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Longitudinal development of speech motor control: Motor and linguistic factors

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When learning to talk, children progress from the unrefined articulator movements produced during babble to the highly controlled and rapid movements characteristic of mature speech. How children acquire the motor skills for speech and other complex movements remains poorly understood. In 1967, the motor theorist Bernstein posited that one essential process in the development of all motor skills is learning to manage and constrain the degrees of freedom. This simple but profound formulation has had a major influence on how scientists and clinicians conceptualize motor development. When applied to speech motor development, it focuses research on testing hypotheses about how oral movements progress from biologic- to goal-driven actions that are optimized for communication efficiency. One such hypothesis, which is tested in the current study, is that children constrain (or eliminate) oral movements that are extraneous to speech output, while reinforcing and retaining movements that engender desired speech targets.

One fundamental motor skill for speech is the ability to form a variety of lip shapes for vowels and consonants. Lip shape is determined by the combined movements of the upper lip, lower lip, and jaw. Most vowel contrasts in English can be approximated by modeling two components (Fromkin, 1964): vertical opening and horizontal spread. Studies of lip movements have revealed that, during the production of English vowels, lip shape is largely driven by the vertical opening (Fromkin, 1964; Green, Nip, Wilson, Mefferd, & Yunusova, 2010). Of course, horizontal spreading and rounding is also prominent for a small number of vowels (Fromkin, 1964; Stevens, 2000) and consonants (e.g., /w/; Chomsky & Halle, 1968; Stevens, 2000). When applied to the development of lip shape control for speech, Bernstein's theory of motor development predicts that the contribution of the vertical opening will increase while that of the horizontal spread will decrease.

Because vertical opening is a highly controlled aspect of lip shape in mature talkers, we sought to determine how the disorganized lip movements of preverbal children (Green, Moore, Steeve, & Reilly, 2002) progress into the tightly constrained and organized lip configurations that characterize mature speech. Specifically, we were interested in understanding the development of lip shape in the context of changes to speech and language development, because speech motor development is thought to be mediated by these factors. For instance, the constraint and catalyst theory of speech motor development (Green & Nip, 2010) specifies that early speech sound inventories are heavily constrained by

anatomic and physiologic properties of the oromotor system (Kent & Murray, 1982) but then rapid gains in expressive vocabulary serve as a catalyst for the acquisition of new speech sounds (e.g., Nip, Green, & Marx, 2011). In this model, speech motor development is expected to regress and progress depending on the destabilizing effects of emerging vocabulary on the emerging speech motor control. The relation between speech sound and vocabulary acquisition is also supported by the lexical restructuring model (Metsala & Walley, 1998), which states that words are initially stored as whole units and then later differentiated at the phonological level to keep newly acquired words distinct from similar items already stored in the lexicon. It, therefore, follows that a growing vocabulary will promote the acquisition of new speech sounds, changes that could initially disrupt - but eventually promote - developmental gains in speech motor control.

Empirical studies supporting the dynamic interactions between language and speech development have demonstrated, for example, that phonological ability is more highly related to vocabulary growth than to chronological age in typically developing and linguistically-advanced toddlers (Smith, MacGregor, & Demille, 2006). In contrast, preschool children with expressive language impairment show a high incidence of comorbid speech delay (e.g., Sices, Taylor, Freebairn, Hansen, & Lewis, 2007) and excessive lip and jaw variability (Goffman, 1999), further illustrating a link between speech motor control and language development.

Purpose of the current study

This longitudinal study investigated the development of speech motor control and its relation to communication development in typically developing children between 3 months and 5 years of age. Three-dimensional optical motion tracking was used to determine how children's control of lip shape changed over time by quantifying the relative contribution of vertical opening to lip area. We hypothesized that the contribution of the vertical opening would increase as a function of age and expressive communication gains but that its development would be nonmonotonic – specifically characterized by transient decreases associated with the rapid expansion in expressive vocabulary that typically occurs at 18 months of age (Fenson et al., 1994).

