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The Coemergence of Cognition, Language, and Speech Motor Control in Early Development: A Longitudinal Correlation Study

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Abstract

Although the development of spoken language is dependent on the emergence of cognitive, language, and speech motor skills, knowledge about how these domains interact during the early stages of communication development is currently limited. This exploratory investigation examines the strength of associations between longitudinal changes in articulatory kinematics and development of skills in multiple domains thought to support early communication development. Twenty-four infants were investigated every three months between the ages of 9 and 21 months. Movements of the upper lip, lower lip, and jaw were transduced using a three-dimensional motion capture system to obtain age-related changes in movement speed and range of movement. Standardized measures of cognition and language from the Battelle Developmental Inventory, 2nd edition and the MacArthur-Bates Child Development Inventory were also collected. Significant associations were identified between orofacial kinematic and the standardized measures of language and cognitive skills, even when age served as covariate. These findings provide preliminary evidence of interactions between cognition, language, and speech motor skills during early communication development. Further work is needed to identify and quantify causal relations among these co-emerging skills.

1. Introduction

Complex social behaviors, like spoken language, are the product of multiple processes including those related to motor, cognitive, and linguistic processes (Levelt, 1989; Smith & Goffman, 2004; Thelen, 2001). These processes co-emerge and interact as children progress through various phases of development. Although investigating these interactions poses immense research challenges, such information is essential for a comprehensive understanding of the many factors that contribute to developmental speech impairments. The current study is motivated, in part, by several findings from investigations demonstrating bidirectional interactions among different domains of knowledge and performance (i.e., speech motor control, phonology, language and affect) during early communication development. Our working hypothesis is that gains in oral motor control, specifically

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increased articulatory speed, coincide with gains in gestural communication, and other cognitive and linguistic skills. Our rationale for this hypothesis is that newly emerging cognitive and linguistic skills are associated with continued articulatory refinement (Green & Nip, 2010). A better understanding of how cognition, language, and speech motor control interact may help to inform theoretical models of speech development and impact early speech intervention.

1.1 The coemergence of symbolic and motor systems: Gestures and symbolic play

The coemergence of symbolic and motor systems in young children is most lucidly demonstrated in the literature on the development of gestures. Like speech, gestures and play skills involve motor skills that are dependent on the interaction of motor, cognition, and language processes. Prior research has shown that these behaviors are correlated with language and cognitive skills at various points in early development. At approximately 9 months of age, the use of deictic (e.g., pointing, giving) gestures is positively associated with receptive vocabulary skills (Thal & Tobias, 1992). Additionally, the use of gestures to label objects is correlated with the rate of expressive vocabulary acquisition (Acredolo & Goodwyn, 1988). Similarly, advanced play skills are associated with advanced language skills. Using and moving objects in a functional and appropriate in play at 13 months of age are associated with standardized language scores at 22 months of age (Ungerer & Sigman, 1984). The simultaneous production of one-word utterances and gesture predicts the emergence of two-word utterances approximately two and a half months later (Iverson, Capirci, Volterra, & Goldin-Meadow, 2008). At approximately 18 months of age, the use of sequenced gestures in play is correlated with the emergence of word combinations (McCune-Nicolich, 1981) and the combined use of gesture with speech is associated with the transition from one-word to two-word utterances (Goldin-Meadow & Butcher, 2003; Özçaliskan & Goldin-Meadow, 2005).

One possible explanation for the correlation between gestures and language at specific periods of development is their reliance on shared underlying processes (Thal, 1991; Thal & Tobias, 1994) such as information processing skills or working memory (Thal, 1991). For example, researchers have proposed that the ability to relate two separate actions is an essential skill for both sequencing actions in play and combining words during verbal communication (Fenson & Ramsay, 1980). Developmental gains in a cognitive process may be similarly associated with simultaneous gains in language and speech motor skills.

1.2 Language and non-symbolic motor acts

These prior investigations on early gestures and symbolic play demonstrate developmental interactions among skills in multiple domains including language, cognition, and symbolic motor acts. Additional evidence of across-domain links in early development comes from studies on the co-morbidity of impairments in language and motor function (i.e., non-symbolic motor performance). Children with specific language impairments have been shown to have fine and gross motor skill deficits. For example, children with delayed language have been shown to have difficulty with hopping (Stark & Tallal, 1981) and balance (Powell & Bishop, 1992). Children with language impairments also have more difficulty performing nonspeech oral motor tasks (Alcock, 2006; Stark & Blackwell, 1997), suggesting that these oral motor skills may be one of many skills needed for later language development (Alcock, 2006).

