EARLY DEVELOPMENT OF THE SPEECH AND GESTURE SYSTEM: THE RELATIONSHIP BETWEEN RHYTHMIC ARM ACTIVITY AND REDUPLICATED BABBLE

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Chastine Lamoureux

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Abstract

Early Development of the Speech and Gesture System: The Relationship Between Rhythmic Arm Activity and Reduplicated Babble

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Chastine Lamoureux

Psychology

Ryerson University

The development of the speech-gesture system was examined by evaluating the relationship between rhythmic arm activity (RAA) and reduplicated babble (RB). Using a novel longitudinal-observational design, infants were observed in-home weekly, for twelve weeks playing with a rattle (22 to 34 weeks old). Video and audio-recordings were submitted by caregivers via a secure file-sharing service. The design was an effective alternative for longitudinal data collection in infant studies. RAA and RB were positively correlated, and infants exhibited greater amounts of tightly synchronized vocal-manual coordination (VMC) over time. Infant threshold was not a significant predictor of RB or VMC, and babble onset did not significantly predict the frequency or the type of VMC. Trajectory analyses revealed synchronous change across RAA, RB, and VMC. Findings suggest the linkage between RB and RAA is not sequential; but is a simultaneous process representing a moment of re-organization to the maturing speech-gesture system.

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Introduction

Early development is a dynamic process, whereby changes to one system can have cascading effects on another (Thelen, 1995). Through periods of stability, instability, and phase shifts, new patterns can emerge. When a behaviour in one domain becomes stable and strong, it is believed to "spill over" and entrain a new behavior in another domain (Boudreau & Bushnell, 2000; Iverson & Thelen, 1999). Understanding the dynamic processes of typical development is key to identifying early risk markers. Throughout history, researchers have explored infant development across a variety of domains and have found temporally predictable relations between language and locomotor development. It is generally accepted that locomotor milestones such as crawling or walking can prompt a significant increase in infant vocabulary, though the mechanism by which this occurs is still in debate. Though generally less studied, the systems activating the mouth and arms have been proposed to influence and entrain one another. One such example is the speech and gesture system which seems to be coordinated from very early in life (Ejiri & Masataka, 2001; Iverson & Wozniak, 2007; Iverson, 2010; Iverson et al., 2007; Iverson & Fagan, 2004; Iverson & Thelen, 1999; Thelen, 1995). Few studies have explored the early stages of this system; however, it has been suggested that during the earlier stages of development, arm activity may help entrain early language acquisition (Ejiri & Masataka, 2001; Iverson & Wozniak, 2007; Iverson et al., 2007; Iverson & Fagan, 2004; Iverson & Thelen, 1999; Thelen, 1995).

The Emergence of an Early Communication System

Recent investigations have provided strong evidence to suggest that a coupling of the speech and gesture systems occurs early in development (Thelen, 1999). Studies have identified four stages in which early linkages may provide a foundation for an integrated speech-gesture system. The first stage is the initial linkage and occurs as early as 10 to 12 weeks gestational age. The first observable event occurs as the Babkin reflex (i.e. application of pressure to the palm of newborns is met with opening of the mouth) (Babkin, 1960). In the second stage (6-8 months), the speech and gesture systems become increasingly linked through repeated practice of rhythmic motor movements and rhythmic vocalizations (Iverson & Thelen, 1999). Prior to this stage, vocalizations and rhythmic motor movements might have occurred independently, but during this second stage they become increasingly coordinated (Iverson & Thelen, 1999). An example of this coordination is the emergence of increasingly integrated patterns of rhythmic arm activity and reduplicated babble (Eilers et al., 1993; Ejiri, 1998; Iverson, Hall, Nickel & Wozniak, 2007; Koopmans-van Beinum & van der Stelt, 1986; Locke, Bekken, McMinn-Larson & Wein, 1995; Oller & Eilers, 1988; Thelen 1979). Stage three (9- 14 months) is characterized by an emergence of gestures and words, while stage four (16-18 months) is demonstrated by synchronous speech and gestures (Iverson & Thelen, 1999). Significant effort has successfully characterized the relational pattern of the speech-gesture system after the babble period and into childhood (Buthcher & Goldin-Meadow, 2000; Esteve-Gibert & Prieto, 2014; Murillo, Ortega, Otones, Rujas & Casla, 2018; Ozcaliskan & Goldin-Meadow, 2005). However, the mechanism driving development during stage two, the emergence of more coordinated patterns of rhythmic arm activity and reduplicated babble, remains unclear and understudied.

Reduplicated babble and rhythmic arm activity. For the purpose of this study, reduplicated babble was defined as "the appearance of repeated strings of well-formed syllables" (Oller, 2000). Examples of such strings include rhythmic production of "da-da" and "ma-ma". Rhythmic arm activity was defined as "all arm movements repeated in approximately the same form at least three times at regular intervals of approximately 1 second or less" (Thelen, 1979).

As per Iverson & Thelen (1999), reduplicated babble and rhythmic arm activity first appear independently from one another. The mean age of onset of rhythmic arm activity occurs between 24 and 25 weeks old (~ 5.5 months), preceding that of reduplicated babble by 2-3 weeks (~ 6 months) (Eilers et al., 1993). As reduplicated babble emerges, rhythmic arm activity peaks (Koopmans-van Beinum & van der Stelt, 1986; Oller & Eilers, 1988). Not until infants reach 6 to 8 months, do these activities become increasingly coordinated (Iverson et al., 2007). When activities occur in coordination, patterns tend to be movement initiated or synchronous (Iverson et al., 2007; Iverson, 2010). By 30 to 31 weeks old (~ 7 months), there is a significant reduction in rhythmic arm activity and a continued increase in reduplicated babble (Locke et al., 1995). Studies have suggested that the emergence of a more coordinated interplay reflects control by a common underlying mechanism which allows for one behaviour to gradually entrain the other (Eilers et al., 1993; Ramset, 1984). It has been proposed that the time of emergence of each behaviour and patterns of coordination are evidence of a sequential linkage from the arm domain to the mouth domain and that this linkage allows for a subsequent period of mutual entrainment in which increased vocal-manual coordination is observed (Eilers et al., 1993; Iverson & Fagan, 2004; Iverson et al., 2007; Iverson, 2010). The period of increased coordination enables both behaviours to become strong, stable, and specific (Iverson & Fagan, 2004; Iverson et al., 2007).

Oscillatory mechanisms. It has been suggested that the "production of repetitive, rhythmically organized arm movements gradually entrains mandibular activity which leads to the emergence of rhythmically organized consonant-vowel sequences central to reduplicated babble" (Cobo-Lewis, Oller, Lynch, & Levine, 1996; Eilers et al., 1993; Iverson & Thelen, 1999; Koopmans-van Benium & van der Stelt, 1986; Oller & Eilers, 1988; Thelen, 1979). In the infant vocal system, mandibular oscillations, known as "the repeated lowering and raising of the mandible which results in a perceived contrast between consonants and vowels" have been argued to be fundamental to reduplicated babble (Iverson, 2010). Similarly, oscillations can be observed in the motor system, such as with "rhythmic, stereotyped behaviours such as shaking, kicking, rocking, and bouncing" (Iverson, 2010). Both of the oscillatory behaviours are frequently observed over the first year of life (Iverson, 2010; Thelen, 1979). When oscillators are coupled, entrainment will occur after one oscillator successfully pulls the activity of the other (Iverson, 2010). The result is a coordinated pattern of activity (Iverson & Fagan, 2004). When a behaviour in one domain becomes stable and strong, it is believed to "spill over" and entrain a new behavior in another domain (Iverson & Thelen, 1999). For entrainment to occur, it is believed that one behaviour must be significantly more activated than the other and that high levels of activation can only be reached after a low threshold has been attained (Iverson & Fagan, 2004). According to the homunculus theory of psychology, the areas of the brain controlling the arm and mouth are adjacent. Given their close neurobiological proximity, it is possible that the observed increase in vocal-manual coordination between 6 and 9 months of age may result from high levels of activation of rhythmic arm activity which "spill over" and entrain the mandible. To achieve high levels of activation, rhythmic arm activity must be strong and stable, and a low threshold needs to be attained (i.e. the behaviour must be seen frequently and in a variety of task contexts) (Iverson & Fagan, 2004). If the behaviour is seen less frequently and requires more effort (i.e. high threshold), greater practice is needed to lower the threshold (Iverson & Fagan, 2004). Hence, a behaviour becomes increasingly more intentional. Children with higher thresholds may thus exhibit less rhythmic arm activity, later babble onset and different patterns of coordination than children with lower thresholds within the period of investigation as they may require more time to achieve maturational control of each behaviour.

Existing Research

There are limited studies which have attempted to conceptualize the relationship between rhythmic arm activity and reduplicated babble as a prelude to the speech and gesture system. Ejiri and Masataka (2001) were amongst the first to investigate this relationship longitudinally between the ages of 6 and 11 months. They demonstrated that vocalizations co-occurred, at high frequency with rhythmic activities in the period preceding the onset of reduplicated babble. Furthermore, they found that during this period of high co-occurrence, vocalizations that co-occurred with rhythmic activities had shorter syllable duration and shorter formant-frequency duration (Ejiri & Mastaka, 2001). Ejiri and Mastaka (2001) concluded that the short syllable and quick transitions identified in infants at this stage and which continued after the disappearance of co-occurring events, were comparable to those found in mature speech. Thus, they believed the co-occurrence of rhythmic activities and vocalizations could be a key contributor to language acquisition. Though promising, there were a few methodological factors that caution interpretation of results. In their study, Ejiri and Masataka (2001) used a very small homogenous sample (4 Japanese infants). Additionally, video data was collected once a month. In infancy, development occurs rapidly and thus they may have failed to capture significant events between collections. Lastly, Ejiri and Masataka (2001) did not control for infants' potential developmental delays.

In a second longitudinal study by Iverson, Hall, Nickel, and Wozniak (2007), 26 infants between the ages of 2 and 19 months were seen at home every two weeks for 45 minutes. However, data analyzed were taken only from three sessions surrounding the onset of reduplicated babble, spaced at approximately four weeks. Sessions coincided with babble onset, one month prior and one month following babble onset. The researchers found differences between babble groups. Younger babblers tended to produce fewer shakes of the rattle overall than older babblers. Both younger and older babblers did demonstrate an increase in rhythmic arm shaking at babble onset. Additionally, they found that most co-occurrences were movement initiated or synchronous (Iverson et al., 2007). It was suggested that the time of babble onset may influence the overall frequency of rhythmic arm activity and vocal-manual co-occurences but not the general pattern of co-occurrences (Iverson et al., 2007). Once again, there are significant methodological factors that must be considered when interpreting these findings. Similar to Ejiri and Masataka (2001), findings were reliant on a small to moderate homogenous sample and monthly video sessions. Additionally, the relationship between rhythmic arm activity, reduplicated babble, and their coordination was conceptualized through group differences based on babble onset.

A first cross-sectional study by Locke, Bekken, McMinn-Laron, and Wein (1995), also identified infants by babble group (i.e., pre-babblers or babblers) and theorized that babbling onset reflects maturation of control mechanisms in the left hemisphere, and that rhythmic arm activity fosters an opportunity for complex, reduplicated babble to voluntarily emerge before vanishing (Locke et al., 1995). In this study, emergence of reduplicated babble was estimated by infant age, thus making it difficult to tease apart whether results were a function of babble onset or of age.

In a more recent series of cross-sectional studies by Iverson and Fagan (2004), at-home naturalistic observation and semistructured play with a primary caregiver was video recorded for infants 6, 7, 8, and 9 months old. Data on the onset of reduplicated babble were reported by parents and confirmed by experimenter observation. There were several interesting findings. First, frequent vocal-manual coordination was found in 41 of the 42 infants in the study, suggesting that this is a robust feature of spontaneous infant behavior (Iverson & Fagan, 2004). Additionally, the rate of production of vocal-manual coordination was most observed between 6 and 9 months of age, with coordination bouts most often movement-initiated or synchronous (Iverson & Fagan, 2004). Furthermore, consonant-vowel repetitions were produced in greater proportion with rhythmic movement than in isolation. Finally, Iverson and Fagan (2004) found that infants who had begun to babble demonstrated greater vocal-manual coordination than same-age prebabblers. This suggests that the increase in vocal-manual coordination is a result of babble onset and not of infant age.

In sum, previous studies support a sequential model in which the manual and vocal systems are linked sequentially *from* the arm *to* the mouth domain early in development. Once this link has been established, infants begin to produce reduplicated babble. The rhythmical organization of the arm activity is then echoed in the vocalizations which subsequently allows for mutual entrainment—observed through increased vocal-manual coordination and a greater proportion of tightly synchronized or movement-initiated co-occurrences. Once entrainment has occurred, co-occurrences decline, and rhythmic arm activity begins to dissipate while reduplicated babble continues to increase. While previous studies have successfully identified a time period in which this relationship can be observed, there have been no reported studies which have collected weekly observations so as to precisely identify the trajectories of the individual components of the system. Additionally, previous studies have not evaluated the relationship using causal analyses. This study was the first to collect weekly observations and to employ growth-curve analyses and multi-level modelling to delineate and describe key transitions which occur during this second developmental stage of the integrated speech and gesture system.

Current Study

Purpose

Understanding the mechanism that drives the relationship between rhythmic arm activity and reduplicated babble is essential for understanding how the speech-gesture system develops during infancy. Evidence suggests that early speech-gesture interactions may be predictive of later impairments or delays in either or both the language and gesture systems. If the underlying mechanism responsible for driving the relationship between rhythmic arm activity and reduplicated babble can be explained by the perspective of dynamic systems, as is suggested by the literature, then it is important for research to examine when and how this relationship develops and changes over time as well as which within-subject factors may influence the directionality of the relationship so that we may develop effective early interventions.

