syllables. If increased velocity of jaw behaviors was a prerequisite for canonical syllable production, then significant results should have appeared in this study. But if an infant does not begin to demonstrate overall increases in jaw speed *until* the task demands of beginning to produce canonical syllables appears, then the CB infants tested in the current study could have been in the process of developing faster jaw speeds, even though they have already demonstrated several instances of mature canonical syllables. The use of vocal tract structures for new behaviors may drive neurophysiological maturation more so than neurophysiological maturation drives new behaviors. The onset of canonical syllables may be an activity-dependent change. Meaning, instead of appearing after adequate anatomical and physiological maturity, the production of canonical syllables may instead drive development of the musculature and control mechanisms required for their production.

A final reason for lack of oral kinematic differences between NB and CB babies in this study may be because kinematic analyses were performed across all the infants' jaw movement types—silent, non-protophonic, protophonic, and canonical. Oral kinematics may differ only for syllable *type* (e.g. marginal versus canonical), rather than across all jaw cycles and vocalization types. Though kinematic analyses between non-protophonic, vowel/marginal, and canonical syllables may have added a needed layer of specificity to the current study, infants simply do not produce an adequate number of mature vocalizations in one data collection session in order to make comparisons. For example, there were only 43 canonical syllables produced from the infants in this study. These syllables were from only 3 infants (thus, 18 babies who typically produce canonical syllables did not produce them during their lab visit), and 35 of these canonical syllables were from one infant who was either "in the mood" to produce canonical syllables or was particularly precocious. Thus, analyses across vocalization types would not be appropriate with the current data set, and require either more participants or more data collection sessions per infant. Analyses across vocalization type were performed, but cannot be generalized for the reasons stated above (*see Exploratory Results*).

One interesting finding regarding infants' jaw velocities was the product of further exploratory data analyses. When comparing jaw cycles that had oral obstruction (e.g. finger or toy in mouth) versus those that did not, the cycle frequencies of these two movement categories were nearly equal, while both opening and closing jaw velocity for cycles with oral obstruction was substantially higher (*see Exploratory Results*). Thus, the increased jaw amplitude required to allow for intraoral toys or fingers affects jaw velocity, while infants seek to maintain constant temporal characteristics per movement episode, as evident in the cycle frequency. Thus, timing has priority to the infant over movement speed, and infants are indeed capable of adjusting their jaw velocities given certain obstructions. This hierarchy of preserving temporal characteristics of jaw cycles and protophones will continue to be important later in development, as linguistic timing parameters will take precedent over articulatory speed when the oral cavity encounters spatial changes. Clearly, infants are quite capable of moving their jaws faster for scenarios that require it, and it may not be a simple motor performance constraint that makes the jaw velocities of younger infants typically slower than the velocities of older infants (Nip et al., 2009). Instead, these movement parameters may be more linguistically-driven.

Another metric that did not reach significance when comparing across group or age, but may be noteworthy for future investigations was the measure of protophonic jaw cycles (protophonic vocalization *with* jaw movement). Of the total 140 protophonic jaw cycles produced by all infants, only 10 (7%) were produced by NB babies. The great majority (N = 103, or 74%) of protophonic jaw cycles came from five 8-month-old CB babies. The metric was not significant between groups because the other 16 CB babies did not produce very many protophonic cycles. However, we predict that these five 8-month-old babies who *do* are demonstrating attainment of an advanced oral kinematic skill that neither group nor age adequately predict. Only 140 of the 810 protophonic vocalizations captured by the Motion Analysis System were accompanied by jaw displacement of $\geq$ 2 mm and cycle frequency $\geq$ 1 second. Thus, only 17% of 6–8-month-old infants' vowels, marginal syllables, and canonical syllables include any jaw movement at all. The remaining 879 jaw cycles produced by the infants did not include vocalization. Thus, pairing the two together—vocalization plus jaw movement—may be an advanced pre-speech skill that is on the cusp of attainment as babies begin producing more and more canonical syllables. Expanding the age range up to 9 months in future studies, so that more infants who have been producing canonical syllables for a longer period of time are included, may clarify this prediction. Previous theories of how infants coordinate jaw movement and vocalization, such as Frame–Content Theory (Davis & MacNeilage, 1995) emphasized that infant vocalizations are characterized by jaw movement plus vocalization. The results of this study indicate, however, that this type of movement is neither obligatory nor even the typical mode employed by infants 6–8 months of age.