1.3 Language and speech sound acquisition

Developmental dependences between speech motor control and language ability may, in part, account for the co-morbidity between expressive language and speech disorders. In comparison to their typically-developing peers, toddlers with expressive language delay tend to have delayed articulatory development (Whitehurst, Smith, Fischel, Arnold, & Lonigan, 1991), more variable lip and jaw movements during speech (Goffman, 1999), restricted consonantal inventory, limited syllable shapes (Carson, Klee, Carson, & Hime, 2003; Paul, & Jennings, 1992; Rescorla & Ratner, 1992; Williams & Elbert, 2003), and limited phonological skills (Williams & Elbert, 2003). In addition, young children with impoverished phonetic repertoires tend also to have limited vocabularies (Stoel-Gammon, 1991). Conversely, children who acquire words at earlier ages tend to have larger vocabulary size and phonetic inventory at 24 months than do children who acquire words later (Stoel-Gammon, 1991). In comparison to age-matched peers, two year-olds with advanced lexicon sizes have fewer articulation errors, cluster reductions, and final consonant deletions (Smith, MacGregor, & Demille, 2006).

In addition, children's early vocalizations patterns have been shown to predict their later developing language skills. The number of different syllables during babbling and a preference for consonant use are positively correlated with language scores five months later for toddlers with expressive language delay (Whitehurst et al., 1991). Children with a higher number of vocalizations containing consonants at 9 months of age had advanced phonology at the age of 3 years compared to children who had fewer consonants at 9 months (Vihman & Greenlee, 1987).

1.4 Speech kinematics, language, and cognition

Although the relevant literature on speech motor development is sparse, several findings support the suggestions that the development of speech motor control may be spurred by increasing demands imposed by emerging phonologic, linguistic, and cognitive abilities. For example, prominent changes in lip and jaw movements have been observed at two-years of age, which is typically the age at which children acquire new sounds into their phonological systems and experience an exponential growth in vocabulary. Specifically, to produce oral closure during bilabial consonants, two-year-old children shift from an articulatory strategy that primarily relies on jaw movement to one that includes a contribution from the lips (Green, Moore, Higashikawa, & Steeve, 2000). During this transition, the children also exhibited a transient increase in the variability of jaw movement patterns (Green, Moore, & Reilly, 2002). Green and colleagues (2002) speculated that the transient spike in variability was spurred by growing demands on the speech motor system imposed by emerging linguistic and cognitive abilities.

Studies demonstrating shifts in articulatory control in response to experimentally controlled levels of speaking task difficulty provide additional evidence of interactions between the speech motor system and other domains. For example, studies on adult articulatory performance have demonstrated that speech performance variability decreases as tasks become less syntactically complex (Kleinow & Smith, 2006; Walsh & Smith, 2002) and cognitively demanding (Dromey & Bates, 2005). Variability in lip and jaw movement patterns have similarly been shown to decrease with age (Goffman & Smith, 1999; Smith & Zelaznik, 2004). Thus, developmental gains in cognitive and linguistic processing may have a stabilizing effect on articulatory movements with age.

Research has also shown that in adults and children the speed of articulator movements increase as speaking tasks become more linguistically and cognitively demanding (Nip & Green, in preparation). When interpreted with respect to the developing child, these findings suggest that articulatory movements will become faster, particularly during the first two years of life when children are rapidly acquiring new language and cognitive skills. Indeed, the effects of task on articulatory speed may underlie some of age-related gains in articulatory speed that have been reported previously (Goffman & Smith, 1999; Smith & Gartenburg, 1984; Smith & Zelaznik, 2004).

1.5 Purpose

The primary goal of this study is to determine the association between orofacial movement speed and standardized measures of cognitive and language development during the early stages of communication development. This exploratory study is intended to provide future directions for studies addressing the interactions among multiple developmental domains during early speech development in typically-developing and speech-delayed children.

2. Methods

2.1 Participants

Participants were infants from monolingual English-speaking families in the Midwest. The families were recruited for a larger longitudinal study through flyers posted in pediatrician offices and newspaper ads. The children were reported by parents to be born at term with no neurological, vision, hearing, or physical impairment. A total of 30 participants were recruited, however six participants did not complete the current study because the family moved (1 participant), were later diagnosed with developmental or speech delays (2 participants), or the families elected to end their involvement with the study (3 participants). A total of 24 children (11 males, 13 females) were studied every three months from 9 to 21 months of age for the current investigation.