To our knowledge, this study was the first to identify within-subject factors (e.g. infant threshold, language status, birth order, developmental performance level) which may influence the developmental trajectories of rhythmic arm activity and reduplicated babble in addition to their interaction using weekly observations for increased precision. Typically developing infants (i.e. no known history of delay or risk of delay) were recruited for this study; however results are expected to inform subsequent studies with at-risk populations.

This study focused on mapping out the trajectories for rhythmic arm activity, reduplicated babble, and vocal-manual coordination over 12 weeks, from 22 to 34 weeks old. Secondly, the study sought to identify causal relations between rhythmic arm activity, reduplicated babble, and vocal-manual co-occurrences so as to determine whether entrainment is sequential (as was suggested in the literature) or simultaneous. Finally, the study intended to identify within-subject factors which significantly contribute to development of a more sophisticated speech and gesture system.

Hypotheses

Based on the literature discussed above, four main hypotheses are proposed.

The first hypothesis posits that the onset of rhythmic arm activity will occur between 24 and 25 weeks of age. The frequency of rhythmic arm activity will then increase until it peaks around 26 to 27 weeks of age. Finally, rhythmic arm activity will significantly decline between 30 and 31 weeks of age (Iverson & Fagan, 2004; Iverson et al., 2007; Koopmans-van Beinum & Van der Steelt, 1986; Locke et al., 1995; Oller & Eilers, 1988).

The second hypothesis asserts that reduplicated babble will emerge roughly 2-3 weeks after the onset of rhythmic arm activity, at peak rhythmic arm activity (26-27 weeks of age) and will subsequently increase over the course of the study (Koopmans-van Beinum & Van der Steelt, 1986; Oller & Eilers, 1988).

The third hypothesis is that the frequency of vocal-manual co-occurrences will increase after the onset of reduplicated babble and over the course of the study (Iverson & Fagan, 2004; Iverson et al., 2007).

Assuming an initial linkage of the mouth and hand are sequential from the arm domain to the mouth domain, as is suggested in previous research, hypothesis four posits that

a) The age of onset of rhythmic arm activity and the frequency of rhythmic arm activity will predict changes in reduplicated babble (Eilers et al., 1993; Ramset, 1984);
b) A greater proportion of activities occurring in coordination will be movement initiated or synchronous rather than vocalization initiated and will occur in greater

quantities for younger babblers in comparison to older babblers (Iverson et al., 2007; Iverson &Fagan, 2004);

c) Greater amounts of rhythmic arm activity will occur for younger babblers than for older babblers (Iverson et al., 2007; Iverson & Fagan, 2004);

d) Infants with lower thresholds (i.e. those requiring less practice to master rhythmic arm activity) will exhibit more frequent bouts of vocal-manual coordination and greater proportions of movement-initiated or tightly synchronized patterns of coordination than their higher threshold peers (Iverson & Fagan, 2004).

Method

Sample

Thirty-three infants (17 boys, 16 girls) participated in the longitudinal study, beginning participation at 22 weeks of age. Demographic data showed that 42.4% of the sample identified as White, 39.4% as mixed race, 12.2% as East Asian, 3% as South Asian, and 3% was unspecified. Younger babblers-infants who were observed by experimenters babbling within the first 9 weeks of the study- comprised 66.7% of the sample. The remaining 33.3% of infants who did not display any babbling by 7 months of age were categorized as older babblers. Additional data on sample characteristics were provided by parent report including the language context and sibling status. Data revealed that 48.5% (n= 16) of infants were monolingual, having only been exposed to English in the home, while 51.5% (n=17) of infants were multilingual, having been exposed to two languages (n= 11) or more (n=6). Languages other than English to which infants were exposed included French (n =5), Cantonese (n= 4), Mandarin (n=3), Portuguese (n=3), Polish (n = 1), Tagalog (n = 1), Taiwanese (n=1), Greek (n= 1), Serbian (n=1), Hebrew (n= 1), Russian (n= 1), Spanish (n=1), and Italian (n= 1). Only-child participants represented 78.8%

(n=26) of the sample, while the remaining 21.2% (n=7) were the second of two children in the home. Families were representative of the diverse ethnic population of the Greater Toronto Area. Specific information on infant and parent socioeconomic status was not collected.

Forty-one families were recruited from a database of parents who had previously indicated interest in participating in research. Six families reported being unable to complete the study, prior to the start of the study; one family was unable to continue the study after week 2. Participating families received a $10 gift card at the end of the study as well as a Fisher Price infant rattle to be used throughout the study. All parent reports were carefully reviewed to identify infants who may have had undisclosed developmental delays.

Procedure

Participating parents were e-mailed a link to a personalized folder, accessible only to the investigating team and the participant, using *DropBox Plus*. *DropBox Plus* is a secure online storage space for videos and files which can store up to 1,000 GB. Parents were encouraged to download the free app for easy file transfer. The participant's personalized folder contained several smaller folders which uniquely included the consent form, the pre-observation questionnaires, the final questionnaire, detailed instructions for recording, a sample video, and twelve weekly folders for video file submissions. Consent was received using an electronic signature and parents were given the primary investigator's contact information if questions or concerns would have arisen. A Fisher price rattle was mailed to participating families via Canada Post. Parents were required to video and audio record their infant playing with the rattle once weekly for 5 minutes using their smartphone beginning when their infant was 22 weeks old and ending when their infant reached 34 weeks old. Parents were instructed to record, whenever possible, while the infant was most active, and the home was free from extraneous distractions.

The infant's arms were required to be observable throughout filming. Weekly reminders were sent to parents via email or text message the day before filming was to occur. Parents then had two days to record their infant and to upload the video to the respective folder. This procedure helped maintain a strict 1-week period between time points.

Measures

The online surveys consisted of two parts. Part 1 was completed in the first week of the study when the infant was 22 weeks old and included a brief demographic questionnaire and the Ages and Stages Questionnaire-3 for infants 5 months 0 days through 6 months 30 days (Squires & Bricker, 2009) (henceforth referred to as the ASQ-6). In the demographic questionnaire, parents reported on the infant's sex and ethnicity, the number and birth order of children in the home, and the languages to which the child receives daily exposure. The ASQ-6 contains 30 multiple choice questions assessing communication, gross motor, fine motor, problem-solving, and personal-social development (6 questions/domain) and 8 short-answer questions assessing infant-parent history. Parents were instructed to mark "yes", "sometimes" or "no" as responses to the multiple-choice questions. Infants with scores below 29.65 in communication, 22.25 in gross motor, 25.14 in fine motor, 27.72 in problem solving, and 25.34 in personal-social were flagged for potential delays in development (Squires & Bricker, 2009). Extensive internal validity and test-retest reliability for the ASQ-6 are reported by Gollenberg, Lynch, Jackson, McGuinness, & Msall, 2009.

Part 2 of the survey consisted of the Ages and Stages Questionnaire-3 for infants 7 months 0 days through 8 months 30 days (Squires & Bricker, 2009) and was completed by parents in the final week of the study when the infant was 34 weeks old. Similarly, the ASQ-8 contains 30 multiple choice questions assessing communication, gross motor, fine motor, problem-solving, and personal-social development (6 questions/domain) and 8 short-answer questions assessing infant-parent history. Parents were instructed to mark “yes”, “sometimes” or “no” as responses to the multiple-choice questions. Infants with scores below 33.06 in communication, 30.61 in gross motor, 40.15 in fine motor, 36.17 in problem solving, and 35.84 in personal-social were flagged for potential delays in development (Squires & Bricker, 2009).

Coding

Infant’s rhythmic arm activity was measured using real-time coding of frame-by-frame analyses using Observer XTi. Trials were coded by two raters to ensure inter-rater reliability. Rhythmic arm activity was coded for both the right and left arms. Movements that were repeated in the same form at least three times at regular, short intervals of approximately one second or less were coded as one occurrence of rhythmic arm activity (Thelen, 1979). Due to the variability in the length of submitted videos, rhythmic arm activity was coded as frequency data whereby the number of identified bouts of rhythmic arm activity was divided by the total amount of observation time (in seconds).

Reduplicated babble was measured using frame-by-frame time-coding using Praat. Trials were coded by two raters to ensure inter-rater reliability. Vocalizations separated from other contiguous vocalizations by 1 second of silence or audible ingressive breaths were coded as distinguished utterances (Dolata, David, & MacNeilage, 2008). Utterances were then coded as coo, babble, or reduplicated babble based on their consonant-vowel characteristics. An utterance string transcribed as having only vowel characteristics was identified as a coo. An utterance string transcribed as having both consonant and vowel characteristics in the absence of repetition was identified as a babble. An utterance string transcribed as having repeated consonant-vowel characteristics was identified as one occurrence of reduplicated babble. The total amount of vocalizations was coded as frequency data whereby the number of identified vocalizations was divided by the total amount of observation time (in seconds). Additionally, ratios for each of the three sub-types of vocalizations were noted.

Vocal-manual coordination was identified using time analysis information from audio and video coding. Every movement bout within a second of a co-occurring vocalization was noted (Iverson & Wozniak, 2007). Subsequent analyses identified whether vocal-manual co-occurrences were synchronous (i.e. arm swinging accompanied by a string of repeated syllables each articulated with a movement cycle) or loosely coupled (i.e. arm swinging accompanied by a short vocalization) (Iverson, 2010). Loosely coupled co-occurrences were subsequently identified as vocalization initiated or movement initiated.

Infant threshold was calculated by dividing the number of occurrences of rhythmic arm activity prior to babble onset by the number of weeks enrolled in the study prior to babble onset (Iverson & Fagan, 2004). For example, an infant who has had 20 bouts of rhythmic arm activity prior to babble onset at week 4 would have a threshold of 5 (20/4). Lower thresholds, indicating less time required to master the behaviour, are indicated by higher threshold numbers Infants with lower thresholds have a higher threshold number (e.g. an infant with a threshold number of 10 has a lower threshold than an infant with a threshold number of 5) (Iverson & Fagan, 2004).

Reliability

To assess inter-rater reliability, three trained observers independently coded 25% of the audio data and 12.2% of the video data. Mean percentage agreement was 79.7% for identifying the occurrence of a vocalization, 87.3% for classifying the vocalization types, 71.1% for identifying the occurrence of rhythmic arm activity, 79.2% for identifying the length of time associated with each bout of rhythmic arm activity, and 77.7% for identifying the number of arm movements within a bout of rhythmic arm activity.

Results

This study utilized an online-observational paradigm in which infants were seen playing with a rattle for five minutes once a week for twelve weeks. The longitudinal data collection was designed to evaluate whether the frequency of rhythmic arm activity changes in relation to reduplicated babble, and whether these changes occurred prior to, at, and/or after the onset of reduplicated babble. Additionally, the longitudinal design was used to identify whether the patterns of change in rhythmic arm activity and/or reduplicated babble predicted changes in the overall frequency and/or quality of vocal-manual coordination. Finally, individual differences such as infant threshold were evaluated for their importance in predicting changes in the behaviours discussed above. Following the presentation of preliminary analyses focusing on initial group differences in babble onset and the need for multilevel modeling, we present data on rhythmic arm activity, reduplicated babble, vocal-manual coordination, and the individual factors which are predicted to influence the patterns of each behaviour. In addition to analyzing the data across the 12 time points, analyses were run using a dataset resembling that of Iverson & Fagan (2004). This dataset included data from 6 months, 7 months, and 8 months (TIMES 4, 8, and 12) Comparisons of results between datasets are discussed.

Preliminary Analyses

A series of analyses were completed to determine the need for multilevel modeling across variables. In the first analysis, a baseline model for rhythmic arm activity was compared to a model in which the intercepts were free to vary based on infant ID and a third model in which the intercepts were free to vary based on infant ID and the slopes were free to vary based on

TIME. In a second analysis, a baseline model for reduplicated babble was compared to a model in which the intercepts were free to vary based on infant ID and the slopes were free to vary based on TIME. A third analysis in which a baseline model for vocal-manual coordination was compared to a model in which the intercepts were free to vary based on infant ID and the slopes were free to vary based on TIME was conducted. ANOVAs revealed significant differences between models for all analyses, whereby the random intercept and random slope model was a better fit ($p < 0.05$). Moving forward, all analyses applied multilevel modeling.

Infants who babbled prior to 7 months of age (n= 22) and those who did not (n= 11) were compared to ensure that all infants were similar at the outset of the investigation. Younger babblers (i.e. babbled prior to 7 months) did not significantly differ from older babblers (i.e. babbled after 7 months) on initial levels of rhythmic arm activity, reduplicated babble, or vocal-manual coordination ($p > 0.05$).

Trajectory Analyses

Rhythmic arm activity. A repeated measures ANOVA controlling and a series of post hoc pairwise comparisons were conducted to test the first hypothesis in which it was predicted that the frequency of rhythmic arm activity would first occur between 24 and 25 weeks of age, subsequently increase and peak around 26 to 27 weeks of age, and then decrease between 30 and 31 weeks of age. Our measure of rhythmic arm activity was the total frequency of observed bouts of rhythmic arm activity divided by the total time (in sec) of observable footage (maximum of 310 sec). Bouts of rhythmic arm activity were coded separately for the left and right arm. The mean age of onset for rhythmic arm activity was 22.14 weeks. A repeated measures ANOVA determined that the frequency of rhythmic arm activity differed significantly between time points (F (11, 1090) =15.09, $P < .0001$) (see Figures 1B and 2B). Post hoc tests using pairwise comparisons revealed that rhythmic arm activity statistically significantly increased between TIME 1 and 2 ($p = 0.009$), decreased between TIME 2 and 3 ($p = 0.013$), increased between TIME 4 and 5 ($p = 0.006$), increased from TIME 6 to 7 ($p = 0.0001$), and did not statistically change from TIME 3 to 4, TIME 7 to 8, TIME 8 to 9, TIME 9 to 10, or TIME 11 to 12 ($p > 0.05$). Marginally significant decreases in rhythmic arm activity occurred from TIME 5 to 6 ($p = 0.059$) and from TIME 10 to 11 ($p = 0.069$).