Methods

Participants

Thirty infants (15 males, 15 females) from Midwest monolingual English-speaking families were recruited to participate. Participants were tested every three months between 3 to 30 months and every 6 months from 36 to 60 months of age (i.e., 5 years old). Because expressive communication is known to advance rapidly prior to 36 months (e.g., Fenson et al., 1994), data collection sessions were scheduled every three months prior to age three and every six months thereafter. Two male participants eventually received a diagnosis of speech sound delay, and, as such, their data were excluded from the current report, resulting in data analysis on 28 participants. On average each participant completed 7 sessions (range 2–14) and each time point included an average of 14 participants ($SD = 5$).

All children were reported by parents to have a normal birth history with no evidence of hearing, vision, neurological, or cognitive impairment. At each visit, hearing was screened using otoacoustic emissions testing for the frequencies of 2, 3, 4, and 5 kHz at 20 dB (ASHA, 1997). All participants lived in Nebraska, in homes where American English with a standard Midwestern dialect was their first language. All participants identified their race as White; 26/28 identified their ethnicity as not Hispanic/Latino and 2 identified as Hispanic/Latino. The majority of families reported that the maternal level of education was college graduate or higher (20/28).

Procedures

Speech and language testing—Participants completed a variety communication testing throughout participation. The Battelle Developmental Inventory-2nd Edition (BDI; Newborg, 2005) was used to assess expressive communication across the age range. The Expressive Communication subtest assesses a child's production and use of sounds, words, gestures, and grammar, and was administered and scored by an experienced, licensed speech pathologist, according to standard procedures. The BDI manual reports high ($r = .90$) test-retest and inter-rater reliability.

Behavioral sampling—Infants were placed in a car seat that was secured to a dental chair and older children sat directly on the dental chair. Each participant's primary caregiver, usually the mother, sat facing the child. Although we did not require that the same caregiver participate in every session, this was typically the case. Each session sampled orofacial movement and speech production during play activities. Parents were provided with toys selected to encourage requesting (e.g., toys in transparent containers, or those with multiple parts, such as Mr. Potato Head), joint attention (e.g., picture books), and social interaction (e.g., dolls and pretend food). Because we were interested in understanding factors related to the coordinative shift from biologically-driven to speech-driven lip shape, we captured and analyzed a diverse variety of lip movements that included (a) spontaneous orofacial movements (Green & Wilson, 2006), (b) prelinguistic vocalizations (e.g., quasi-vowels, vowels, quasi-consonants, consonants, babble), and (c) words (e.g., spontaneous word production or repetition of real words, nonwords, and phrases such as "buy bobby a puppy"). For tokens that were elicited in imitation, a live model was provided by the caregiver or the experimenter. See Appendix A for a list of stimuli elicited in imitation.

Vegetative behaviors (e.g., hiccups, smiling, laughing, crying) were not analyzed (Green & Wilson, 2006; Nip, Green, & Marx, 2009). Productions were coded according to a previously reported protocol (Nip, Green, & Marx, 2009). Utterances that consisted of a vowel were coded as vocalizations. Utterances that contained an adult-like consonant but no apparent meaning were coded as babble. Utterances were coded as words if they contained an adult-like word form and limited speech errors. Specifically, if a word contained three or fewer phonemes, it could have a maximum of one speech error. If the word contained four or more phonemes, it was permitted to have up to two speech errors. Word attempts that did not meet these criteria were coded as possible words and included in analyses. Utterances containing two or more words were coded as phrases. Inter-rater reliability for coding of

productions was calculated on 10 randomly selected sessions and reached 89.4% agreement (Nip, Green, & Marx, 2009).

Productions were collected within a range of contexts that included: structured and unstructured play, and imitation and repetition of real words, nonwords, and utterances (e.g., buy bobby a puppy). Data collection sessions each lasted between 30 to 60 minutes. Spontaneous movements and prelinguistic utterances decreased with age, while words increased. The relative occurrence of each movement type produced at each age is displayed in Figure 1.