2.2 Procedure

Each child was seen for two sessions at each age level. At the first session, a speech-language pathologist administered the Battelle Developmental Inventories, 2nd edition (Newborg, 2005). The BDI-2 is a developmental test that includes subtests in receptive and expressive communication skills, gross and fine motor skills, and cognitive subtests. Parents were also asked to complete the MacArthur Communication Developmental Inventories (Fenson et al., 1993). Hearing was screened using the AuDX (Biologic Systems, Ltd.), which tests otoacoustic emissions at 2, 3, 4, 5 kHz. On occasional data points, some infants did not pass the hearing screening. Typically, this was the result of the infant being fussy, vocalizing, or congested, situations in which reliable otoacoustic emission results cannot be obtained. We used the criteria that two consecutive “refer” readings would eliminate the child from the study; however, this did not occur with any of the infants.

Orofacial behaviors were captured using an eight-camera optical motion capture system (Motion Analysis, Ltd.) in a follow-up session approximately a week before or after the developmental screening. Fifteen reflective markers were placed on each infant’s face. Two markers were placed above each eyebrow. One marker was placed on the bridge of the nose and one on the nose tip. One marker was placed on the upper lip on the vermillion border, and one on the lower lip, directly below the upper lip marker. Markers were also placed at the corners of the mouth, at oral commissure. Three markers were placed on the jaw. One was placed at the center (mental protruberance) and one on each side a couple of centimeters to the left and right of the central jaw marker. Four markers were placed on a rigid head marker, which also housed a microphone that was used to record vocalizations and speech. The head marker was placed on the central forehead, with the top of the marker at the hairline. This head marker was later used to subtract head movement from the other markers during data analysis.

Kinematic data of the orofacial behaviors were captured at 120 frames per second. Audio was captured at 44.1 kHz, 16 bits. High-resolution digital video was also captured to assist in data parsing.

Children sat in a car seat that was secured to a chair. Each infant's primary caregiver, usually the mother, sat in front of the child. To sample orofacial movement during a wide variety of communication contexts, each data collection session consisted of several different conditions. At the beginning of each session, spontaneous interactions were captured between the child and parent. The parents were asked at that time to play with their child while the motion system was being calibrated. After a few minutes passed, the caregiver was given a set of toys and asked to take a few turns with the toy and then pause and wait to see what the child would do ("play" condition).

Three different sets of toys were eventually provided for each parent-child dyad. One set of toys were designed to elicit requesting, including toys in transparent containers, and toys with multiple parts (e.g., Mr. Potatohead with various body parts). The second set of toys was designed to elicit joint attention. These toys included picture books, and "surprise" bags (bags with various toys inside). The last set of toys encouraged social interaction. Toys in this set included pretend food, dolls, and pretend tools. On average, each bin of toys was used for approximately 4-5 minutes before being replaced by another. The length of each testing and motion capture session typically lasted up to 45 minutes, depending on the child's mood.

2.3 Data Parsing and Transcription

Trained laboratory assistants identified all speech movements within each motion capture session, using the digital video recording to guide their transcriptions. Speech movements were defined as orofacial movements that were accompanied by vocalizations. Movements were considered separate epochs if the transcriber did not observe movement on the video for 500 ms or longer. The final data corpus included spontaneous movements and vocalizations such as babbles, words, and phrases. Each speech movement was parsed into a separate file and the markers were then labeled (e.g., lower lip, upper lip, etc.). All movement traces were then low-passed filtered (F_{LP} = 10 Hz).

2.4 Measures

2.4.1 Cognitive, language, motor, self-care skills development—The Battelle Developmental Inventories II (BDI-2, Newborg, 2005), a norm-referenced assessment battery of developmental skills was given to assess general development of all the children at each age. The BDI-2 examines skills in personal-social, communication, motor, cognitive and adaptive (ability to integrate skills in the other four domains for daily-living skills) domains. The age-equivalent scores from the receptive communication, expressive communication, attention and memory, and perception and concepts subtests were included in the analyses.

2.4.2 Vocabulary—The MacArthur Communication Developmental Inventories (CDI, Fenson et al., 1993) was used to obtain detailed information regarding each child's receptive and expressive vocabulary and early communicative gesture competence. This test is a norm-referenced parent report that examines receptive and expressive vocabulary in children from 9 to 15 months using the Words and Gestures form and 16 to 30 months of age using the Words and Sentences form. This assessment provided information on words understood, phrases understood, total gestures produced from the Words and Gestures form, and words produced from both forms.

Because each participant was seen at 9, 12, 15, 18 and 21 months of age, data was collected using the Words and Gestures form at the ages of 9, 12, and 15 months and then the Words and Sentences form at the ages of 18 and 21 months. Scores were only obtained up to 15 months for the following measures, which were only on the Words and Gestures form not on the Words and Sentences form: the number of phrases understood, the number of words understood, and the total number of gestures produced. Consequently, only the number of words, which was on both forms, was reported from 9 to 21 months.

