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SHORT REPORT

Infant vocal productions coincide with body movements

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Abstract

Producing recognizable words is a difficult motor task; a one-syllable word can require the coordination of over 80 muscles. Thus, it is not surprising that the development of word productions in infancy lags considerably behind receptive language and is a known limiting factor in language development. A large literature has focused on the vocal apparatus, its articulators, and language development. There has been limited study of the relations between non-speech motor skills and the quality of early speech productions. Here we present evidence that the spontaneous vocalizations of 9- to 24-month-old infants recruit extraneous, synergistic co-activations of hand and head movements and that the temporal precision of the co-activation of vocal and extraneous muscle groups tightens with age and improved recognizability of speech. These results implicate an interaction between the muscle groups that produce speech and other body movements and provide new empirical pathways for understanding the role of motor development in language acquisition.

KEYWORDS

infancy, motor development, synergistic movements, vocal production

Research Highlights

1. The spontaneous vocalizations of 9- to 24-month-old infants recruit extraneous, synergistic co-activations of hand and head movements.
2. The temporal precision of these hand and head movements during vocal production tighten with age and improved speech recognition.
3. These results implicate an interaction between the muscle groups producing speech with other body movements.
4. These results provide new empirical pathways for understanding the role of motor development in language acquisition.

1 INTRODUCTION

Studies of infant vocal behavior typically consider spontaneous vocalizations as precursors of language (Flack & Leavens, 2018; Locke, 1995; Nathani et al., 2006; Oller, 1980; Stark, 1980). Early vocalizations train the vocal apparatus and its articulators (Kent, 2022; Malas et al., 2017; McCarthy, 1952; Nip et al., 2011; Vihman, 2017) and incrementally become specific to the language being learned and ultimately words recognizable in that language (Locke, 1995; Stoel-Gammon, 2011; Vihman, 2017; Vihman et al., 2009). This is no easy feat as intelligible speech is comprised of a hierarchy of interacting linguistic components including phonological features, vowels, consonants, syllables, words, and prosodic envelopes. The development of articulatory control underlying each of these linguistic components is a protracted and highly variable process relying on the ability to precisely integrate multiple functional, anatomical modules (Kent, 2022; McLeod & Crowe, 2018; Vihman, 2014).

The earliest sounds produced by infants are often considered to be reflexive, a result of the infant's immature ability to control their breathing and digestion (Oller, 1980, 2000; Stark, 1980). The emergence of sounds recognizable as speech-like occurs by 3 months and includes oral, vowel-like sounds which often occur in the context of caregiver-infant vocal turn-taking (Bloom et al., 1987). The repertoire of sounds expands with these interactions and has been characterized as including loud, high pitch sounds, trills, friction noises, and considerable phonetic variability as the infant explores the limits of their vocal apparatus (Kent, 1992, 2022). As a result of increasing articulator and respiratory control around 6 to 8 months of age, the first adult-like pattern of sound production emerges: canonical babbling (Davis & MacNeilage, 1995; Fagan, 2009; MacNeilage & Davis, 1990; Oller, 1980). After several months of producing these rhythmic, speech-like syllable sounds, the first recognizable words begin to emerge (Lewis, 1936; McCune & Vihman, 2001; Tomasello, 1995). Even with the emergence of recognizable words, the produced sounds are not considered to be completely mastered and articulatory control continues to develop well into childhood (McLeod & Crowe, 2018). This protracted development is not surprising given the complexity of the mechanics of human vocalization.

Vocalizations are produced by vibrating the vocal folds of the larynx, pushing air through the vocal-tract airways (Ghazanfar & Rendall, 2008; Kent, 2022; Zhang, 2016), and coordinating multiple articulatory muscle groups (Jürgens, 2002; Thelen, 1991). A one-syllable production requires the coordination of over 80 muscles, many of which are also vital for behaviors such as breathing, swallowing, and chewing (Gavrilov et al., 2017; Hage et al., 2013; Jürgens, 2002). While the coordination of these muscles and articulators during sound production in infancy lay the foundation for spoken communication, it is less clear how the development of articulatory control relates to the general motor development of the infant. Oral-motor development is typically studied separately from general motor development and computational models of voice production in humans rarely consider effectors outside of the lungs and vocal apparatus such as body posture or head orientation (Zhang, 2016). One possibility is that the development of articulatory control to produce recognizable words is self-contained; the orofacial cavity and the vocal apparatus could develop independently from the rest of the body.