C. Sex and protophonic vocalizations

Sex was taken into account as a covariate in the current study. Of all the kinematic and vocalization measures, sex was found to be a significant variable only in the number of protophonic vocalizations produced per minute. Females produced nearly twice as many protophonic vocalizations as males. The higher rate of vocalization in female infants has been observed in previous studies (Lewis, 1969; Lewis & Freele, 1973). No other kinematic measures were significant by sex, including number of jaw cycles produced, jaw cycles velocities, and jaw cycle frequency. Thus, males move their jaws just as often as females and with the same movement speeds, but do not produce as many pre-speech vocalizations as females.

D. Limitations and considerations

a. Missing data

The first source of missing data was due to infant participation. Of the 30 infants, 22 infants completed all four conditions in full, three infants had a reduced data set or no data for one condition, and five infants had a reduced data set or no data for two or more conditions. Of all the infants with reduced data sets, two infants were removed because of intolerance to the head reference array, one infant had his hand obstructing the jaw marker for an entire test condition, one infant was willing to participate but equipment error prevented a full session from being collected, and the other four infants started crying at some point during the 16-minute data collection session.

Another source of missing data in the current study was jaw marker obstruction. As one would predict, infants frequently bring their hands to their mouths or put toys near or in their mouth. Anytime the jaw marker was blocked from the view of at least two of the infrared motion capture cameras, the jaw marker trajectory was temporarily interrupted. Also, the markers do not reflect when wet, and some infants drooled so much that it would drip onto the jaw marker or get on the jaw marker from the infant's hands or toys. Any wet marker became non-reflective and disappeared from the movement trajectory until it was dried off for the next test condition.

In total, 32% of the potentially-collectable data were not available for analyses. This total is comprised of: 18.5% of data missing due to jaw marker dropping from view of the infrared motion capture cameras (drool, hand obstructing, or toy obstructing), 12.5% of data missing due to infant non-compliance (crying, removing equipment), and 1% of data missing due to experimenter error.

b. Sources of potential error

Sources of potential error in this study were minimal. First, parents may have inaccurately reported their infant's motor, cognitive, or vocal behaviors, which would have affected both their inclusion/exclusion from the study as well as the group they were placed in (NB vs. CB). Secondly, experimenter error in coding could have occurred in any of the following data processing steps: coding presence vs. absence of oral obstruction, counting of protophonic vocalizations, separation of jaw cycles into the categories: silent, non-protophonic, vowel/marginal, and canonical (though inter-rater reliability for this measure was shown to be 93% between the first author and one additional rater). Also, the Motion Analysis System tracking resolution (~0.15 mm) contributes to accuracy of 3D coordinate localization in the infant's work space volume.

c. Limitations of current study with considerations for future studies

There are several areas of potential improvement in the design and execution of the current study. Some are at the control of the experimenter and can be easily incorporated into future studies. Other limitations are due to equipment and technology, and would require hardware, software, or technical development.

First, in order to further explore and explain the orofacial kinematic results obtained in this study, more data should be collected on infants within and around this age range. The length of data collection sessions should not be increased, because 16 minutes is near the maximum amount of time infants will tolerate participating in a study that includes sitting in a high chair and activities chosen by the experimenter. Instead, the best way to obtain more canonical syllables, for instance, would be to increase the number of study participants or have each infant participate several times.

Also, the differences in amount of movement and number of vocalizations obtained across the different play conditions was substantial. These results only introduce further areas of inquiry that should be tested in future studies. For example, one question that remains is: were infants still and silent during the Social condition because there was another person present and looking at them, or because that other person was vocalizing and the infant wanted to listen? What would happen if the other person was present and interacted with the infant with eye contact and gestures, but did not vocalize to them? What if the adult played alongside the infant, instead of modeling the vocalizations to the infant with eye contact? There are many modifications that could be made to the Social condition. Also, with the video condition, are infants still and silent during this condition because of the inability to interact and make manipulations to the physical world while watching the Video? What if the video did offer the opportunity for the infant to interact and induce change to the visual environment. For example, the modern Wii technology could be incorporated so that the infant could move his or her hands or arms to move objects across the screen. The Motion Analysis system offers the ability to program such options, as well. If the infant could move his or her arms to move items across the television screen, would this make the condition more like the LargePlay or SmallPlay conditions and induce more jaw movements and vocalizations? Or does the infant need to be able to touch and mouth objects in order for them to be conducive to eliciting vocalizations?