2.4.3 Quantitative analyses of the three-dimensional kinematic traces—Custom MATLAB (Mathworks, Ltd.) algorithms were used to obtain movement characteristics of a given utterance. To obtain facial movements that were independent from those of the head, the movement of the lips and jaw were expressed as the 3D Euclidean distance from the right top head marker. Movement of the lower lip marker resulted from the net movement of the lower lip and jaw. Jaw movement was obtained from the markers that were left or right of the center of the jaw in order to minimize error in fleshpoint tracking of the mandible (Green, Wilson, Wang, & Moore, 2007). Periods at the beginning and end of each epoch with no movement in all three markers (lower lip, upper lip, and jaw) were discarded before obtaining specific kinematic measures. For each epoch and marker, the peak opening and closing speeds (mm/s) were recorded. The range of movement (mm) for each marker, as determined between the distance between the maximum and minimum position of the marker from the head marker for a given movement epoch, was also obtained and represented how much a child moved an articulator during the epoch. The range of movement of a epoch was used as a proxy for movement space, which has been shown to change over the first year of life (Green & Wilson, 2006).

Peak speed of lip and jaw movement was used as an indicator of speech motor development in this study because prior research has shown that speed increases across development (Goffman & Smith, 1999; Smith & Gartenburg, 1984; Smith & Zelaznik, 2004) and because it can easily be derived from a wide variety of utterances.

2.5 Statistical Analyses

To screen for outliers, the values for each kinematic variable (e.g., closing speed) across all sessions were examined to determine if the observations fell within the normal distribution. Least-square means were calculated by age and orofacial behavior. Residuals were taken for each observation. The residuals were then fit in a normal curve and observations that fell outside of the normal curve were removed. A total of 41 observations out of 8872 movement epochs were removed using this procedure. The means of each session for each participant were then calculated.

The mean opening and closing speeds and ranges of movement were taken for the upper lip, lower lip, and jaw markers for each participant at each age level. The scores from the BDI-2 and the CDI were correlated with each kinematic measure. Because the data were collected longitudinally over a year, partial correlations controlling all variables for age were also conducted. Previous studies (Smith & Zelaznik, 2004) have indicated that articulatory movement speeds increase with age. Similarly, the scores from the standardized tests would also be expected to increase with age. If correlations between the two sets of variable were found, overall maturation could be the causal variable. Partial correlations would help to determine if age might be a “third variable” or the underlying reason for significant correlations between standardized test scores and the kinematic measures. We hypothesized that there will be some significant positive, partial correlations between kinematic characteristics of speech, specifically speed of movement, and language and cognition scores.

3. Results

Table 1 presents the means and standard errors for the mean of opening and closing speeds and range of motions for the jaw, lower lip, and upper lip markers at each age level. Table 2 presents the means and standard deviations of the age-equivalent scores for the receptive communication, expressive communication, attention and memory, and perception and concept subtests of the BDI-2 as well as the number of phrases understood, number of words understood, number of words produced, and the number of gestures produced of the CDI. Table 3 presents the correlation of sex with each of the kinematic variables. Overall the female infants had faster speeds and range of movements than the male infants.

3.1 BDI Scores

Table 4 presents the correlation between each kinematic variable and sex and the age equivalent scores for the receptive communication, expressive communication, attention and memory, and perception and concepts subtests of the *BDI-2*.

The receptive communication subtest positively correlated with many of the kinematic variables for the jaw, lower lip, and upper lip. The age-equivalent score for receptive communication correlated with the opening speed and closing speed of the jaw and the upper lip. Receptive communication was significantly correlated with lower lip opening speed, closing speed, and range of movement.

The age equivalent scores of the *BDI-2* expressive communication subtest were significantly associated with mandibular opening speed, and closing speed but not with range of movement. All of the kinematic variables of the lower lip and upper lip, including opening speed, closing speed, and range of movement were significantly correlated with expressive communication.

Jaw opening and closing speed measures were significantly correlated with the attention and memory subtest of the *BDI-2*. For the lower lip, opening speed, closing speed, and range of movement were all significantly correlated with the attention and memory subtest. None of the kinematic variables for the upper lip were significantly correlated with attention and memory.

The perception and concepts subtest of the *BDI-2* was associated with some of the kinematic variables. The age equivalent scores of the perception and concepts were significantly correlated with mandibular opening speed and closing speed. All of the lower lip kinematic variables were significantly correlated with perception and memory; however, none of the upper lip kinematic variables were significantly correlated with the attention and memory subtest.

Sex was positively correlated with expressive communication and attention and memory subtests. Specifically, female infants had higher expressive communication and attention and memory scores than the male infants.