Kinematic testing—An optical-based, three-dimensional (3D) motion capture system (Motion Analysis, Ltd.) was used to record orofacial movements of participants during play. Lip and jaw movements were captured at 120 frames per second. Fifteen reflective markers were placed on the infant's face, lips, and jaw in the following configuration: one marker was attached above the crests of each eyebrow; one was attached to the bridge of the nose and one to the nose tip; one on the midline of the upper lip at the vermillion border and one on the midline of the lower lip directly below the upper lip marker; one on each of the two lip corners at the oral commissures; one on the midline of the jaw at the mental protuberance; and one on each side of the jaw about 2–3 cm to the left and right of the midline jaw marker. Figure 2 provides an illustration of marker placement. The head marker served as a reference for subtracting head movement from the facial markers. The precision of 3D optical movement tracking of the articulators is estimated to be better than 0.1 mm (Green & Nip, 2010).

A miniature condenser microphone was attached to a rigid head marker affixed to the forehead. Video and audio (44.1 kHz and 16 bits) signals were digitally recorded and used to aid in data parsing, transcription, and for additional analyses (e.g., acoustic).

Data processing and analysis—Research assistants parsed motion capture sessions to identify all periods (i.e., epochs) of orofacial movement. Continuous movement sequences were parsed into separate epochs that were separated by a 500 ms or longer interval of no lip movement (Nip, Green, & Marx, 2009). Custom MATLAB (Mathworks, Ltd.) algorithms were used to pre- and post-process movement data (Green, Wang, & Wilson, 2013). All movement traces were low-passed filtered ($F_{LP} = 10$ Hz) and, prior to analysis, the translation and rotation of head movements were removed from articulator movement signals. Time series were calculated for three different features of lip shape (shown on figure 2): (a) vertical opening (mm), which reflects the midsagittal vertical opening of the mouth, was calculated as the 3D Euclidean distance between the upper and lower lip markers; (b) lip spread (mm), which reflects that horizontal opening of the mouth, was calculated as the 3D Euclidean distance between the left and right corners of mouth at the oral commissures; and (c) lip area (mm^2), which was computed, frame-by-frame, as the area within a complex polygon (convex hull fit) that was bounded by the four lip markers (i.e., upper lip, lower lip, left and right corner at the oral commissures). The fit did not assume symmetry between the upper and lower lip, nor between the right and left corners of the mouth.

Pearson correlations were calculated between the vertical opening and lip area time series data to determine the extent that vertical opening accounted for the variance in lip area. This correlation coefficient was squared and is the dependent variable of interest and will be referred to as “lip shape verticality.” Because correlations are not affected by scale, the potential influence of anatomic growth on the association between vertical opening and lip area was minimized. The lip area variance that is not explained by vertical opening is largely accounted for by horizontal spread. Although spread was not tested as a dependent variable in this study, it is included in Figure 2 to illustrate the decreasing role that lip spread plays in driving lip shape during development.

Statistical analyses—Two linear mixed models using restricted maximum likelihood fit were applied to determine the effect of “age” (i.e., the fixed effect with 15 levels—one level for each age bin—3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 36, 42, 48, 54, 60 months) and “expressive communication” (BDI scaled score) on the dependent variable “lip shape verticality”, respectively. Because expressive communication is well-known to increase with age, we subtracted the age effect by using age-normalized scaled scores from the BDI as a predictor in the linear mixed model. “Participant identification number” was entered as the random effect for both models.

Results

The purpose of this study was to investigate the longitudinal development of lip shape control and its relation to communication development, in children between 3 to 60 months of age. We predicted that lip shape verticality would increase non-monotonically with age, and would relate to changes in expressive communication.

Lip shape verticality is predicted by age and expressive communication

Lip shape verticality as a function of age is displayed in Figure 3. The linear mixed models revealed that age, $F(14, 179) = 10.28, p < .001$, and expressive communication scaled scores, $F(1, 171) = 34.63, p < .001$, were significant predictors of lip shape verticality. In addition, visual inspection of the lip shape data revealed a transient decrease between 18 and 21 months of age that co-occurred with increased gains in expressive communication.