Alternatively, since the vocal apparatus is embedded in a body, it may be yoked to the general motor development of the infant. During the early development of many motor skills, including reaching, kicking, and walking, there is a broad, synergistic activation of muscle groups that extend beyond the muscles necessary for the specific action (Bernstein, 1967; Latash, 2020, 2021). Thus, early reaches activate leg movements and early kicking activates hand movements (D'Souza et al., 2017; Gesell, 1954; Gibson & Pick, 2000; Soska et al., 2012; Sporns & Edelman, 1993; Thelen, 1985) These extraneous movements to hand actions and leg movements typically decrease with increasing skill and have been discussed in terms of increasing specialization and differentiation of functional motor systems in the brain (Gordon et al., 2023; Johnson, 2011) as well as increasing inhibition of task irrelevant motor movements (Aoyama et al., 2019). Critically, the activation of task irrelevant muscle groups is often observed in new skill acquisitions or difficult skills throughout life (Frère & Hug, 2012; Latash & Anson, 2006; Muceli et al., 2010) as well as in stroke patients (Jo et al., 2016; Latash & Huang, 2015).

Other evidence indicates that motor development is associated with advances in language development. The acquisition of walking is correlated with vocabulary development, even when accounting for age (Walle & Campos, 2014). Children with language delay exhibit general movement deficits (Geuze & Kalverboer, 1994; Hill et al., 1998; Wolff et al., 1990) and a significant delay in several locomotor transitions, particularly the onset of walking (Trauner et al., 2000). One specific pathway to link language and motor development is the development of articulatory control in vocalization. The present study examines this link by investigating whether vocalizations co-occur with other ancillary body movements.

Hand motions have been reported in the context of reduplicated babbling and canonical vocalizations (Iverson, 2010; Iverson et al., 2007; Thelen, 1979). Nonetheless, it is unknown whether similar principles of increasing isolation and coordination of relevant muscle groups during the acquisition of motor skills apply to the development of articulation. Here, in a combined cross-sectional and longitudinal dataset, we examined vocalizations by a cohort of infants from 9 to 24 months of age, a developmental period of marked growth in the complexity and quality of vocal productions. We specifically asked: do early vocalizations co-activate other body movements? And if so, what is the developmental course? To capture movement outside of the articulators, head and hand movement were measured using motion capture sensors as infants participated in tabletop play with a caregiver. This broad age range spans a period where infants readily produce many types of vocalizations but are still learning to produce mature speech (Flack & Leavens, 2018; Iverson, 2010; Locke, 1995; Tamis-LeMonda & Bornstein, 1990).

The main empirical question is whether the measured hand and head movements occur synchronously to a vocalization. If so, this would indicate that the development of vocal production has similar developmental principles to the acquisition of other motor skills.

The secondary question was to determine possible developmental changes in these synchronous movements during this broad developmental period. Early in development, infants often have difficulty in timing the precise movement of their articulators, resulting in unrecognizable vocalizations. With increasing age, infants incrementally advance, developing more precise control in producing language targets. Our initial working hypothesis was that as speech production skills increased during this period, temporally linked motor movements would decrease.

2 | METHODS

2.1 | Participants

A total of 44 infants (22 male) participated in a combined cross-sectional and longitudinal design at 9, 12, 15, 18, 21, or 24 months of age. Caregivers did not report any atypicalities in motor development or language delays. Each infant participated at different ages for a median of 3 sessions (SD = 1.33) yielding a total of 132 sessions distributed across the 6 ages at testing. Table 1 shows the data for the sessions contributed by each participant. The sample of infants was broadly representative of Monroe County, Indiana (84% European American, 5% African American, 5% Asian American, 2% Latino, 4% Other) and consisted of predominantly working- and middle-class families. All research was approved by the Human Subjects and Institutional Review Board at Indiana University (Protocol #0808000094). Caregivers volunteering their infants for the study were fully informed of the study procedures and completed written informed consent and permission forms in advance of the study.

2.2 | Experimental setup

Infants sat at a small table (61 cm × 91 cm × 64 cm) while their caregiver sat across the table from them. The child was seated in a highchair that did not restrain hand and head movements. They were free to shift, lean, and rotate their upper body, head, and to reach for objects in play on the tabletop. A wired motion capture system (Polhemus Liberty, Polhemus) was used to measure head and hand movement. Three sensors were used: one sensor was affixed to a head band on the right temple of the infant's head and two sensors were embedded in the back of fingerless gloves, providing measurement from the back of the left and right hand. The motion-capture sensor collected rotational position data (roll, pitch, and yaw) at 60 Hz. Vocalizations were recorded at 16 kHz using a small microphone worn by the infant. The microphone was mounted on the right side of a head-mounted eye tracker and positioned in front of the child's mouth.

2.3 | Instructions and procedure

Caregivers were told the goal of the experiment was to study how infants manually and visually explored objects and that they should encourage their infants to interact with the objects as naturally as possible. The infants were engaged with the objects for up to 4 trials, each approximately 1.5 min in duration, resulting in roughly 6 min of data per session.