Partial correlations, controlling for the effect of age, between sex, the kinematic, BDI-2, and the CDI variables were also calculated. Aside from a positive correlation ($r = .32$, $p = .04$) with upper lip opening speed, sex was not shown to be correlated with any of the variables. To reduce collinearity, sex was removed from the calculation of partial correlations between the kinematic, BDI-2, and CDI variables. The partial correlations, with sex removed as a variable, between the kinematic variables and the BDI-2 are shown in Table 5. Receptive communication was partially correlated with lower lip closing speed and range of movement. Expressive communication was only significantly correlated with lower lip closing speed after controlling for the effect of age. Attention and memory were significantly partially correlated with mandibular closing speed, and significantly negatively correlated with upper lip range of movement. Finally, the perception and concepts subtest was found to have a significant association with jaw opening speed and range of movement.

3.2 CDI Scores

Table 6 presents the correlations between each kinematic variable, sex, and results from the number of phrases understood (Words and Gestures form), number of word understood (Words and Gestures form), number of words produced (Words and Gestures and Words and Sentences forms), and total number of gestures produced (Words and Gestures form) from the *CDI*.

The number of phrases understood correlated with jaw and lower lip opening and closing speeds, and lower lip range of movement. The number of words understood was positively correlated only with lower lip kinematic variables, including opening and closing speeds and range of movement. The number of words produced was significantly correlated with jaw and lower lip opening speeds, closing speeds, and ranges of movement. For the upper lip, only the correlation between maximum velocity and number of words was significant ($r = .21$, $p = .047$).

The number of gestures produced was significantly correlated with mandibular opening and closing speeds. The number of gestures was significantly correlated with lower lip opening speed, closing speed, and range of movement. Significant correlations of number of words were found with the upper lip closing speed and opening speed.

Finally, sex was shown only to be correlated with the number of words produced. Female participants generally produced more words than the male participants.

To control for the effect of age, partial correlations were also conducted as described above. The partial correlations, with sex removed as a variable, between the kinematic measures and the CDI scores are presented in Table 7. The number of phrases understood and the number of words understood were significantly correlated with lower lip opening speed after controlling for the effect of age. The number of words produced had significant partial correlations with the jaw closing speed, and the upper lip opening and closing speeds. The number of gestures was significantly correlated with all the lower and upper lip kinematic variables after controlling for the effect of age.

4. Discussion

In this longitudinal study, developmental changes in orofacial movement speeds were correlated with developmental gains in language and cognitive skill; some of these correlations remained even after the variables were controlled for age. Because the current findings were only based on correlation analyses, future work is required to identify the causal relations among changes across domains. Although speculative, several plausible mechanisms could account for the observed association between the development of articulatory movement speeds and cognitive and language skills. The observed associations are consistent with theories of communicative development that posit across domain interactions (Smith & Goffman, 2004; Thelen, 1995) and potentially shared underlying processes (Thal, 1991).

4.1 Sex Effects

Sex was correlated with some of the CDI, BDI, and kinematic variables. Specifically, the total number of words differed between male and female participants in the CDI, similar to previous findings (Bavin et al., 2008; Dale, Bates, Reznick, & Morriset, 1989). Previous studies have also identified sex differences in kinematic variables at some ages. For instance, between 4 and 5 years of age, boys exhibit greater variability than girls in the vertical opening of the lips during speech (Smith & Zelaznik, 2004). However in the present study, the associations between sex and all variables, except for upper lip opening speed, were no longer present after age was controlled for.

4.2 Shared Underlying Processes

One potential reason for the association between kinematic measures and cognitive and language test scores is that these skills rely on the same underlying processes. Researchers have proposed that gestures are correlated with specific cognitive skills at specific points in development because both tap into the same underlying processes (Thal, 1991). In the current study, the increased memory sub-test of the BDI-2 was associated with faster jaw speeds and smaller upper lip range of movement, even controlling for age. Working memory has been proposed as an underlying process that allows a child to make gains in language and gesture (Thal, 1991). Specifically, the phonological loop of working memory may assist in maintaining auditory input and planning speech movements for novel words (Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1990). Gains in working memory capacity may allow for more efficient speech motor planning thereby affecting the speed at which phonemes in babbling and words are produced, resulting in faster movement speeds and smaller range of movements.