Lip shape verticality was measured on a variety of spontaneous and elicited productions and the proportion of elicited productions increased with age such that elicited productions accounted for 90% of responses at 60 months. See table 1 for the percentage of elicited productions at each age level. The speech stimuli that were used to elicit responses were intentionally loaded with sounds that elicited labial movement (i.e., bilabial and labiodentals phonemes). Because the number of these elicited productions was significantly greater in our older participants than in our younger participants, the observed changes in lip verticality with age could have been significantly influenced by differences in the proportion of production type (i.e., spontaneous vs elicited) across the age groups. Therefore, to determine the main effect of production type on verticality we conducted an ANOVA where each utterance was classified as either 1- spontaneous or 2- elicited (See Figure 4). Next, we conducted two post hoc mixed model analyses in which “age” and “production type” were regarded as fixed effects and “participant identification number” was

the random effect. Results of the ANOVA showed that, as expected, production type had a significant effect on lip shape verticality where elicited utterances were produced with more verticality than were the spontaneous movements, $F(1, 260) = 15.44, p < .001$. In addition, the age trend was statistically significant for both spontaneous, $F(14, 164) = 5.29, p < .001$, and elicited productions, $F(11, 84) = 10.60, p < .001$. A Pearson's product moment correlation revealed that the developmental trend in lip shape verticality was highly correlated between spontaneous and elicited productions, $r(10) = .82, p = .001$. Combined, these findings suggest that the developmental trend of growth in lip verticality was only minimally affected by type of production.

Discussion

This study documented the longitudinal development of lip shape control from 3 months to 5 years of age and how it relates to communication development. Lip movement data were collected from a variety of communication contexts and a similar pattern of lip shape development was observed across children. At the youngest ages, lip shape was primarily driven by horizontal spreading of the lips. As children aged, they converged on a pattern that was almost exclusively driven by vertical opening. We propose that this transition represents a process whereby young children minimize the aspects of mouth movements that are nonessential to sound production, such as horizontal spread.

The developmental gains in lip shape verticality appeared to correspond with three phases: prelinguistic/early speech, rapidly emerging linguistic, and linguistic/speech refinement. These phases are consistent with contemporary theories that emphasize bidirectional interactions between language and speech development (i.e., lexical restructuring model, Metsala & Walley, 1998; constraint and catalyst theory of speech motor development; Green & Nip, 2010).

Phases of lip shape development—Results revealed that lip shape control could be predicted by age and expressive communication and appeared to progress in three phases. During the first phase (3–15 months of age), children produced predominantly prelinguistic vocalizations and spontaneous oral movements. During this phase, the contribution of vertical opening to lip shape was minimal but stable, suggesting that the lip shape produced in infancy is primarily driven by horizontal spreading. The high proportion of spontaneous and prelinguistic movements during this phase suggests a period of exploration in which infants begin to learn about their system and start to develop mappings between articulatory configurations and acoustical outcomes (e.g., Guenther, 1995; Thelen, 1995).

During the second phase (15–21 months of age), the contribution of vertical opening to overall lip shape showed a transient increase at 18 months that was followed by a precipitous decline at 21 months. Consequently, participants evidenced less vertical opening at 21 months than they did at 15 months. The decline in lip shape verticality between 18–21 months could be related to the destabilizing effects of the rapid expansion in expressive vocabulary (Fenson et al., 1994) that is well known to occur at this age. That is, linguistic knowledge and intentional communication may exceed the functional capacity of the oromotor system during this period.