Another limitation of the current study was the inability to collect either lip or tongue data, which would further inform knowledge of the infants' oromotor skill repertoire. Current intra-oral technologies that can measure tongue position and displacement are simply not appropriate for use with infants. These include: x-ray technology, magnetic resonance imaging (MRI), ultrasound imaging, or electromagnetic articulography (EMA). Cost and restrictive methods are some of the disadvantages of MRI and ultrasound technologies. Radiation exposure is a major concern with using x-ray technology and simply is not safe enough for exploratory data collection in infants. The EMA system requires small sensors to be placed in the mouth on the surface of the tongue and is majorly invasive for young participants. Though appropriate for adults and older children, EMA presents a swallowing risk for young children and infants and compliance for marker placement would be nearly impossible. Future technologies that reduce or eliminate the hazards that current technologies present could allow for easier measurement of infant tongue movement and aid understanding of infant orofacial kinematics.

The Motion Analysis System allows for markers to be placed on any external bodily surface, including the lips, and is appropriate for measuring lip motion. However, for infants 6–8 months of age in particular, the drooling and licking that occurs on the surface of their lips makes lip tracking near impossible. The markers must stay dry in order to be trackable, and with infants this age, anything placed on the lips is only dry for a brief moment. Attempts were made during the piloting phase of this study to raise the surface level of the markers so that the drool would fall around the marker instead of atop it, which would allow for better lip movement tracking. However, the greater the height of the marker away from the skin's surface, the more likely the infant was to notice and lick, touch, or remove the marker. Future development of reflective marker technologies should seek to create markers that reflect when wet or a system that can view wet markers.

E. Research and clinical applications

This study represents the first attempt to measure how the play environment affects infants' rate of protophonic vocalization and jaw kinematics. Clearly, the drawbacks of using video media as stimuli for infants in both research studies and in the home are significant. For infants ages 6–8 months, there are also drawbacks of having an adult present, which should be noteworthy for both researchers and clinicians. Speech–Language Pathologists (SLPs) are interested in what vocalizations an infant is able to make and seek to elicit these vocalizations from the infant in order to further shape their vocal output and elicit change. If having an adult present and interacting with the infant tends to make the infant silent, however, then SLPs should consider revising their methods of eliciting and shaping vocalizations of infants at the age of onset of canonical babbling. Also, the finding that gross motor play movements with the arms elicit fewer simultaneous protophonic vocalizations than play with larger toys that do not elicit large waving and banging motions is also noteworthy. Not all toys are alike in their ability to extract a large number of vocalizations from the infant, and play routines that involve large, fast, gross motor movement should likely be avoided when attempting to elicit and modify vocalizations in young infants.

The current study was conducted in a laboratory environment, which is already known to be particularly stifling to infants' rate of vocalization, compared to the home environment (Delack, 1978; Lynch et al., 1995). Just as SLPs should take note of the adjustments that could be made to their assessment and treatment routines with infants, as should infant speech–

language researchers, who often spend an hour or more attempting to elicit vocalizations from young infants while switching from activity to activity (Steeve & Moore, 2009; Steeve & Price, 2010; Fagan, 2009). The techniques that both scientists and clinicians use to elicit vocalizations from infants must be productive and efficient, and this study provides a direction for determining the best possible methods.

This study was also the first to examine both protophonic vocalizations and jaw kinematics in infants ages 6–8 months, while the current literature base is focused almost exclusively on infants 9 months and older (e.g. Green & Nip, 2010; Nip et al,. 2009). Though the current study did not identify kinematic differences among infants on the basis of age or canonical babbling status, exploratory analyses did reveal some noteworthy findings that can inform our understanding of infant orofacial kinematics as well as inform future research. For example, the finding that protophonic jaw cycles were produced almost exclusively by 8-month-old canonical babblers indicates that coordinating vocalization and jaw movement simultaneously may be an advanced skill that was emerging in some of the infants in this study. Frame–Content Theory, which is based on the notion that jaw movement serves as the frame for which vocalizations occur, is based entirely on the notion that infant jaw movement *does* occur with vocalization (Davis & MacNeilage, 1995; Locke, 1983; Moore, 2004). Though this may certainly be true for older infants, infants 6–8 months of age produce most of their vocalizations without jaw movement. Also, this study revealed that infants are able to increase their jaw opening and closing velocities upon encountering an intraoral obstruction that increases the mandibular opening amplitude. Thus, infants will preserve jaw open–close cycle temporal characteristics over spatial characteristics and movement speed. This preference to adjust in favor of timing characteristics indicates the importance of the completion of the jaw open–close cycle. This natural preference can inform theories of both infant oral kinematic development and linguistic development.

Speech is one of the most precisely-timed and complex motor behaviors humans produce. Understanding what skills are required in order for an infant to both begin and continue producing high rates of mature canonical syllables will contribute to theories of how infants develop this skill, as well as aid advancement of diagnostic and treatment protocols for infants who are delayed in babbling production and thus at-risk for speech and language delay.

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