4.3 Embodied Cognition

Several of the current observations were consistent with predictions made by the theory of embodied cognition. This theory posits that cognitive concepts are developed due to the constraints of our physical bodies, environment, and sensorimotor skills (Iverson & Thelen, 2006; Thelen, Schöner, Scheier, & Smith, 2001). Infants' actions are considered vital in shaping abstract, cognitive concepts (Thelen, 1995; von Hofsten, 2007). Infants are born with an awareness of their bodies due to prenatal spontaneous movements and this awareness of their physical capabilities may explain some of infants' early skills (Gallagher, 2005; Green & Wilson, 2006). For instance, Gallagher (2005) suggests that neonates' prenatal spontaneous movements of their facial structures provide them with an understanding of the capacity of facial movements by the time they are born. Gallagher (2005) argues that this understanding is the reason neonates are visually biased to human faces. The resulting awareness of their capacities and the bias to faces is what allows neonates to perceive and consequently imitate facial expressions moments after birth (Gallagher, 2005).

Conceivably, infants with more experience with their bodies through spontaneous motility, and thereby a greater understanding of their physical capacities and capabilities, may have a greater understanding of the world around them. The association seen in this study between faster jaw opening speeds and the perception and concepts subtest may reflect the role of embodied cognition in development. Speech movement speeds generally increase with age (Nip & Green, 2006; Smith & Zelaznik, 2004) and faster articulatory speeds may indicate a more mature speech motor system and greater experience with the physical body. This increased awareness of the body, including the articulators, may allow an infant to more readily acquire cognitive concepts that form the basis of early communication.

4.4 Bidirectional relations between speech motor and language skills

The associations found between cognition, language, and speech motor performance are consistent with the results of previous studies demonstrating the variable influences of cognitive and linguistic processing demands on speech motor planning and programming. For example, the variability of speech movement patterns has been observed to increase as utterances become increasingly more complex linguistically (Dromey & Bates, 2005; Kleinow & Smith, 2006; Maner, Smith, & Grayson, 2000). The variability of speech movement patterns also increases during the performance of concurrent cognitive task, such as mental arithmetic (Dromey & Benson, 2003). In addition, task demands have been shown to influence articulatory movement speed in older children and adults (Nip & Green, 2006) and during early speech development (Nip, Green, & Marx, 2009). For instance, articulatory movements produced during words or babbling are significantly faster than during silent spontaneous movements (Nip, Green, & Marx, 2009). Additional studies are needed to better understand the influence of cognition and language formulation on the development of early speech motor performance and whether this influence changes as children become older.

Models of communication development also need to consider the influence of speech motor development on phonologic and expressive language development. Green and colleagues (2002) found that during the first two years of life, lower lip movements were not independent of the jaw. This potential constraint on independent lower lip movement may explain why labiodental fricatives tend to not appear earlier than two years of age (Green et al., 2002). The constraints on speech motor skills may be one limiting factor affecting the acquisition of speech sounds. A toddler's phonetic repertoire may, in turn, limit the rate of new word acquisition as toddlers tend to produce words that contain sounds in their existing phonetic repertoire (de Boysson-Bardies, Sagart & Bacri, 1984; Locke, 1989; Oller, Wieman, Doyle & Ross, 1976; Stoel-Gammon, 1985; Vihman, 1986). This relation between phonetic repertoire and lexicon size may account for the current finding that the number of words and the number of gestures is positively correlated with every kinematic variable in the current study. A larger phonetic inventory may result not only in more possible words an infant can produce but also more mature speech movement, such as increased range of movement and faster speed (Nip, Green, & Marx, 2009).

Recently, Green and Nip (2010) proposed a conceptual framework for examining the interaction between the development of speech motor control and other domains. They broadly characterized the factors that influence the developmental course of speech as either *catalysts* or *functional constraints*. Catalysts are factors that ultimately accelerate speech development and functional constraints are factors that limit speech motor control in early development (Green & Nip, 2010). Catalysts to speech motor development represent factors that pressure the speech system to adapt to newly emerging communication demands. Conceivably, in the current study, the observed correlation between articulatory speed, cognitive, and language skills may reflect the catalyzing effects of emerging demands imposed by increasing cognitive and linguistic abilities (i.e., production of longer and more complex utterances and acquisition of new words) on emergent speech motor skills. Support for this assertion is provided by a recent finding that the speed of lip and jaw movements increase from 9 to 15 months, when children are beginning to use first words (Nip, Green, & Marx, 2009). The association of cognition, language, and articulatory speed appears to be present throughout development. Speaking tasks involving greater cognitive and linguistic processing needs are associated with faster articulatory speeds in children and adults (Nip & Green, 2006). Further understanding of how different skills and domains may act as catalysts or functional constraints during speech development is essential for advancing theories of speech and language development and for improving the early identification of children at risk of speech delays at earlier ages.