Utilizing the time points from Iverson & Fagan (2004) the frequency of rhythmic arm activity also differed statistically significantly between time points ($F(2, 262) = 4.48$, $p = 0.012$) (see Figure 3B). Post hoc tests revealed a significant increase from TIME 4 to TIME 8 ($p = 0.037$) but no significant change from TIME 8 to TIME 12 ($p > 0.05$).

Results demonstrate an earlier onset of rhythmic arm activity than predicted and the absence of a peak in activity. However, there is support for significantly increased activity between 25 and 26 weeks of age and decreased activity around 31 weeks of age.

Reduplicated babble. To test the second hypothesis in which reduplicated babble was predicted to emerge around 26 to 27 weeks of age and subsequently increase over the course of the study, a repeated measures ANOVA and a series of pairwise comparisons were conducted. Our measure of reduplicated babble was the total frequency of observed episodes of reduplicated babble divided by the total time (in sec) of auditory footage (maximum of 310 sec). The mean age of onset for reduplicated babble was 26.7 weeks. A repeated measures ANOVA determined that the frequency of reduplicated babble differed statistically significantly between time points ($F(2, 262) = 4.48$, $P = 0.012$) (see Figures 4 Band 5B). Post hoc tests using pairwise comparisons revealed that reduplicated babble significantly decreased from TIME 2 to 3 ($p = 0.048$), increased from TIME 4 to 5 ($p = 0.006$), and increased from TIME 10 to 11 ($p < 0.0001$). There was no significant change in reduplicated babble from TIME 1 to 2, TIME 3 to 4, TIME 5 to 6, TIME 6 to 7, TIME 8 to 9, TIME 9 to 10, or TIME 11 to 12 ($p > 0.05$).

Utilizing the time points from Iverson & Fagan (2004) the frequency of reduplicated babble also differed statistically significantly between time points ($F(2, 262) = 13.44$, $p < 0.0001$) (see Figure 6B). Post hoc tests revealed a significant increase from TIME 4 to TIME 8 ($p = 0.01$) and from TIME 8 to TIME 12 ($p = 0.008$).

Thus, findings from the current study are consistent with previous findings in that reduplicated babble emerged around 26 to 27 weeks of age and increased over the course of the study. In addition, this study identified a significant increase in reduplicated babble around 31 weeks of age, a change in activity that was missed when utilizing monthly time points.

Vocal-manual coordination. It was predicted that vocal-manual co-occurrences would increase after the onset of reduplicated babble (i.e. after week 26) and continue to do so throughout the study. Our measure of vocal-manual coordination was the total frequency of observed episodes in which a vocalization occurred closely in time with rhythmic arm activity divided by the total time (in sec) of footage (maximum of 310 sec). This measure included occurrences of coo, babble, or reduplicated babble. A repeated measures ANOVA determined that the frequency of vocal-manual coordination did not statistically significantly change between time points ($F(1, 1100) = 3.29$, $p = 0.07$) (see Figures 7B and 8B). Despite marginal effects, post hoc tests using pairwise comparisons were conducted. It was hypothesized that due to the speed at which infants develop, analyses measuring general changes in the frequency of vocal-manual coordination over time may fail to capture important transitions from week to week. They revealed that vocal-manual coordination significantly increased from TIME 4 to 5 ($p = 0.006$) and decreased from TIME 8 to 9 ($p = 0.014$). There was no significant change in vocal-manual coordination from TIME 1 to 2, TIME 2 to 3, TIME 3 to 4, TIME 5 to 6, TIME 6 to 7, TIME 9 to 10, TIME 10 to 11, or TIME 11 to 12 ($p > 0.05$).

Utilizing the time points from Iverson & Fagan (2004) the frequency of vocal-manual coordination differed statistically significantly between time points ($F(2, 262) = 9.69$, $p < 0.0001$) (see Figure 9B). Post hoc tests revealed a significant increase from week 4 to week 8 ($p < 0.0004$) but no significant change from week 8 to 12 ($p > 0.05$).

Results did not support the third hypothesis. Vocal-manual coordination and reduplicated babble increased simultaneously around 26 weeks of age. In addition, vocal-manual coordination did not consistently increase through the course of the study. Rather, it significantly decreased between 29 and 30 weeks of age.

Hypothesis 4: Entrainment from the Arm to the Mouth Domain

Rhythmic arm activity as a predictor of reduplicated babble. Two series of modelling were conducted to test whether onset of rhythmic arm activity and/or the frequency of rhythmic arm activity predicted the frequency of reduplicated babble. It was hypothesized that both measures of rhythmic arm activity would significantly predict reduplicated babble. Thus, there would be evidence to suggest a sequential linkage from the arm to the mouth domain.

Two-level random coefficient models predicted reduplicated babble between 23 and 34 weeks of age. These models accounted for variation in reduplicated babble over time (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for reduplicated babble across time to estimate variation in infant-level growth.

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in reduplicated babble over time. On average, infants' frequency of reduplicated babble increased by a ratio of 0.009 every week ($p = 0.002$).

Predictor 1: Onset of rhythmic arm activity.

Model 2 included the time of onset of rhythmic arm activity and offered insight into whether entrainment occurred from the arm domain to the mouth domain (see Table 1A). The time-varying coefficient reflected the reduplicated babble growth associated with onset of rhythmic arm activity while capturing between-infant variation in reduplicated babble over time. On average, infants' frequency of reduplicated babble increased by 0.0007 as onset of rhythmic arm activity increased though not significantly ($p > 0.05$).

To account for additional characteristics that may have affected the frequency of reduplicated babble, Model 3 conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, infants' reduplicated babble decreased by 0.001 as onset of rhythmic arm activity increased, though not significantly ($p > 0.05$). Among the covariates, there were no significant predictors of reduplicated babble ($p > 0.05$).

Akaike information criteria (AIC) and Bayesian information criteria (BIC) indicated that Model 1 was preferred (AIC=-2083.7; BIC= -2053.5).

A second series of identical analyses were run with the second dataset resembling the Iverson & Fagan (2004) study. As per Model 1, infants' frequency of reduplicated babble increased by a ratio of 0.01 every week ($p = 0.038$). Model 2 indicated that infants' frequency of reduplicated babble decreased by 0.005 as rhythmic arm activity increased, though not significantly ($p > 0.05$). Model 3 identified that, after controlling for additional variables, infants' frequency of reduplicated babble decreased by 0.01 as onset of rhythmic arm activity increased ($p = 0.015$). Akaike information criteria (AIC) and Bayesian information criteria (BIC) indicated that Model 1 was preferred (AIC=-670.67; BIC= -648.51).

In sum, the onset of rhythmic arm activity was not a significant predictor of reduplicated babble and thus there is insufficient evidence to support a sequential linkage from the arm to the mouth domain.

Predictor 2: Frequency of rhythmic arm activity.

Model 2 included the frequency of rhythmic arm activity and offered insight into whether entrainment occurred from the arm domain to the mouth domain (see Table 2A). It was not a significant model improvement: LR test= χ^2 (7) =0.37, p=0.54. The time-varying coefficient reflected the reduplicated babble growth associated with change in rhythmic arm activity while capturing between-infant variation in reduplicated babble over time. On average, infants' frequency of reduplicated babble increased by 0.12 as rhythmic arm activity increased though not significantly ($p > 0.05$).

To account for additional characteristics that may affect the frequency of reduplicated babble, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, infants' reduplicated babble increased by 0.28 as rhythmic arm activity increased, though not significantly ($p > 0.05$). Among the covariates, there were no significant predictors of reduplicated babble ($p > 0.05$).

A second series of analyses were run with the second dataset resembling the Iverson & Fagan (2004) study. Model 1 indicated that on average, infants' frequency of reduplicated babble increased by a ratio of 0.01 every week ($p = 0.038$). Model 2 was not a significant model improvement: LR test= χ^2 (7) =1.89, $p > 0.05$. On average, infants' frequency of reduplicated babble decreased by 0.36 as rhythmic arm activity increased though not significantly ($p > 0.05$). Model 3 revealed that on average, after controlling for additional variables, infants' frequency of reduplicated babble decreased by 0.2 as rhythmic arm activity increased though not significantly p >0.05).

In sum, the frequency of reduplicated babble was not a significant predictor of reduplicated babble and thus there is insufficient evidence to support a sequential linkage from the arm to the mouth domain.

Correlational data. Pearson's correlational analyses were conducted to identify whether there exist significant correlations between onset of rhythmic arm activity, onset of reduplicated babble, frequency of rhythmic arm activity, and frequency of reduplicated babble. There was no significant correlation between onset of rhythmic arm activity and onset of reduplicated babble ($p > 0.05$). There were very weak significant correlations between onset of rhythmic arm activity and frequency of reduplicated babble ($r = -0.07$, $p = 0.02$), frequency of rhythmic arm activity and onset of reduplicated babble ($r = 0.07$, $p = 0.04$), and frequency of rhythmic arm activity and frequency of reduplicated babble ($r = 0.089$, $p = 0.003$). Given the small sample size and the weak correlations, results should be interpreted with caution. These findings suggest that infants with earlier onset of rhythmic arm activity exhibit less reduplicated babble and that infants with greater rhythmic arm activity exhibit greater reduplicated babble and earlier onset of reduplicated babble.

Taken together, results appear to suggest that despite correlations between rhythmic arm activity and reduplicated babble, there is no causal relationship between the two variables. Thus, there is insufficient evidence to support a sequential linkage from the arm to the mouth domain.

Differences in the proportions of each type of vocal-manual coordination. If entrainment occurs from the arm to the mouth domain, a greater proportion of activities occurring in coordination was predicted to be movement initiated or synchronous rather than vocalization initiated.

Two-level random coefficient models predicted the proportion of the different types of activities occurring in coordination between 23 and 34 weeks of age. These models accounted for variation in the frequency of each type of vocal-manual coordination (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for the frequency of each type of vocal-manual coordination across time to estimate variation in infant-level growth (see Table 3A).

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in the frequency of vocal-manual coordination. On average, as time increased, infants' frequency of vocal-manual coordination significantly increased by 0.009 (β=0.009, SE=0.002, $p < .00001$).

Model 2 included the type of vocal-manual coordination and offered insight into whether infants exhibited more or less of a particular vocal-manual coordination pattern (i.e. loosely coupled-vocalization initiated, loosely coupled-movement initiated, or tightly coupled). It was a significant model improvement: LR test= χ^2 (7) =18.5, $p < .0001$. The time-varying coefficient reflected the change in the frequency of vocal-manual coordination associated with each of the three given patterns while capturing between-infant variation in frequency of vocal-manual coordination over time. On average, infants' frequency of vocal-manual coordination increased by 0.42 as the pattern of vocal-manual coordination changed (β=0.42, SE=0.01, $p < .00001$).

To account for additional characteristics that may have affected the frequency of vocal-manual coordination, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, after controlling for these variables, infants' frequency of vocal-manual coordination increased by 0.05 as the pattern of vocal-manual coordination changed (β=0.05, SE=0.01, $p <.00001$). Among the covariates, Birth order was the only significant predictor ((β=-0.096, SE=0.035, $p =0.01$).

Akaike information criteria (AIC) indicated that Model 3 was the superior model, although Bayesian information criteria (BIC) indicated that Model 2 was preferred (AIC=229.50; BIC= 280.65).

In Model 4, a three-way interaction with time, vocal-manual pattern, and birth order was conducted. There was a main effect of vocal-manual pattern (β=0.03, SE=0.01, $p =0.007$), but no significant interactions or main effect of birth order ($p >0.05$).

It was hypothesized that a greater proportion of vocal-manual coordination would be movement initiated or tightly coupled. Using dummy coded variables, tightly synchronized vocal-manual coordination was compared to both types of loosely coupled patterns of coordination. Results revealed two significant negative relationships, whereby infants exhibited a greater proportion of tightly synchronized vocal-manual coordination than movement-initiated ((β=-0.103, SE=0.019, $p <0.00001$) and vocalization-initiated patterns (β=-0.083, SE=0.019, $p <0.00001$). In addition, vocalization-initiated co-occurrences was compared to movement-initiated co-occurrences and revealed no significant difference ($p >0.05$).

The above analyses were similarly conducted using the Iverson & Fagan (2004) equivalent time points. Model 1 indicated that on average, as time increased, infants' frequency of vocal-manual coordination decreased by 0.007, though not statistically significantly ($p >0.05$). Model 2 was a significant model improvement: LR test= χ^2 (7) =7.66, p=0.006. It demonstrated that on average, infants' frequency of vocal-manual coordination increased by 0.05 as the pattern of vocal-manual coordination changed (β=0.049, SE=0.02, $p =0.006$). According to Model 3, on average, after controlling for additional variables, infants' frequency of vocal-manual coordination increased by 0.05 as the pattern of vocal-manual coordination changed (β=0.05, SE=0.02, p =0.02). Among the covariates, Birth order was the only significant predictor ((β=-0.12, SE=0.05, p =0.02). Model 4 indicated no main effects or significant interactions ($p >0.05$). Akaike information criteria (AIC) and Bayesian information criteria (BIC) indicated that Model 2 was preferred (AIC=42.6 BIC= 68.5).

Using dummy coded variables, tightly synchronized vocal-manual coordination was compared to both types of loosely coupled patterns of coordination. Results revealed two significant negative relationships, whereby infants exhibited a greater proportion of tightly synchronized vocal-manual coordination than movement-initiated ((β=-0.10 SE=0.04, p =0.01 and vocalization-initiated patterns (β=-0.10, SE=0.04, p =0.006). There were no significant differences between patterns of loosely coupled co-occurrences ($p >0.05$).