Children younger than 18 months age produced mostly prelinguistic vocalizations and spontaneous orofacial movements. Beginning at 18 months children began to produce a high percentage of words (45% of total movements) compared to prelinguistic productions. Children may therefore adapt to the oft-cited vocabulary burst that is characteristic of this age (Reznick & Goldfield, 1992) by altering their speech motor planning and execution processes to accommodate the rapidly expanding lexicon. The current data suggest that children seem to revert to an earlier horizontal lip shape pattern in response to the putative disruption imposed by rapid vocabulary expansion.

Regression to earlier motor patterns is not uncommon during development. When developing locomotion, infants often demonstrate a U-shaped developmental trend similar to the pattern we observed in lip shape development (Thelen, 1985). That is, although walking seems to emerge towards the end of the first year of life, locomotion is initially evident during early infancy as the newborn stepping response. This behavior, in which supported infants will place one foot in front of the other when their soles touch a flat surface, regresses at around 2 months due to changes in body mass and composition. Thelen (1985) suggests that walking and other skills require the “confluence and interaction of many developing components” and that these components may develop at different rates, such that an individual component may “facilitate, mask, or inhibit performance . . . and may be identified as *rate-limiting*” (p. 1498). In walking, anatomical changes are proposed to mask the stepping response during early infancy. We propose asynchronous development of expressive communication and speech motor control and that the surge in expressive communication temporarily disrupts or inhibits lip shape development.

The third phase (ages 21–60 months) was characterized by a slow, steady increase in vertical opening and continued improvements in expressive communication. By 30 months of age, words accounted for over 90% of total movements recorded. Previous work on speech sound acquisition shows that the greatest gains in speech sound accuracy occur between ages 3 and 4 years, followed by continued development through age 9 years (Smit, Hand, Freilinger, Bernthal, & Bird, 1990). During this phase, we propose that vocabulary growth works as a catalyst to promote increased articulatory accuracy and the predominance of the vertical lip opening pattern, an explanation that is supported by the lexical restructuring model (Metsala & Walley, 1998).

The lexical restructuring model (Metsala & Walley, 1998) posits that words are initially stored as whole units and later differentiated at a more fine-grained level as a result of the need to differentiate newly acquired words from known words. Continued tuning of the articulatory system may be a byproduct of an increasing need to keep words distinct in the rapidly growing lexicon. In support of this notion, previous research (Hogan, 2010) found that only young children with high vocabulary showed evidence of lexical restructuring (see also De Cara & Goswami, 2003). We could therefore predict that lexical restructuring serves to promote the learning of lip movements that engender speech sounds, while minimizing the occurrence of lip movements that do not facilitate speech sound accuracy or efficiency. This suggestion is supported by the observed increases in lip shape verticality between ages 3 and 4 years; and the known improvements in speech sound accuracy that occur during this phase (Smit et al., 1990). We also found that lip shape verticality continued to increase, such

that at age 5 years, 76% of the variance in lip shape area was accounted for by vertical opening. Although this high proportion of verticality may be similar to that of adults, gains in lip shape control may extend beyond the ages that were measured in the current study. Prior research shows a protracted time course for speech motor control (e.g., Goffman & Smith, 1999; Green, Moore, Higashikawa, & Steeve, 2000; Smith & Zelaznik, 2004). For example, the coordination of upper lip, lower lip, and jaw increases during the first few years of life, whereas refinement of these articulators continues beyond age 6 (Green et al., 2000). Likewise, lip shape variability (stability) does not achieve adult-like levels until after 14 years of age (Smith and Zelaznik, 2004). Although we found that significant gains in lip shape were made by age 5, the extant literature suggests that refinement of lip shape will likely continue in older children.

Limitations

Missing data—Although each age level included an average of 14 participants, two time points had fewer than 10 subjects: 21 months ($n = 7$) and 60 months ($n = 4$). Missing data at 21 months was due to 1- mistracking of the lower lip marker due to poor reflectivity caused by saliva saturation, 2- participants pulling off facial markers due to poor tolerance, and 3- occlusion of markers caused by a participant's hand or toy blocking the camera view.