4.5 Conclusions

This exploratory study identified relations between kinematic variables and standardized measure of language and cognitive skills. Of course, additional work is needed to determine the causal relations and to explore potential implications for understanding the mechanisms underlying communication impairments. The current investigation used subtests from the BDI-2, a tool that is meant to provide a global snapshot of a child's development. In the future, more sensitive measures of language and cognitive skills should be used to determine the relations between specific aspects of language and cognition with movement characteristics. Future work is also needed to identify which specific skills, such as attention, working memory, syntactic skills, and language comprehension, act as a catalyst or functional constraint on speech motor development. In addition, longitudinal studies utilizing structural equation modeling or multilevel modeling are needed across a longer period of development to determine if the strength and direction of the observed relations remain static across development or change at varying points of development. Eventually, a better understanding of the relations of cognition, language, and speech motor development may allow for earlier identification of children at risk of developing later speech and language delays.

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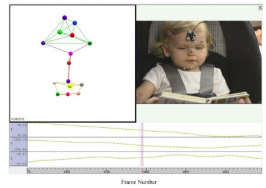

Figure 1.

Marker placements used to record upper lip, lower lip, and jaw movements (right pane), 3-dimensional model of the markers (left pane), and movement trace of the lower lip (bottom pane). Originally published in Nip, Green, and Marx, (2009)

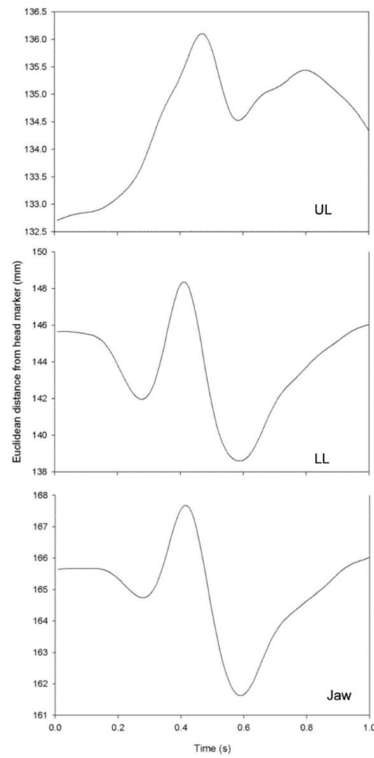

Figure 2.
Example of upper lip (top panel), lower lip (middle panel), and jaw (bottom panel) of a 21 month-old saying the word "grape." Euclidean distance (mm) from the head marker is on the vertical axis with time (s) on horizontal axis. Originally published in Nip, Green, and Marx (2009).

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Table 1

Means and standard errors of the mean for the closing and opening speeds and ranges of movements for the upper lip, lower lip, and jaw at each age level

	Age				
	9 months	**12 months**	**15 months**	**18 months**	**21 months**
Jaw					
N	21	22	18	22	17
Cl. Speed	28.66 (1.63)	32.59 (2.65)	41.05 (3.92)	39.02 (2.58)	40.07 (2.81)
Op Speed	25.46 (1.14)	29.90 (3.17)	36.64 (4.39)	34.85 (2.66)	36.41 (2.25)
R.O.M.	5.99 (.38)	5.87 (.45)	6.64 (.58)	6.20 (.34)	6.47 (.35)
Lower Lip					
N	20	20	15	12	11
Cl Speed	37.02 (2.93)	52.39 (4.62)	57.83 (6.37)	76.97 (9.53)	67.69 (8.24)
Op Speed	36.30 (2.52)	45.98 (4.81)	52.16 (7.05)	58.89 (8.91)	52.28 (7.38)
R.O.M.	7.74 (.61)	8.73 (.71)	8.75 (.71)	11.07 (1.03)	10.21 (.95)
Upper Lip					
N	21	21	18	20	16
Cl Speed	12.53 (.77)	12.40 (1.20)	13.83 (.93)	15.57 (1.45)	15.56 (.94)
Op Speed	15.39 (.96)	13.65 (1.22)	16.50 (1.15)	18.07 (1.42)	17.83 (1.16)
R.O.M.	2.87 (.20)	2.51 (.21)	2.56 (.13)	3.09 (.19)	3.42 (.22)