In sum, the hypothesis that a greater proportion of activities occurring in coordination would be movement-initiated or synchronous rather than vocalization-initiated is only partially supported. While there is evidence of greater proportions of tightly synchronized patterns of co-occurrences, findings from the current study do not report any significant differences between the two types of loosely coupled patterns of coordination. Thus, there is insufficient evidence to support a sequential linkage from the arm to the mouth domain. Nor is there evidence to support a sequential linkage from the mouth to the arm domain. However, results may support a simultaneous account of entrainment.

Babble onset and vocal-manual coordination. In support of sequential entrainment from the arm to the mouth domain, it was hypothesized that younger babblers would exhibit a greater frequency of vocal-manual coordination than older babblers.

Two-level random coefficient models predicted the frequency of vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different babble groups. These models accounted for variation in the frequency of vocal-manual coordination (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for the frequency of vocal-manual coordination across time to estimate variation in infant-level growth (see Table 4A).

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in the frequency of vocal-manual coordination. On average, as time increased, infants' frequency of vocal-manual coordination increased by 0.0003 ($p < 0.001$).

Model 2 included the babble group and offered insight into whether infants who babbled prior to 7 months of age exhibited more or less vocal-manual coordination than infants who did not babble until after 7 months of age. It was not a significant model improvement: LR test= χ^2 (7) =0.39, p=0.53. The time-varying coefficient reflected the change in rhythmic arm activity associated with each of the two babble groups while capturing between-infant variation in frequency of vocal-manual coordination over time. On average, infants' vocal-manual coordination increased by 0.0004 as the babble group changed, though not significantly ($p > 0.05$).

To account for additional characteristics that may have affected the frequency of vocal-manual coordination, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, after controlling for these variables, infants' frequency of vocal-manual coordination increased by 0.0003 as babble group changed, though not significantly ($p > 0.05$). Among the covariates, Birth order was the only significant predictor; whereby infants who were the only child exhibited less vocal-manual coordination than those with a sibling (β=-0.002, SE=0.0008, p =0.02).

The same analyses described above were repeated with the three time points aligning with the Iverson & Fagan (2004). Model 1 indicated that on average, as time increased, infants' frequency of vocal-manual coordination marginally increased by 0.0003 (p =0.05). Model 2 was not a significant model improvement: LR test= χ^2 (7) =0.13, p=0=0.72. On average, infants' vocal-manual coordination marginally decreased by 0.0004 as babble group changed (p =0.05). Model 3 revealed that on average, after controlling for additional variables, infants' frequency of vocal-manual coordination marginally increased by 0.0003 as babble group changed (p =0.055). Among the covariates, Birth order was the only significant predictor of frequency of vocal-manual coordination; whereby infants who were the only child exhibited less vocal-manual coordination than those with a sibling (β=-0.004, SE=0.002, p =0.02).

In conclusion, there were no differences between younger and older babblers in the frequency of vocal-manual coordination exhibited through the course of the study. Thus, the current study does not support a sequential hypothesis of entrainment in which the initial linkage occurs from the arm to the mouth domain.

Babble onset and rhythmic arm activity. It was predicted that entrainment from the arm to the mouth domain was evidenced by greater amounts of rhythmic arm activity produced by younger babblers compared to older babblers.

Two-level random coefficient models predicted the frequency of rhythmic arm activity occurring between 23 and 34 weeks of age for different babble groups. These models accounted for variation in the frequency of rhythmic arm activity (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for the frequency of rhythmic arm activity across time to estimate variation in infant-level growth (see Table 5A).

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in the frequency of rhythmic arm activity. On average, as time increased, infants' frequency of rhythmic arm activity increased by 0.001 ($p < 0.0001$).

Model 2 included the babble group and offered insight into whether infants who babbled prior to 7 months of age exhibited more or less rhythmic arm activity than infants who did not babble until after 7 months of age. It was not a significant model improvement: LR test= χ^2 (7) =0.37, p =0.54. The time-varying coefficient reflected the change in rhythmic arm activity associated with each of the two babble groups while capturing between-infant variation in frequency of rhythmic arm activity over time. On average, infants' rhythmic arm activity increased by 0.002 as babble group changed, though not significantly ($p > 0.05$).

To account for additional characteristics that may have affected the frequency of rhythmic arm activity, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, after controlling for these variables, infants' frequency of rhythmic arm activity increased by 0.005 as babble group changed, though not significantly ($p > 0.05$). Among the covariates, there were no significant influences ($p > 0.05$).

The same analyses described above were repeated with the three time points aligning with the Iverson & Fagan (2004) study. Model 1 indicated that on average, as time increased, infants' rhythmic arm activity increased by 0.0005, though not significantly ($p > 0.05$). Model 2 was not a significant model improvement: LR test= χ^2 (7) =0.20, p =0.658. On average, infants' rhythmic arm activity decreased by 0.0015 as babble group changed, though not significantly (p

>0.05). Model 3 revealed that on average, after controlling for additional variables, infants' frequency of rhythmic arm activity decreased by 0.002 as babble group changed, though not significantly (p >0.05). Among the covariates, there were no significant influences (p >0.05).

It was hypothesized that infants who had begun to babble prior to 7 months would exhibit greater rhythmic arm activity than infants who began to babble after 7 months of age. This hypothesis was not supported. Thus, there is insufficient evidence to support a sequential linkage from the arm to the mouth domain.

Infant threshold and vocal-manual coordination. Infants with lower thresholds (i.e. those requiring less practice to master rhythmic arm activity) were predicted to have more frequent bouts of vocal-manual coordination and greater proportions of movement-initiated or tightly synchronized patterns of coordination than their higher threshold peers.

Frequency of vocal-motor coordination. Two-level random coefficient models predicted the frequency of vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different thresholds. These models accounted for variation in the frequency of vocal-manual coordination (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for the frequency of vocal-manual coordination across time to estimate variation in infant-level growth (see Table 6A).

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in the frequency of vocal-manual coordination. On average, as time increased, infants' frequency of vocal-manual coordination increased by 0.0003 (p <0.001).

Model 2 included the threshold value and offered insight into whether infants with lower thresholds exhibited more or less vocal-manual coordination than infants with higher thresholds. Akaike information criteria (AIC) and Bayesian information criteria (BIC) indicated that Model

1 was preferred (AIC=-69117.7; BIC=-9087.5). The time-varying coefficient reflected the change in vocal-manual coordination associated with changes in threshold level while capturing between-infant variation in frequency of vocal-manual coordination over time. On average, infants' vocal-manual coordination increased by 0.004 as threshold level increased, though not significantly ($p > 0.05$).

To account for additional characteristics that may have affected the frequency of vocal-manual coordination, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, after controlling for these variables, infants' frequency of vocal-manual coordination increased by 0.0003 as threshold level increased, though not significantly ($p > 0.05$). Among the covariates, Birth order was the only significant predictor of frequency of vocal-manual coordination. Infants who were the only child exhibited less vocal-manual coordination than those with a sibling (β=-0.003, SE=0.0008, $p = 0.002$).

Using the dataset representative of Iverson & Fagan (2004), similar analyses were run to predict the frequency of vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different thresholds. Model 1 indicated that on average, as time increased, infants' frequency of vocal-manual coordination marginally increased by 0.0003 ($p = 0.05$). Akaike information criteria (AIC) and Bayesian information criteria (BIC) indicated that Model 1 was preferred over model 2 (AIC=-2291.20; BIC=-2269.03). On average, infants' vocal-motor coordination increased by 0.00403 as threshold level increased, though not significantly ($p > 0.05$). Model 3 revealed that on average, after controlling for additional variables, infants' frequency of vocal-manual coordination increased by 0.0003 as threshold level increased, though not significantly ($p > 0.05$). Among the covariates, Birth order was the only significant predictor of frequency of vocal-manual coordination. Infants who were the only child exhibited less vocal-manual coordination than those with a sibling (β=-0.007, SE=0.007, p =0.001).

It was hypothesized that infants with lower thresholds would exhibit greater vocal-manual coordination than infants with higher thresholds. This was not supported.

Vocal-manual coordination patterns. It was predicted that infants with lower thresholds would a greater proportion of tightly synchronized and movement-initiated patterns of coordination than their higher threshold peers.

Tightly synchronized coordination. Two-level random coefficient models predicted the frequency of tightly synchronized vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different thresholds. These models accounted for variation in the frequency of tightly synchronized vocal-manual coordination (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for the frequency of tightly synchronized vocal-manual coordination across time to estimate variation in infant-level growth (see Table 7A).

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in the frequency of tightly synchronized vocal-manual coordination. On average, as time increased, infants' frequency of tightly synchronized vocal-manual coordination increased by 0.01 (p =0.02).

Model 2 included the threshold value and offered insight into whether infants with lower thresholds exhibited more or less tightly synchronized vocal-manual coordination than infants with higher thresholds. Akaike information criteria (AIC) and Bayesian information criteria (BIC) indicated that Model 2 was preferred (AIC=480.2; BIC=513.5). The time-varying coefficient reflected the change in tightly synchronized vocal-manual coordination associated with changes in threshold level while capturing between-infant variation in frequency of tightly synchronized vocal-manual coordination over time. On average, infants' vocal-manual coordination increased by 0.70 as threshold value increased ($p = 0.04$).

To account for additional characteristics that may have affected the frequency of vocal-manual coordination, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, after controlling for these variables, infants' frequency of tightly synchronized vocal-manual coordination increased by 0.40 as threshold value increased, though not significantly ($p > 0.05$). Among the covariates, Birth order was the only significant predictor of frequency of tightly synchronized vocal-manual coordination. Infants who were the only child exhibited less tightly synchronized vocal-manual coordination than those with a sibling ($\beta = -0.28$, $SE = 0.07$, $p = 0.002$). While Akaike information criteria (AIC) identified model 3 as being the best, Bayesian information criteria (BIC) indicated that Model 2 was preferred (AIC=454.2; BIC=513.5).

Using the dataset representative of Iverson & Fagan (2004), similar analyses were run to predict the frequency of tightly synchronized vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different thresholds. Model 1 indicated that on average, as time increased, infants' frequency of tightly synchronized vocal-manual coordination increased by 0.01, though not significantly ($p > 0.05$). Model 2 revealed that on average, infants' vocal-manual coordination increased by 0.48 as threshold value increased, though not significantly ($p > 0.05$). Model 3 indicated that on average, after controlling for additional variables, infants' frequency of tightly synchronized vocal-manual coordination increased by 0.14 as threshold value increased, though not significantly ($p > 0.05$). Among the covariates, Birth order and Sex were the only significant predictors of frequency of tightly synchronized vocal-manual coordination. Infants who were the only child exhibited less tightly synchronized vocal-manual coordination than those with a sibling (β=-0.46, SE=0.06, p <0.0001) and boys demonstrated less tightly synchronized vocal-manual coordination than girls (β=-0.16, SE=0.06, p =0.03). Akaike information criteria (AIC) and Bayesian information criteria (BIC) identified model 1 as being the best (AIC=71.77; BIC=93.93).

There is insufficient evidence to support or refute the claim that infants with lower thresholds exhibit greater amounts of tightly synchronized coordination than infants with higher thresholds.

Movement-initiated coordination. Two-level random coefficient models predicted the frequency of movement-initiated vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different thresholds. These models accounted for variation in the frequency of movement-initiated vocal-manual coordination (Level 1) and estimated variation between infants (Level 2). Level 2 calculated a random slope for the frequency of movement-initiated vocal-manual coordination across time to estimate variation in infant-level growth (see Table 8A).

Model 1 included a time component (week in study) in Level 2 that captured between-infant variation in the frequency of movement-initiated vocal-manual coordination. On average, as time increased, infants' frequency of movement-initiated vocal-manual coordination increased by 0.01 (p <0.001).

Model 2 included the threshold value and offered insight into whether infants with lower thresholds exhibited more or less movement-initiated vocal-manual coordination than infants with higher thresholds. The time-varying coefficient reflected the change in movement-initiated vocal-manual coordination associated with changes in threshold level while capturing between-infant variation in frequency of movement-initiated vocal-manual coordination over time. On average, infants' vocal-manual coordination increased by 0.1 as threshold value increased, though not significantly ($p > 0.05$).

To account for additional characteristics that may have affected the frequency of movement-initiated vocal-manual coordination, Model 3 was conditioned on variables related to infant demographics and developmental skill in fine motor, gross motor, and communication. On average, after controlling for these variables, infants' frequency of movement-initiated vocal-manual coordination decreased by 0.03 as threshold value increased, though not significantly ($p > 0.05$). Among the covariates, there were no significant predictors of frequency of movement-initiated vocal-manual coordination.

Using the dataset representative of Iverson & Fagan (2004), similar analyses were run to predict the frequency of movement-initiated vocal-manual coordination occurring between 23 and 34 weeks of age for infants of different thresholds. Model 1 indicated on average, as time increased, infants' frequency of movement-initiated vocal-manual coordination increased by 0.14, though not significantly ($p > 0.05$). Model 2 concluded that on average, infants' vocal-manual coordination increased by 0.42 as threshold value increased, though not significantly ($p = 0.07$). Model 3 revealed that on average, after controlling for additional variables, infants' frequency of movement-initiated vocal-manual coordination increased by 0.27 as threshold value increased, though not significantly ($p > 0.05$). Among the covariates, Birth order, Communication skills at 6 months, and Fine motor skills at 6 and 8 months were predictors of frequency of movement-initiated vocal-manual coordination. Infants who were the only child exhibited less movement-initiated coordination (β=-0.12, SE=0.05 $p = 0.02$), infants with lower scores in communication at 6 months exhibited less movement-initiated coordination (β=-0.008, SE=0.003 p =0.02), infants with lower scores in fine motor skill at 6 months exhibited less movement-initiated coordination (β=-0.004, SE=0.001 p =0.04), and infants with higher scores in fine motor skill at 8 months exhibited less movement-initiated coordination (β=0.007, SE=0.002 p =0.006).