2.4 | Data processing

An individual vocalization was defined as any sound emitted by the infant's mouth with a minimum inter-vocalization-interval of 300 ms, regardless of intentionality or linguistic content. This included vegetative sounds such as coughs and yawning as even incidental sounds use the same vocal apparatus as intentional sounds. The minimum interval of 300 ms has been used in previous literature on infant-adult vocal turn-taking to distinguish between individual vocalizations (Gratier et al., 2015). A total of 3245 vocalizations were identified. All sounds uttered by the child were labeled and included in the present study. To code the onset and offset of vocalizations, the .wav file of the experimental session was imported into Audacity (Audacity, The Audacity Team) and a video of the session with a clear view of the child's face was played using VLC Player (VLC media player, VideoLan). While these two signals were not synchronized during the coding process, the audio from the video in the VLC player allowed the research assistants to easily align audio in Audacity to video. The onset and offset of a child vocalization were identified by listening to the audio of the session while visually examining the sound amplitude waveform, the spectrogram, and referencing the video of the session.

The recognizability of the vocalizations was coded by research assistants responsible for coding many different projects and naïve to the specific hypotheses or experimental questions of this study. A random subset of 80% of the vocalizations was randomly distributed to four research assistants so that each vocalization was coded four times. Research assistants were asked whether the vocalization they heard was recognizable as an English word or a novel object name. Research assistants were given a list of the names of the novel objects to refer to during this task. Each vocalization was then given a recognizability score corresponding to the sum of the responses the four research assistants gave (0 = completely unrecognizable, 4 = completely recognizable).

2.5 | Rotational velocity

The placement of the motion sensors was not consistent between subjects during the experiment due to infant behavior. Experimenters needed to place the sensor and adjust it in one or two moves, or else the infant would pull it off. Therefore, small variation was allowed in final placement. While the sensors are at the same location (right temple, the back of both hands) the orientation of the sensor varies. Any displacement of a sensor would register as movement. Thus, changes in position are an unreliable measure and rotation was used. Measuring rotation gives us the angular displacement of the head and hands. Rotation signals were filtered using a second order, low-pass Butterworth filter at 0.3 Hz. The rotational velocity of the head and each hand was

TABLE 1 Breakdown of subject participation for each age level. Age at which subject was tested with 'x' indicating when tested.

Subject ID	9 months	12 months	15 months	18 months	21 months	24 months	Total sessions
1						x	1
2	x		x				2
3	x		x	x			3
4				x	x	x	3
5					x		1
6	x	x	x	x	x	x	6
7		x	x		x	x	4
8		x	x			x	3
9		x	x		x	x	4
10	x			x		x	3
11	x			x	x	x	4
12					x	x	2
13	x		x	x	x	x	5
14	x		x	x	x	x	5
15			x		x		2
16	x				x		2
17	x			x	x	x	4
18		x	x				2
19	x	x	x	x	x	x	6
20					x		1
21				x	x	x	3
22	x			x	x	x	4
23	x	x	x	x	x	x	6
24		x		x	x	x	4
25	x	x	x				3
26	x					x	2
27		x		x	x	x	4
28		x					1
29	x		x	x	x	x	5
30	x	x	x				3
31	x	x					2
32	x		x				2
33	x	x					2
34	x	x	x				3
35	x	x	x				3
36	x	x	x				3
37				x	x	x	3
38	x		x				2
39				x	x	x	3
40					x	x	2
41				x	x	x	3
42				x	x		2
43				x		x	2
44				x	x	x	3

then calculated by taking the difference in angular rotation between subsequent samples divided by the change in time between samples. Rotational velocities exceeding the 99th percentile for each individual per age level were replaced with NaNs in Matlab and excluded from further analysis. Acceleration in movement was calculated by taking the difference in velocity between subsequent samples. No other interpolation was used.

No distinction was made between purposeful and incidental hand movements in the present analysis. To measure overall body movement, the average velocity across the head, left hand, and right hand was calculated. Median body movement was also calculated for a period of time before vocal onset and after vocal offset equal to the duration of the vocalization. These periods of time overlapped across vocalizations, and we did not directly control or treat for this overlap.

To determine whether the rotational velocity of the head or hands exceeded chance, a bootstrapped baseline significance test was conducted. For each of the 1000 permutations, random portions of data were chosen for each session equal in number and duration to the vocalizations produced. At the end of the simulation, the 2.5 and 97.5 percentiles of each bin were calculated and moments of rotational velocity exceeding these bounds were considered statistically significant.

Precision in timing of movement for each vocalization was calculated by finding periods of time when acceleration in movement was positive. Throughout the data there were instances of 1 or 2 datapoints exhibiting acceleration, corresponding to 16–33 ms. To ensure we were not capturing incidental noise, we implemented a threshold whereby acceleration had to be sustained for at least 100 ms to be considered a movement. This corresponds to at least 6 consecutive datapoints with positive acceleration (at a sampling rate of 60 Hz). Precision in movement timing was defined as the duration in time from the onset of the accelerative movement just prior to the vocalization to the vocalization's onset.