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Table 2

Means and standard deviations of the BDI and CDI subtests at each age level

	Age				
	9 months	12 months	15 months	18 months	21 months
BDI					
N	22	22	23	22	20
Rec.Comm.	6.36 (2.89)	11.82 (2.97)	16.09 (3.72)	21.55 (4.03)	25.45 (3.85)
Exp. Comm	8.23 (1.63)	12.38 (2.01)	16.00 (3.32)	20.18 (4.68)	26.00 (5.88)
Att/Mem	9.59 (2.94)	14.38 (3.06)	17.52 (2.84)	18.77 (2.31)	21.45 (4.09)
Per/Conc.	8.86 (1.96)	11.29 (2.10)	14.13 (3.14)	17.64 (2.75)	21.85 (4.02)
CDI					
N	23	21	20	20	19
# Phr Und	5.04 (4.58)	12.30 (5.87)	20.60 (4.63)		
# Wds Und	14.39 (20.00)	51.05 (47.87)	124.25 (76.50)		
# Wds Prod	1.26 (1.86)	6.00 (11.15)	27.50 (34.62)	103.95 (107.74)	187.00 (125.86)
# Gest Prod	8.36 (6.35)	21.29 (8.12)	35.85 (10.03)		

Table 3

Correlations between kinematic variables and sex

Variable	Sex
Jaw Opening Speed	.28*
Jaw Closing Speed	.32**
Jaw R.O.M.	.24*
LL Opening Speed	.34*
LL Closing Speed	.31*
LL R.O.M.	.34*
UL Opening Speed	.14
UL Closing Speed	.24*
UL R.O.M.	.17

LL = lower lip, UL = upper lip, R.O.M. = range of movement

Positive correlations associated with higher values for female participants

* $p < .05$

** $p < .001$

Table 4

Correlations between kinematic variables and age-equivalent scores of BDI-2 subtests

Variable	Receptive Communication	Expressive Communication	Attention & Memory	Perception & Concepts
Sex	.09	.20*	.21*	.11
Jaw Opening Speed	.29*	.30*	.30*	.34**
Jaw Closing Speed	.37**	.36**	.39**	.35**
Jaw R.O.M.	.10	.13	.11	.19
LL Opening Speed	.31*	.30*	.29*	.28*
LL Closing Speed	.51**	.54**	.45**	.41**
LL R.O.M.	.35*	.41**	.26*	.37*
UL Opening Speed	.24*	.24*	.13	.15
UL Closing Speed	.24*	.22*	.17	.19
UL R.O.M.	.18	.21*	.05	.18

LL = lower lip, UL = upper lip, R.O.M. = range of movement

Positive correlations associated with higher values for female participants

* $p < .05$

** $p < .001$

Table 5

Partial Correlations between kinematic variables and age-equivalent scores of BDI-2 subtests

Variable	Receptive Communication	Expressive Communication	Attention & Memory	Perception & Concepts
Jaw Opening Speed	.12	.15	.15	.22*
Jaw Closing Speed	.19	.17	.24*	.16
Jaw R.O.M.	.06	.12	.06	.23*
LL Opening Speed	.21	.16	.15	.12
LL Closing Speed	.28*	.29*	.14	.02
LL R.O.M.	.24*	.32	.04	.21
UL Closing Speed	−03	−.02	.04	.04
UL Opening Speed	.10	.09	−.07	−.07
UL R.O.M.	−.07	.02	−.22*	−.04

LL = lower lip, UL = upper lip, R.O.M. = range of movement

* $p < .05$

** $p < .001$

Table 6

Correlations between kinematic variables and scores of CDI subtests

Variable	# Phrases Understood	# Words Understood	# Words Produced	# Gestures Produced
Sex	.001	.07	.22*	.10
Jaw Opening Speed	.31*	.16	.42**	.30*
Jaw Closing Speed	.33*	.27*	.41**	.38*
Jaw R.O.M.	.10	.03	.26*	.16
LL Opening Speed	.54**	.47**	.29*	.54**
LL Closing Speed	.46**	.46**	.46**	.58**
LL R.O.M.	.31*	.30*	.33*	.45*
UL Opening Speed	.16	.25	.25*	.32*
UL Closing Speed	.16	.22	.23*	.29*
UL R.O.M.	.004	.04	.23*	.11

LL = lower lip, UL = upper lip, R.O.M. = range of movement

Positive correlations associated with higher values for female participants

* $p < .05$

** $p < .001$

Table 7

Partial correlations between kinematic variables and scores of CDI subtests

Variable	# Phrases Understood	# Words Understood	# Words Produced	# Gestures Produced
Jaw Opening Speed	.08	−.07	.12	.07
Jaw Closing Speed	.02	.00	.17	.09
Jaw R.O.M.	.03	−.09	.07	.15
LL Opening Speed	.41*	.32*	.18	.42*
LL Closing Speed	.19	.21	.10	.38*
LL R.O.M.	.23	.21	.12	.48**
UL Closing Speed	.08	.06	.17	.25
UL Opening Speed	.14	.14	.19	.37*
UL R.O.M.	.21	.11	.18	.38*

LL = lower lip, UL = upper lip, R.O.M. = range of movement

* $p < .05$

** $p < .001$