There is insufficient evidence to support differences in movement-initiated coordination based on infant threshold. Rather, the frequency of movement-initiated coordination is best predicted by birth order, communication skills at 6 months, and fine motor skills at 6 and 8 months.

In conclusion, the fourth hypothesis which posited that entrainment occurred from the arm to the mouth domain was not supported by the findings of the current study. However, results may be suggestive of a simultaneous linkage in which mutual entrainment of the arm and mouth domains occurs.

Discussion

To our knowledge, this is the first longitudinal study to investigate the relationship between rhythmic arm activity and reduplicated babble using weekly observations. This research used a novel online-longitudinal design to gather data relevant to examining the relationship between rhythmic arm activity and reduplicated babble in infants. Few studies have previously explored this topic, and none have done so using weekly observations. One of the first studies (Locke et al., 1995) approached the topic using a cross-sectional design. They focused on identifying a mechanism in which manual activity facilitates vocal behaviour before disappearing. Another study (Ejiri and Masataka, 2001) followed four infants longitudinally between 6 and 11 months, to identify the onset of reduplicated babble and the period of co-occurrence between manual activity and reduplicated babble. They were able to identify that during this period, most vocalizations co-occurred with rhythmic movements and that a peak in rhythmic movements coincided with reduplicated babble onset. Iverson and Fagan (2004), were interested in expanding on Ejiri and Masataka (2001)'s findings and argued that the relationship between babble and rhythmic arm activity was a prelude to later speech-gesture coordination and that oscillatory-coupling was driving this relationship. An interpretation of results suggested that rhythmic movements influenced vocal activity, and that onset of reduplicated babble provided an opportunity for mutual entrainment of the vocal and manual systems. Iverson et al. (2007) further supported a model in which mutual entrainment of vocalization and manual activity occurred as a result of babble onset which allowed for both systems to become strong, specific, and stable. In sum, previous research suggests that between 6 and 9 months of age, early development of a speech and gesture system can be observed from the relationship between rhythmic arm activity and reduplicated babble. This research purports that the relationship occurs as a result of oscillator-coupling whereby rhythmic oscillators from the arm domain prepare the infant for rhythmic speech. Then, only once a sequential linkage from the arm to the mouth domain has occurred, does the onset of reduplicated babble occur and subsequently allow for mutual entrainment of the vocal and manual systems. Mutual entrainment then enables both systems to become strong, stable, and specific.

The present study was uniquely designed to overcome the limitations of previous studies and the inherent limitations of developmental research. In conducting longitudinal data in infant studies, there is a tendency towards homogeneity, high attrition rates, high cost, and timely data collection. However, the use of an online submission portal allowed for greater ethnic and cultural heterogeneity, a 3% attrition rate, relatively low costs to researchers (i.e. no transportation costs, minimal cost of materials and shipping, reimbursement), and minimal time commitments for caregivers (i.e. 15 minutes/week) and researchers (i.e. simultaneous data collection). Additionally, over the course of the 12 weeks, there was a 96% submission rate. Taken together, the online design was effective at reducing barriers to participation in infant studies and was an optimal model for collecting large samples in a limited timeframe. By using an online submission portal, weekly observations were collected. The multitude of data points allowed for the first ever series of complex trajectory analyses and multi-level modelling.

There was no evidence for sequential entrainment from the arm domain to the mouth domain. However, results do suggest the presence of key moment in early development in which mutual entrainment of the arm and mouth domains is representative of a maturing speech and gesture system. The mechanism by which the early speech and gesture system develops is discussed below in the context of dynamical systems and mutual entrainment theories. Implications and future directions are to follow.

According to Iverson and Thelen (1999), between 6 and 8 months of age, the speech and gesture systems become increasingly linked through repeated practice of rhythmic motor movements and rhythmic vocalizations. Though these movements may have appeared independently prior to this stage, they become increasingly coordinated during this developmental period. Given the age of onset, the trajectories of both behaviours, and the coordination patterns previously observed, it was believed that the emergence of a increasingly more coordinated interplay reflected control by a common underlying mechanism (Eilers et al., 1993; Koopmans-van Beinum & van der Stelt, 1986; Locke et al., 1995; Oller & Eilers, 1988; Ramset, 1984). An oscillatory mechanism was believed to drive rhythmic arm activity and to subsequently entrain mandibular activity responsible for rhythmic speech (i.e. reduplicated babble). (Cobo-Lewis, Oller, Lynch, & Levine, 1996; Eilers et al., 1993; Iverson & Thelen, 1999; Koopmans-van Benium & van der Stelt, 1986; Oller & Eilers, 1988; Thelen, 1979). It was theorized that the developmental period spanning 6 to 8 months of age was a critical window in which entrainment from the arm domain to mouth domain could be observed (Iverson, 2010; Iverson & Fagan, 2004). Following the onset of reduplicated babble, mutual entrainment would allow both domains to become strong, stable, and specific.

Initial Linkage

Evidence for an initial linkage from the arm to the mouth domain comes from observations of earlier onset of rhythmic arm activity compared to that of reduplicated babble and a greater proportion of movement-initiated or tightly coupled vocal-manual co-occurrences as opposed to co-occurrences which were vocalization-driven (Ejiri and Masataka, 2001; Iverson & Fagan, 2004; Iverson et al., 2007; Locke et al., 1995). As the first study to utilize a multilevel modelling approach to data analysis, there was no evidence for a causal relationship between earlier onset of rhythmic arm activity and reduplicated babble, despite weak correlations. Neither the onset of rhythmic arm activity nor the frequency of rhythmic arm activity was predictive of reduplicated babble. Thus, a sequential linkage *from* the arm domain *to* the mouth domain was not supported in the current study.

Iverson and Fagan (2004) believed that a coordinated pattern of activity signified successful entrainment from one domain to another. In this context, they suggested that entrainment would occur if rhythmic arm activity was high and infant threshold was low. Their reasoning was that mastery of rhythmic arm activity would allow for oscillators to “spill over” and entrain those in the vocal domain. Thus, infants who required more practice to achieve high activation of rhythmic arm activity would exhibit less vocal-manual coordination and less movement-initiated or tightly synchronized patterns of coordination than infants with lower thresholds (Iverson &

Fagan, 2004). Results from the current study, did not identify differences in the frequency of vocal-manual coordination between infants with higher or lower thresholds. Additionally, there were no differences in the proportion of movement-initiated coordination across threshold level. However, there may be differences in the frequency of tightly synchronized co-occurrences across threshold. Infants with lower thresholds were more likely than infants with higher thresholds to exhibit co-occurrences which were tightly synchronized. When controlling for individual differences in developmental stage, language acquisition, and birth order, this association was no longer observed. Further examination of the type of vocal-manual coordination exhibited by infants offers insight into the processes of entrainment occurring during this period of time. Despite previous findings, this study did not find a difference in the proportion of co-occurrences which were movement-initiated or vocalization-driven. However, there was a significantly greater proportion of vocal-manual coordination which was tightly synchronized rather than loosely coupled. Given the frequency with which coordinated patterns of activity were observed, entrainment must have occurred (Iverson, 2010; Iverson & Fagan, 2004). However, the absence of a dominant domain, the absence of clear differences between infants of varying thresholds, and the significantly greater proportion of tightly synchronized patterns of coordination provides evidence of mutual entrainment but not of a sequential linkage from the arm to the mouth domain.

Babble Onset: Group Differences

Previous studies have argued that mutual entrainment and subsequent strengthening of the speech and gesture systems results from the onset of reduplicated babble. They purport that differences in the frequency of vocal-manual coordination between younger and older babblers supports a model in which rhythmic arm activity, when well-practiced, activates and entrains vocal activity. As these behaviours begin to co-occur, the rhythmic oscillators of the manual behaviour are echoed in vocalizations (Iverson & Fagan, 2004; Iverson et al., 2007). However, once reduplicated babble has emerged, these vocal-manual co-occurrences increase in frequency, thus strengthening the link between the speech and gesture systems. Results from this study do not support this claim. There were no significant differences in the frequency of vocal-manual coordination over time between younger and older babblers. It is worth noting that when conducting analyses using only monthly observations at 6, 7, and 8 months, results did demonstrate marginal group differences in the frequency of vocal-manual coordination over time. After controlling for individual differences and developmental performance, infants who babbled prior to 7 months had greater vocal-manual coordination. Thus, the importance of having weekly observations appears to be critical in identifying the true relationship between reduplicated babble and rhythmic arm activity. While previous researchers believed that the onset of reduplicated babble enabled activation of mutual entrainment and the subsequent strengthening of a vocal-manual system, trajectory analyses from the current study, as previously discussed, do not support this claim.

Developmental Trajectories

An examination of the trajectories of rhythmic arm activity, reduplicated babble, and vocal-manual coordination provided insight into the development of a more mature speech-gesture system. This study was the first to use weekly observations to map the trajectories of rhythmic arm activity, reduplicated babble, and vocal-manual coordination from 22 to 34 weeks of age.

Reduplicated babble. Consistent with previous findings, the mean age of onset for reduplicated babble was 26.7 weeks old (Koopmans-van Beinum & Van der Steelt, 1986; Oller

& Eilers, 1988). Whereas previous research stipulated that reduplicated babble steadily increases over the course of the next few months, weekly observations identified a period of instability between 23 and 26 weeks of age, followed by a period of stabilization between 27 and 30 weeks old, and a significant increase in activity between 31 and 32 weeks of age. When using monthly observations consistent with Iverson et al., (2007), these findings were not captured. Rather, reduplicated babble appeared to increase steadily over the course of the three months.

Rhythmic arm activity. Conversely, the mean age of onset for rhythmic arm activity was identified as occurring at 22 weeks of age, 2-3 weeks earlier than the previously identified 24-25 weeks of age (Koopmans-van Beinum & Van der Steelt, 1986; Locke et al., 1995; Oller & Eilers, 1988). It is possible that the mean age of onset for rhythmic arm activity occurs even sooner, given many infants were already exhibiting the behaviour in the first week of the study. Future research should observe changes in rhythmic arm activity prior to 22 weeks of age to identify with more certainty the mean age of onset. Additionally, whereas previous research has identified a peak in rhythmic arm activity around 26-27 weeks of age followed by a significant decrease in activity around 30-31 weeks of age, results from this study partially replicate these findings. Using weekly observations, rhythmic arm activity appears to vary widely between 22 and 28 weeks of age. Following the onset of rhythmic arm activity, decreased activity is observed between 23 and 24 weeks of age, followed by increased activity from 24 to 25 weeks, decreased activity between 26 and 27 weeks, and increased activity from 27 to 28 weeks of age. Rhythmic arm activity then appears to stabilize until 31 to 32 weeks of age, at which point it is observed to decrease (albeit marginally). Using monthly observations, rhythmic arm activity appears to increase significantly from 6 to 7 months of age, but then steadily decreases from 7 to

8 months, revealing the necessity of using more frequent measurements in time in order to capture the true developmental trajectory.

Vocal-manual coordination. Finally, previous research identified an increase in vocal-manual coordination between 6 and 9 months of age, with stabilization occurring by 7 months of age (Iverson et al., 2007). Findings from this study partially support this notion. Vocal-manual coordination significantly increased from 25 to 26 weeks of age and then decreased between 29 and 30 weeks of age at which point coordination appears to stabilize. Using monthly observations, vocal-manual coordination significantly increased from 6 to 7 months and then appears to stabilize between 7 and 8 months.

What Does This Mean?

According to the Dynamic Systems Theory, through periods of stability, instability, and phase shifts, new patterns can emerge (Thelen, 1995). Berstein (1967) stated that joints and muscles are functionally linked as a coordinated structure, working towards a mutual goal. These networks are made up of many components which may change over time (Kelso, Holt, Kugler, & Turvey, 1980). The order and patterns that arise from interactions between components are self-organizing, spontaneously switching between anti-phase (moving in opposite directions) and in-phase (moving in the same direction) patterns when a critical point is reached. From a dynamical systems theory perspective, the rhythmic characteristics of movements function like nonlinear coupled oscillators. When a key moment is reached, there is an observed phase shift towards a coordination mode which is more energy efficient for the system (Diepstra, 2015). This coordination mode, known as an attractor state, is characterized by a stable pattern of coordination. When shifting from one attractor state to another, there must first be a period of increased variability or instability. Hence, a new pattern of coordination can only emerge after the old pattern is disrupted. The observed changes in rhythmic arm activity, reduplicated babble, and vocal-manual coordination between 22 and 34 weeks of age may represent a period of self-organization within the speech and gesture system, wherein there are two spontaneous switches from in-phase to anti-phase patterns; one between 25 and 26 weeks of age and another between 31 and 32 weeks of age.

The trajectories for rhythmic arm activity and reduplicated babble were near identical between 22 and 30 weeks of age. However, these trajectories diverged between 31 and 32 weeks. High instability in both rhythmic arm activity and reduplicated babble was observed between 22 and 25 weeks of age, followed by a simultaneous increase in activity in both domains around 26 weeks and subsequent stabilization between 27 and 30 weeks old. Both behaviours appeared independently from one another throughout this period. However, at the same time as rhythmic arm activity and reduplicated babble are observed to simultaneously increase (25-26 weeks old) a significant increase in vocal-manual coordination is also observed. This spontaneous increase followed by subsequent stabilization of all three observables, may be the first key transition in which we can observe a movement to an in-phase attractor state. A shift into in-phase patterns would suggest a similar goal-directed behaviour. During the period of subsequent stabilization, mutual entrainment of the vocal and manual systems would thus become progressively strengthened.