Restricted range—Extant research reports that socio-economic status (SES) is highly correlated with vocabulary and language processing in children such that by 18 months a performance gap exists between groups of children that differ in SES (e.g., Fernald, Marchman, & Weisleder, 2013). In the current study, we observed that age-normalized expressive communication scaled scores increased linearly with age, which was an unexpected finding. Future research should investigate lip shape development in groups of participants stratified for SES.

Conclusion and future directions

Lip shape verticality increased throughout toddlerhood and emerged as a function of age and communication development. The growth of lip shape verticality was nonmonotonic, and appeared to be characterized by three phases: (a) a period of minimal change (Phase 1) (b) a rapid increase followed by a precipitous decrease at 18 months that co-occurred with the well-established vocabulary burst (Phase 2), and (c) a steady increase that co-occurred with the expected gains in speech sound accuracy and ongoing vocabulary expansion (Phase 3). These transient regressions and progressions in speech motor performance are predicted by the constraint and catalyst theory of speech motor development (Green & Nip, 2010), and the lexical restructuring model (Metsala & Walley, 1998).

Future work is required to further explore the apparent inverse relation observed between the speech motor and linguistic systems during the vocabulary burst. In addition, research is needed to determine the functional significance of the observed changes in lip shape control for identifying children at risk for speech and language impairments. The observation that participants eventually converged on the vertical lip opening pattern motivates additional research that to determine the diagnostic sensitivity of this early index of speech motor development for identifying children at risk for abnormal speech and oromotor development.

Given the apparent bidirectional relation we observed between speech motor and communication development, we may expect protracted lip shape verticality development in children with speech and language disorders. Previous research (Alcock, 2006), for example, showed a relation between vocabulary and complex oral motor movements in children between 21 to 24 months where children who had poor oral movement ability had poor language skills whereas those with good oral movement abilities evidenced a broad range of language skills. Together with the current findings, this study motivates future research on lip shape verticality in children at risk for speech and language disorders.

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Appendix A. List of stimuli that were elicited in imitation

/aba/	/afa/	/ama/	/apa/	/ava/	/awa/
/bami/	/beimi/	/bimi/	/bumi/		
bats	beets	boots			
ba	baba				
ma	mama				
pa	papa				
Bob	Bobby	Buy bobby a puppy

Figure 1.

Stacked column graph showing the relative occurrence of each movement type as a function of age. Children 15 months and younger typically produced prelinguistic vocalizations and spontaneous orofacial movements, whereas older children produced an increasingly larger proportion of words.

Figure 2.

Facial marker configuration and kinematic lip shape time series data. Figure 2a shows data from a participant at 3 months age and 2b shows data for the same child at 54 months. Note that at 3 months age, horizontal spread and vertical opening both drive lip area as this child makes prelinguistic spontaneous movements. At 54 months age, lip area is driven primarily by vertical opening as this child produces the phrase “buy Bobby a puppy.”

Figure 3.

Lip shape verticality, horizontal spread, and expressive communication scaled scores (BDI) presented by age. Verticality is the correlation between vertical opening and lip area time series data, where horizontal spread is the correlation between horizontal opening and lip area. Error bars represent standard error of the mean across subjects.

Figure 4.

Lip shape verticality for spontaneous and elicited productions presented across age levels. Mixed model analyses showed that age significantly predicted lip shape verticality for spontaneous and elicited productions.

Table 1

Percent elicited productions and average verticality (r^2) for spontaneous and elicited movements at each age level.

Lip shape verticality (r^2)				
Age (mo)	n	Elicited	Spontaneous	Percent Elicited Productions
03	20		0.39	0
06	22		0.40	0
09	20		0.47	0
12	19		0.47	0
15	14	0.38	0.41	13
18	9	0.66	0.58	20
21	7	0.29	0.40	6
24	11	0.49	0.44	23
27	16	0.48	0.49	23
30	14	0.56	0.50	20
36	12	0.71	0.54	36
42	12	0.69	0.58	41
48	11	0.79	0.64	78
54	10	0.76	0.72	75
60	4	0.80	0.61	91