A few weeks after stabilization, vocal-manual coordination declines around 29 weeks of age. This decline is subsequently followed by a decrease in rhythmic arm activity and an increase in reduplicated babble at 31 weeks. Again, all behaviours appear to stabilize after the observed change. The spontaneous decline of vocal-manual coordination and rhythmic arm activity and the increase in reduplicated babble, may be a second key transition in which we observe a movement to an anti-phase attractor state. Researchers have previously argued that following the onset of reduplicated babble and a period of high co-occurrence, rhythmic arm activity diminishes due to its decreased functionality (Ejiri & Masataka, 2001; Iverson & Fagan, 2004; Iverson et al., 2007; Locke et al., 1995). The claim is based on the notion that rhythmic arm activity prepares the infant for rhythmic speech and that once it has accomplished its function, the behaviour disappears as it is no longer needed. However, the aforementioned changes in all three observables after the first period of stabilization may merely suggest a change in state so as to optimize energy expenditure while maintaining the vocal-manual link.

The trajectory analyses of this study support the existence of a developmental relationship between early vocal and manual systems as a function of coupled oscillators that can mutually entrain one another. Contrary to previous studies which theorized that the period of mutual entrainment was the result of sequential coupling of oscillators from the arm to the mouth domain, results from this study support a seemingly spontaneous coupling of oscillators from both domains. This period of entrainment allows for the speech and gesture system to become increasingly intertwined and thus strengthened. While it was previously believed that once this link had become strong and stable, rhythmic arm activity had little function and thus began to dissipate while reduplicated babble, which maintained a developmental function (i.e. language mastery) continued to develop, results from this study may suggest a different developmental explanation.

Infants are born with a fundamental coordinated structure composed of manual and vocal components working towards a more intentional speech and gesture system. Over time, this structure spontaneously switches from in-phase to anti-phase patterns, with unstable states preceding a phase shift and stable states following the shift so as to optimize energy expenditures while working towards the system's goal. Through development, there are key moments in which self-organization of the system can be observed. The relationship between rhythmic arm activity and reduplicated babble is one example of a key moment in which there are changes to the system. While infants may have previously exhibited rhythmic arm activity and vocalizations independently from one another; between 22 and 26 weeks of age we see a successful shift into an in-phase state. During this transition, rhythmic arm activity and reduplicated babble are highly unstable, reflexive, and have yet to be mastered. When behaviours are unstable they require more energy. To maximize energy efficiency, the system will couple oscillators from the manual and vocal domains. In doing so, there is increased vocal-manual coordination which allows for mutual entrainment and the strengthening of each of the behaviours. During bouts of entrainment, the rhythmical organization of arm movements are echoed in vocalizations and the rhythmical organization of speech is echoed in movements of the arms. Hence, the vocal-manual link becomes progressively stronger and more intentional. Once the link has been sufficiently strengthened, the system re-organizes its energy allocation. Thus, when infants begin to demonstrate less vocal-manual coordination, less rhythmic arm activity, and more reduplicated babble around 32 week of age, there is a shift to an anti-phase state in which a greater proportion of energy is allocated to language development, as opposed to manual development, so as to drive maturation of the speech and gesture system from a reflexive system to a more intentional communication system.

Implications, Limitations, and Future Directions

There are several implications to the view that the relationship between rhythmic arm activity and reduplicated babble represents one key moment in the development of a sophisticated speech and gesture system. The first has to do with the well-known association between speech and language impairments and motor difficulties in childhood disorders. Bishop (2002) argued that children with co-occurring motor and language impairments may have a genetic predisposition whereby genes for communication impairments may also affect motor development. For example, children with autism spectrum disorder (ASD) have difficulties in the vocal and motor systems (Iverson, 2010). Despite delays being reported as early as infancy, ASD cannot be accurately diagnosed prior to the age of two with current diagnostic criteria. However, given the well-documented existence of difficulties in language, gesture, and motor abilities in older children with ASD, atypical vocal-manual coordination or speech-gesture development may serve as an early diagnostic marker for the disorder. In a study by Iverson & Wozniak (2007), patterns of vocal-manual coordination over 3 time points were recorded for typically developing, low-risk, and high-risk infants. Findings showed that infants at high-risk for later diagnosis of autism had somewhat attenuated rhythmic arm activity from pre-babble to babble onset. Unfortunately, findings were inconclusive in that delays or atypicalities in early vocal-manual links were characteristic of only some high-risk infants (Iverson & Wozniak, 2007). With regard to gesture-speech development, perhaps identification of absent or attenuated in-phase and anti-phase transitions, as identified in this study, rather than identification of changes in rhythmic arm activity form pre-babble to babble onset will allow for a more robust system for early identification of ASD.

The second implication of this study is methodological in nature. In longitudinal research within developmental psychology, it is common to collect in-lab video and audio data once monthly. In-lab videotaped data can provide an abundance of qualitative information. For many purposes, this may be adequate; but I would argue that in collecting in-lab observations only once per month, researchers fail to capture a phenomenon in its entirety. With recording devices and online storage systems becoming more easily accessible, caregivers can play a more active role in data collection; making weekly observational data more obtainable to researchers. Additionally, an online video submission protocol permits researchers to capture more naturalistic behaviours (i.e. at-home recording). This will not only reveal more about the relationship between motor and language development but could be critical in any early developmental context in which changes occur rapidly.

The study described above represents an important extension of previous literature investigating the relations between rhythmic arm activity and reduplicated babble. However, limitations do exist in the present research. First, although the longitudinal design used was effective in identifying key transitions in the early development of the speech and gesture system, many infants were already engaging in rhythmic arm activity at the beginning of the study. Additionally, the second key transition was identified within the last few weeks of the study with only two weeks of stabilization proceeding the shift. Following all infants from an earlier age and to a later age would have enriched the present investigation to ensure that all key transitions within this second stage of development of the speech-gesture system have been correctly identified.

It would also be informative to explore biological and social factors that facilitate the acquisition of rhythmic arm activity and rhythmic speech (e.g., body proportion, household environment, sibling interactions) to determine the role of such factors in the observed increase in vocal-manual coordination.

Finally, this study did not correct for multiple comparisons when identifying key transitions in the relationship between rhythmic arm activity and reduplicated babble. It was hypothesized—and confirmed—that the use of monthly observations may fail to capture key transitions during early infant development. As the first study to collect weekly observations, it was important to explore how behaviours changed from one week to the next. This study was successful in identifying specific weeks in which there exist significant changes in the frequencies of each behaviour. Replication is needed to confirm the existence of these significant changes.

In conclusion, researchers have proposed that this speech and gesture system pre-exists from birth and I have suggested here that entrainment of the manual and vocal domains during this second stage of the development of the system is complex and simultaneous rather than simple and sequential. Throughout development there are key moments of re-organization to the system in which greater vocal-manual coordination is observed. The emergence and trajectories of reduplicated babble, rhythmic arm activity and their coordination is one occurrence of self-organization which may have far-reaching consequences on later development of the speech and gesture system. Studying the ways in which the vocal and manual systems interact from early in development may not only yield a more comprehensive picture of the emerging language and motor domains; it may also provide fundamental insights into the processes underlying the speech and gesture system.

Appendix A

Table 1A

Onset of rhythmic arm activity as a predictor of reduplicated babble

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	-0.015	0.028	-0.012	0.028	-0.090	0.100
TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.010*	0.005	0.010*	0.005	0.011*	0.005
ONSET RAA			-0.365	0.264	-0.375	0.298
BIRTH ORDER					-0.025	0.032
SEX					0.003	0.026
LANGUAGE STATUS					0.012	0.026
ASQ6-COM					0.0005	0.001
ASQ6-FINE					-0.0004	0.001
ASQ6-GROSS					-0.000	0.001
ASQ8-COM					0.0005	0.001
ASQ8-FINE					-0.0003	0.001
ASQ8-GROSS					0.001	0.001
RANDOM EFFECTS	Model 1		Model 2		Model 3	
LEVEL 2 (TIME)						
CONSTANT (SD)	0.026		0.026		0.027	
LEVEL 1 (Infant)						
RESIDUALS	0.057		0.057		0.059	

LOG LIKELIHOOD	341.34	342.28	281.35
AIC	-670.67	-670.57	-530.69
BIC	-648.51	-644.71	-474.22

Note: ONSET RAA= Onset of rhythmic arm activity; SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 2A

Frequency of rhythmic arm activity as a predictor of reduplicated babble

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	-0.006	0.001	-0.009	0.018	-0.086	0.057
TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.009**	0.003	0.009**	0.003	0.010**	0.003
RAA			0.001	0.003	-0.001	0.003
BIRTH ORDER					-0.016	0.021
SEX					0.015	0.020
LANGUAGE STATUS					0.000	0.015
ASQ6-COM					-0.000	0.001
ASQ6-FINE					0.000	0.001

ASQ6-GROSS		0.000	0.001
ASQ8-COM		0.001	0.001
ASQ8-FINE		0.000	0.001
ASQ8-GROSS		0.000	0.001
RANDOM EFFECTS	Model 1	Model 2	Model 3
LEVEL 2 (TIME)			
CONSTANT (SD)	0.016	0.016	0.017
LEVEL 1 (Infant)			
RESIDUALS	0.090	0.094	0.086
LOG LIKELIHOOD	1047.85	900.86	853.66
AIC	-2083.70	-1787.72	-1675.32
BIC	-2053.50	-1753.21	-1598.86

Note: RAA= Frequency of rhythmic arm activity; SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 3A

Differences in the proportions of each type of vocal-manual coordination

	Model 1		Model 2		Model 3		Model 4	
	Estimate	SD	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	0.040	0.020	-0.002	0.021	-0.084	0.103	0.060	0.020

TIME-VARIANT INDICATOR								
WEEK IN STUDY	0.010***	0.002	0.010***	0.002	0.010***	0.003	0.007	0.004
VMGROUP			0.042***	0.010	0.050***	0.011	0.03**	0.012
BIRTH ORDER					-0.096*	0.035	-0.002	0.020
SEX					-0.043	0.030		
LANGUAGE STATUS					-0.000	0.030		
ASQ6-COM					-0.001	0.002		
ASQ6-FINE					-0.001	0.001		
ASQ6-GROSS					0.000	0.001		
ASQ8-COM					0.001	0.001		
ASQ8-FINE					0.002	0.001		
ASQ8-GROSS					-0.000	0.002		
TIME x VMGROUP							0.003	0.003
TIME X BIRTH ORDER							-0.0003	0.95
VMGROUP X BIRTH ORDER							-0.016	0.012
TIME X VMGROUP X BIRTH ORDER							0.001	0.003
RANDOM EFFECTS	Model 1		Model 2		Model 3			
LEVEL 2 (TIME)								
CONSTANT (SD)	0.002		0.002		0.002		0.003	
LEVEL 1 (Infant)								
RESIDUALS	0.267		0.264		0.27		0.26	

LOG LIKELIHOOD	-124.98	-115.71	-98.75	-113.61
AIC	261.95	245.41	229.50	251.21
BIC	292.15	280.65	307.42	311.62

Note: VMGROUP= Type of vocal-manual coordination; SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 4A

Babble onset as a predictor of reduplicated babble

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	0.0003	0.001	0.000	0.001	-0.003	0.002
TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.0003***	0.000	0.0003***	0.000	0.0003**	0.000
BABBLE GROUP			0.0004	0.001	0.0003	0.001
BIRTH ORDER					-0.002*	0.001
SEX					-0.001	0.001
LANGUAGE STATUS					-0.000	0.001
ASQ6-COM					-0.000	0.000
ASQ6-FINE					0.000	0.000

ASQ6-GROSS					-0.000	0.000
ASQ8-COM					0.000	0.000
ASQ8-FINE					0.000	0.000
ASQ8-GROSS					0.000	0.000
RANDOM EFFECTS	Model 1		Model 2		Model 3	
LEVEL 2 (TIME)						
CONSTANT (SD)	0.0005		0.0005		0.0005	
LEVEL 1 (Infant)						
RESIDUALS	0.004		0.004		0.004	
LOG LIKELIHOOD	4564.84		4565.03		3906.13	
AIC	-9117.68		-9116.07		-7780.27	
BIC	-9087.48		-9080.83		--7702.35	

Note: SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 5A

Babble onset as a predictor of frequency of rhythmic arm activity

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	0.005	0.002	0.003	0.003	-0.011	0.012

TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.001***	0.000	0.001***	0.000	0.001***	0.000
BABBLE GROUP			0.002	0.003	0.005	0.003
BIRTH ORDER					-0.004	0.004
SEX					-0.001	0.003
LANGUAGE STATUS					0.004	0.003
ASQ6-COM					0.000	0.000
ASQ6-FINE					0.000	0.000
ASQ6-GROSS					0.000	0.000
ASQ8-COM					0.000	0.000
ASQ8-FINE					0.000	0.000
ASQ8-GROSS					-0.000	0.000
RANDOM EFFECTS	Model 1		Model 2		Model 3	
LEVEL 2 (TIME)						
CONSTANT (SD)	0.001		0.001		0.001	
LEVEL 1 (Infant)						
RESIDUALS	0.013		0.013		0.014	
LOG LIKELIHOOD	3217.96		3218.15		2722.45	
AIC	-6423.93		-6422.30		-5412.9	
BIC	-6393.73		-6387.06		-5334.98	

Note: SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion *p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 6A

Infant threshold as a predictor of vocal-manual coordination

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	0.0003	0.001	0.000	0.001	-0.006	0.003
TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.003***	0.000	0.0003**	0.000	0.0003**	0.000
THRESHOLD			0.004	0.004	0.003	0.003
BIRTH ORDER					-0.004**	0.001
SEX					0.000	0.001
LANGUAGE STATUS					-0.000	0.001
ASQ6-COM					0.000	0.000
ASQ6-FINE					-0.000	0.000
ASQ6-GROSS					-0.000	0.000
ASQ8-COM					0.000	0.000
ASQ8-FINE					0.000	0.000
ASQ8-GROSS					0.000	0.000
RANDOM EFFECTS	Model 1		Model 2		Model 3	
LEVEL 2 (TIME)						

CONSTANT (SD)	0.0005	0.0005	0.0005
LEVEL 1 (Infant)			
RESIDUALS	0.004	0.004	0.004
LOG LIKELIHOOD	4564.84	3444.77	2920.41
AIC	-9117.68	-6875.53	-5808.83
BIC	-9087.48	-6842.20	-5735.36

Note: SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 7A

Infant threshold as a predictor of frequency of tightly synchronized coordination

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD
CONSTANT	0.086	0.043	0.056	0.048	-0.314	0.260
TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.012*	0.005	0.014**	0.005	0.012*	0.006
THRESHOLD			0.70*	0.33	0.400	0.302
BIRTH ORDER					-0.282**	0.068
SEX					-0.050	0.068
LANGUAGE STATUS					-0.053	0.063

ASQ6-COM					0.001	0.004
ASQ6-FINE					-0.004	0.002
ASQ6-GROSS					-0.001	0.003
ASQ8-COM					0.002	0.003
ASQ8-FINE					0.006	0.003
ASQ8-GROSS					0.004	0.003
RANDOM EFFECTS	Model 1		Model 2		Model 3	
LEVEL 2 (TIME)						
CONSTANT (SD)	0.025		0.022		0.023	
LEVEL 1 (Infant)						
RESIDUALS	0.304		0.30		0.311	
LOG LIKELIHOOD	-312.56		-233.086		-211.26	
AIC	637.11		480.17		454.53	
BIC	667.31		513.50		528.00	

Note: SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Table 8A

Infant threshold as a predictor of frequency of movement-initiated coordination

	Model 1		Model 2		Model 3	
	Estimate	SD	Estimate	SD	Estimate	SD

CONSTANT	-0.005	0.013	-0.001	0.015	0.018	0.105
TIME-VARIANT INDICATOR						
WEEK IN STUDY	0.010***	0.003	0.010***	0.003	0.008**	0.003
THRESHOLD			0.100	0.116	-0.030	0.123
BIRTH ORDER					-0.060	0.028
SEX					-0.023	0.028
LANGUAGE STATUS					-0.009	0.025
ASQ6-COM					-0.002	0.001
ASQ6-FINE					-0.001	0.001
ASQ6-GROSS					0.000	0.001
ASQ8-COM					-0.000	0.001
ASQ8-FINE					0.001	0.001
ASQ8-GROSS					0.002	0.001
RANDOM EFFECTS	Model 1		Model 2		Model 3	
LEVEL 2 (TIME)						
CONSTANT (SD)	0.012		0.011		0.011	
LEVEL 1 (Infant)						
RESIDUALS	0.189		0.196		0.186	
LOG LIKELIHOOD	247.88		161.12		174.68	
AIC	-483.75		-308.25		-317.36	
BIC	-453.55		-274.92		-243.89	

Note: SE= Standard Error; SD= Standard Deviation; AIC= Akaike information criterion; BIC= Bayesian information criterion

*p<.05, **p<.01, ***p<.001

Highlighted values represent the best model fit according to AIC and BIC

Appendix B

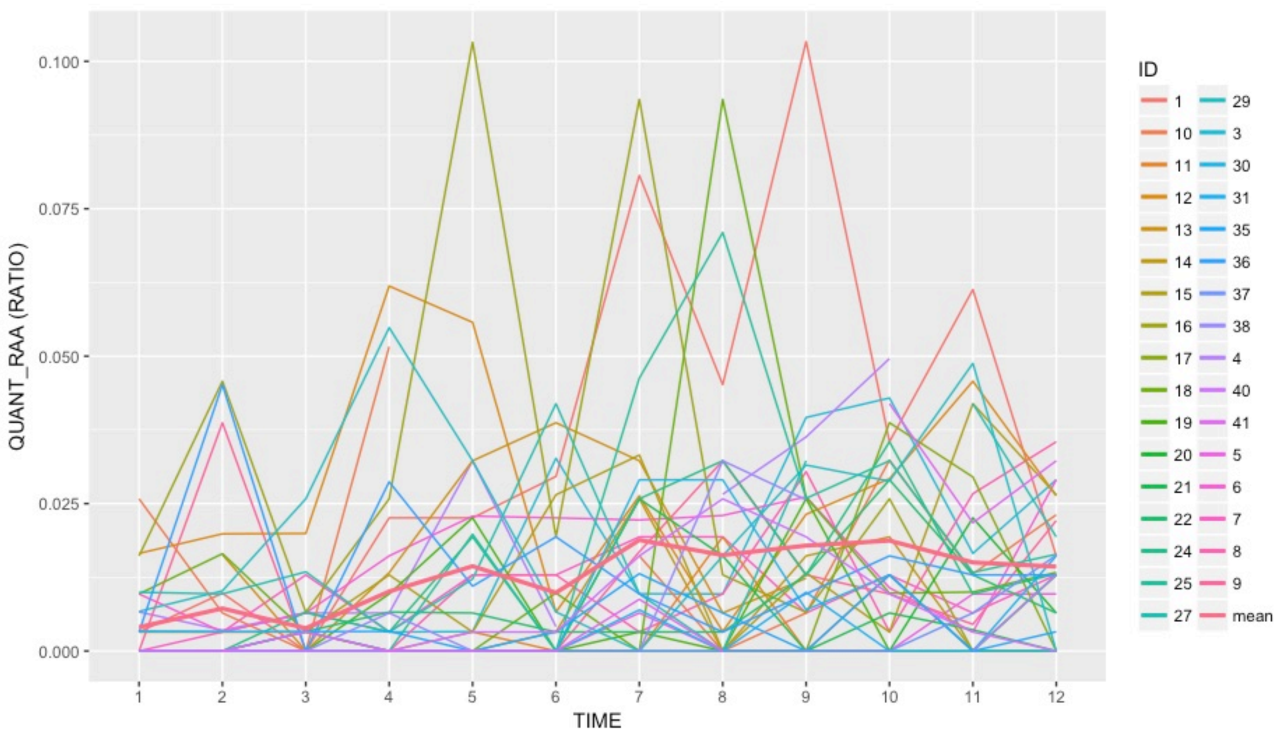

Figure 1B. Mean frequency of rhythmic arm activity over time using twelve time points and divided by participant ID.

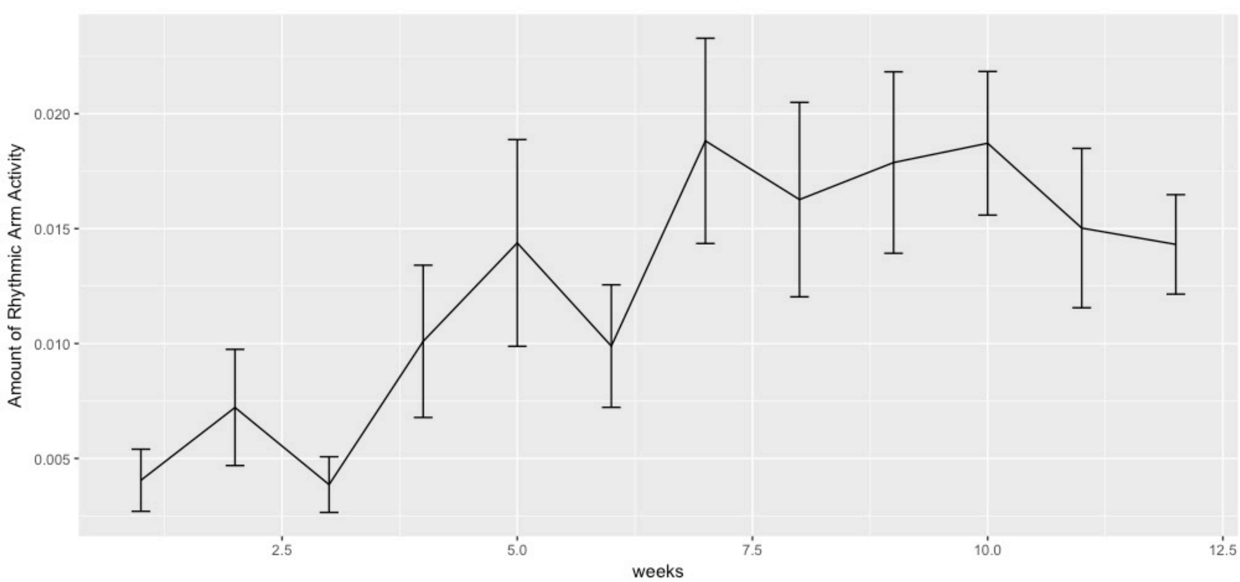

Figure B2. Mean frequency of rhythmic arm activity over time using twelve time points with error bars.

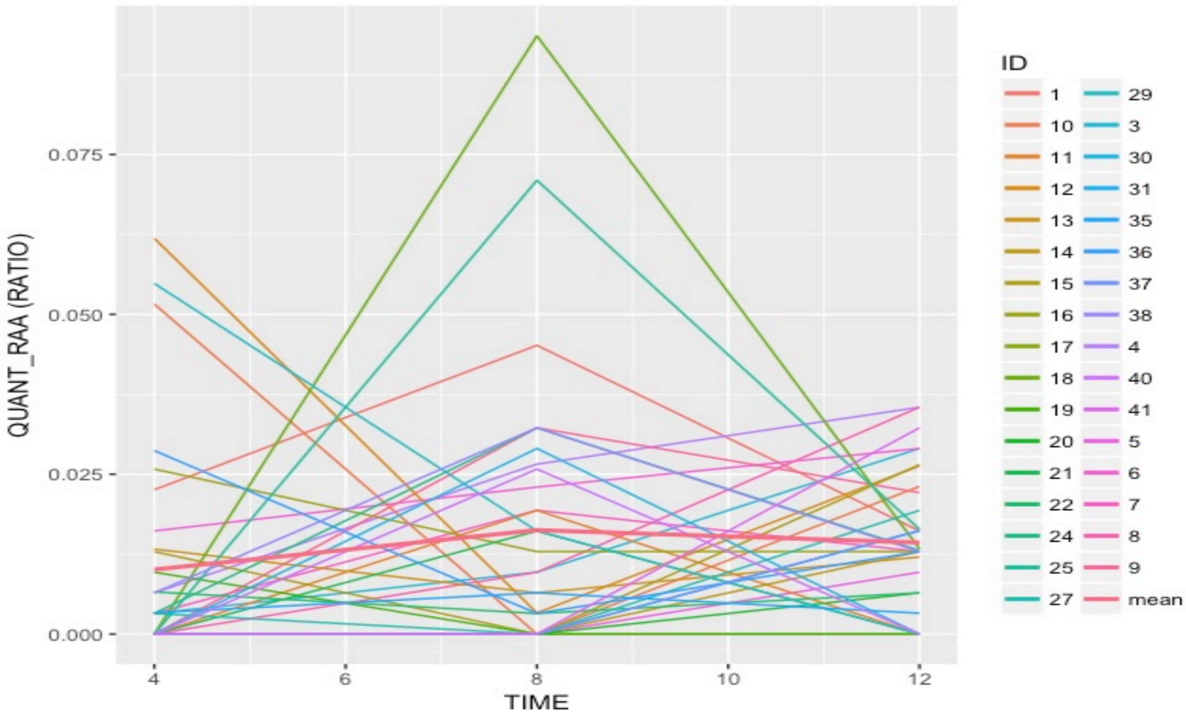

Figure 3B. Mean frequency of rhythmic arm activity over time using three time points.

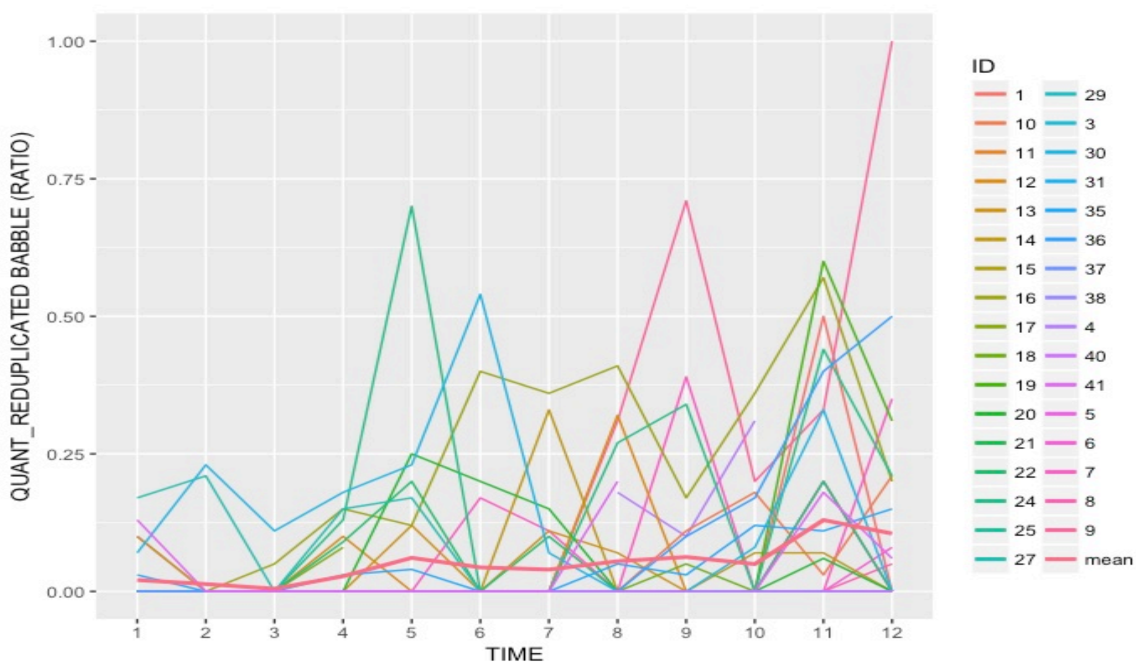

Figure 4B. Mean frequency of reduplicated babble over time using twelve time points for every participant ID.

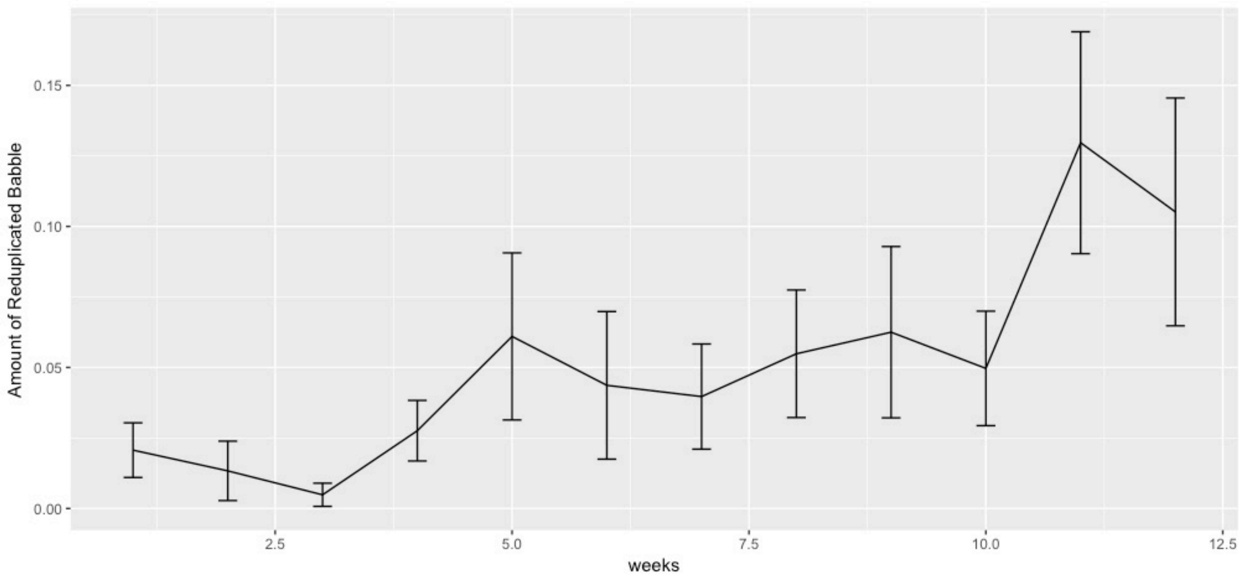

Figure 5B. Mean frequency of reduplicated babble over time using twelve time points with error bars.

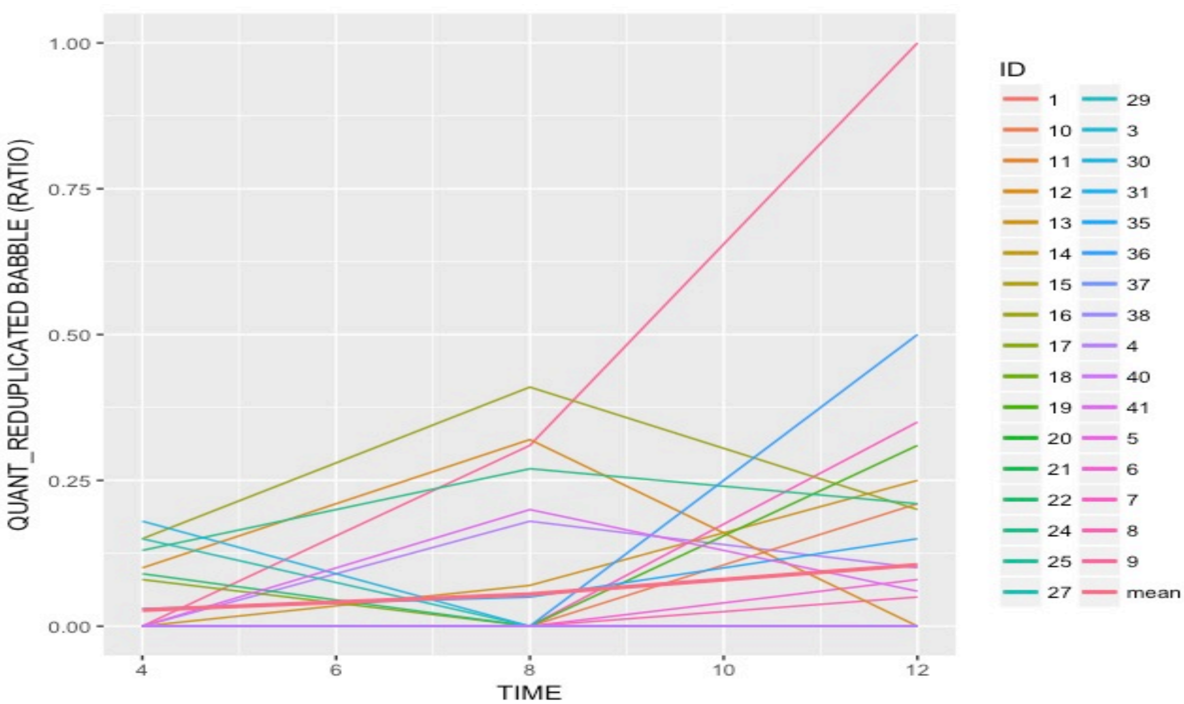

Figure 6B. Mean frequency of reduplicated babble over time using three time points.

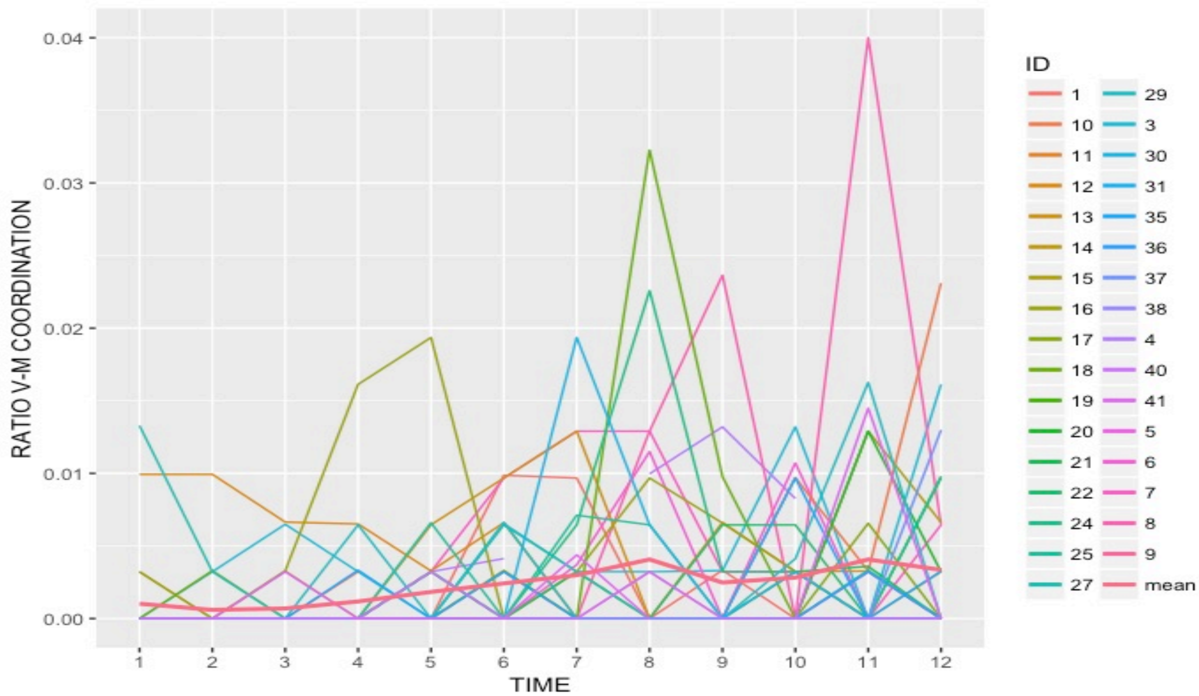

Figure B7. Mean frequency of vocal-manual activity over time using twelve time points for every participant.

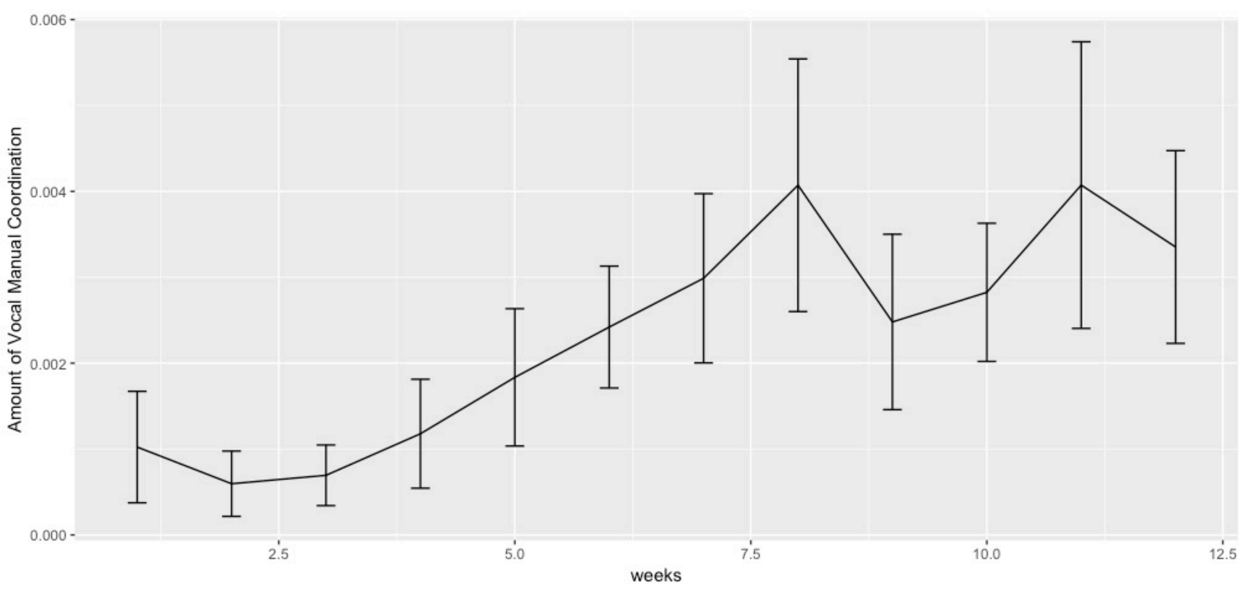

Figure 8B. Mean frequency of vocal-manual activity over time using twelve time points with error bars.

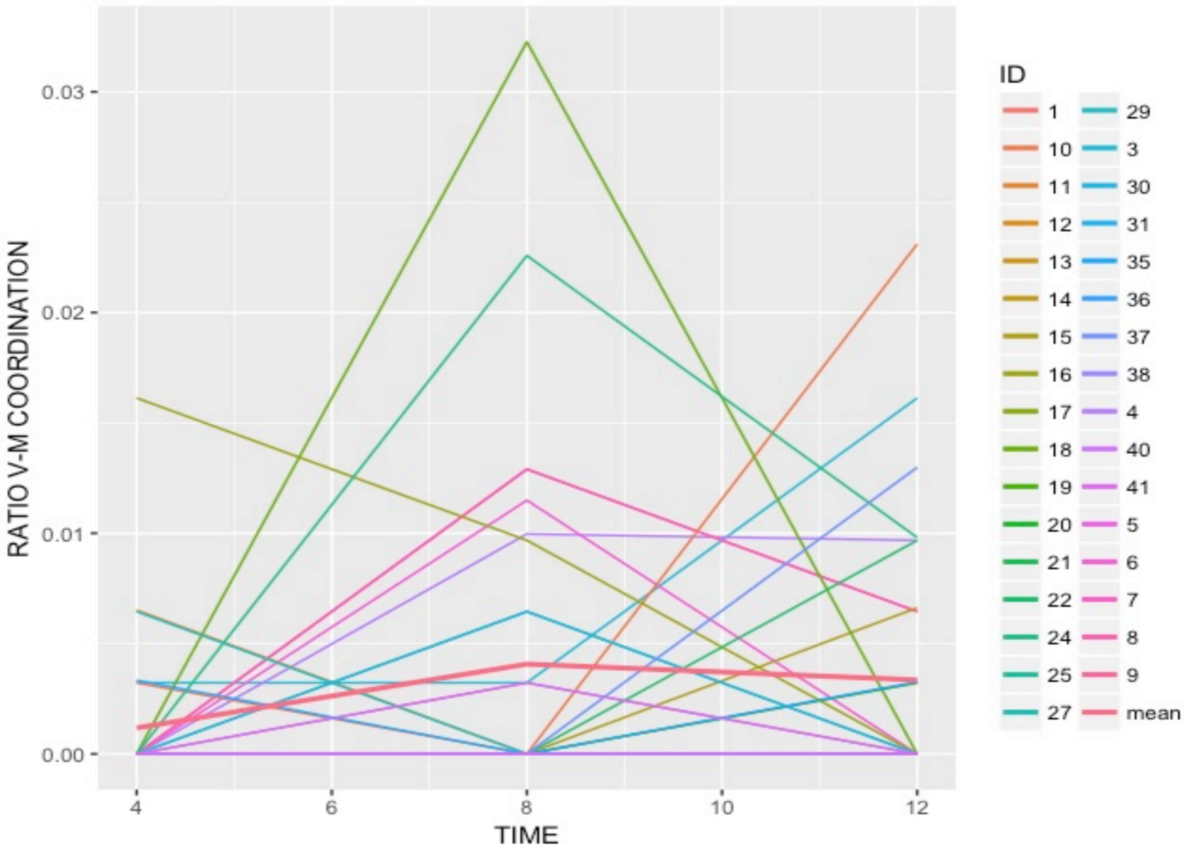

Figure B9. Mean frequency of vocal-manual activity over time using three time points.

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