2.6 | Statistical approach

To incorporate variability between the rotational velocity of the head, left hand, and right hand, the average rotational velocity was calculated to represent overall body velocity. Given recognizability scores are comprised of discrete values, the average was used to incorporate variability in scores as well. All other calculations use median and interquartile range (IQR) as measures of central tendency and variability.

For all the analyses reported in this paper, the alpha level was set at 0.01 to minimize the likelihood of false positives. *P*-values for each conducted analysis were corrected for multiple comparisons using the Bonferroni-Holm correction (Holm, 1979). Using fitlme in Matlab, linear mixed effects (LME) models were constructed for each dependent measure with a continuous predictor variable. Dependent measures were the number of infant vocalizations, vocalization duration, the proportion of recognizable words receiving a maximum score of 4, the average recognizability score per individual, and the precision of movement. Logistic regressions were constructed in Matlab using fitglme for dependent variables with binary outcomes: whether a vocalization was recognizable (value of 1) or not (value of 0). For both LMEs and the logistic regressions, subject identity and total number of trials were included as a random effect and infant age level was included as a fixed effect. The formula for the LME and logistic regression was as follows:

$$\text{dependent variable} \sim \text{age} + (1|\text{subject identity}) + (1|\text{number of trials})$$

The main effects were determined by running an ANOVA on the LME and logistic regression.

3 | RESULTS

The number of infant vocalizations produced in each session (median session duration 5.052 min, IQR = 2.921 min) increased from 9- to 24-months-of-age (LME, $F(5, 126) = 7.837$, $p < 0.0001$) with infants producing a median of 14 vocalizations (IQR = 9) per session (3.202 vocalizations per minute) when they were 9 months old and a median of 31.5 vocalizations (IQR = 34) per session (6.013 per minute) when they were 24 months old (Table 2). The duration of infant vocalizations ranged from a median of 0.653 s (IQR = 0.450) at 9 months of age and 0.896 s (IQR = 0.263) at 24 months of age (Table 2). There was no main effect of age on the duration of vocalizations produced (LME, $F(5, 126) = 2.495$, $p = 0.034$).

We determined whether the vocalizations were attempted words by asking four adult listeners to score the audio of the vocalizations as a recognizable word, yielding a recognizable word score of 0 to 4 (see Methods). The proportion of recognizable words that received a maximum recognizability score of 4 (Figure 1a, LME, $F(5, 126) = 15.319$, $p < 0.0001$) increased with age as did the average recognizability score for each individual (Figure 1b, LME, $F(5, 126) = 17.456$, $p < 0.0001$). The average recognizability score varied from a mean of 0.384 (STD = 0.431) for the 9-month-old infants to 1.833 (STD = 0.549) for the 24-month-old infants (Table 2). This increase of recognizable word scores with age shows the expected age-related increases in attempted word production and the increasing closeness of those vocal productions to a recognizable adult form.

The rotational velocity of the motion sensors affixed to the head and both hands was calculated 3 s before the onset of a vocalization until 3 s after for all age groups. Approximately 97% of all vocalizations were less than 3 s in duration. Figure 1b shows two individual exemplars of vocalizations and co-occurring hand and head movements from one participating infant when the infant was 9 and 24 months of age.

Infants at every tested age moved their head and both hands when producing a vocalization. Figure S1 shows the median rotational speed for the head, left hand, and right hand for every age group with confidence intervals. These movements are significantly faster than baseline (calculated from a bootstrapped permutation test of randomly selected portions of data for each subject, see Methods). Changes across the three effectors appeared to be simultaneous as indicated by z-scored

TABLE 2 Breakdown of the median and interquartile ranges for the number of vocalizations per session, the duration of vocalizations per session, and the proportion of recognizable words per session. The average recognizability score per subject at each age level with standard deviation.

	Number of vocalizations per session	Duration of vocalizations per session	Proportion of recognizable words per session	Average recognizability score per subject
9 months	11 (9)	0.653 (0.450)	0 (0)	0.384 (0.489)
12 months	11 (14.75)	0.837 (0.464)	0.053 (0.172)	0.847 (0.470)
15 months	17.5 (16.5)	0.874 (1.152)	0.094 (0.167)	0.927 (0.614)
18 months	21 (24)	1.128 (1.281)	0.121 (0.165)	1.230 (0.959)
21 months	34.5 (31)	0.737 (0.263)	0.279 (0.238)	1.669 (0.717)
24 months	31.5 (34)	0.896 (0.263)	0.304 (0.182)	1.833 (0.594)

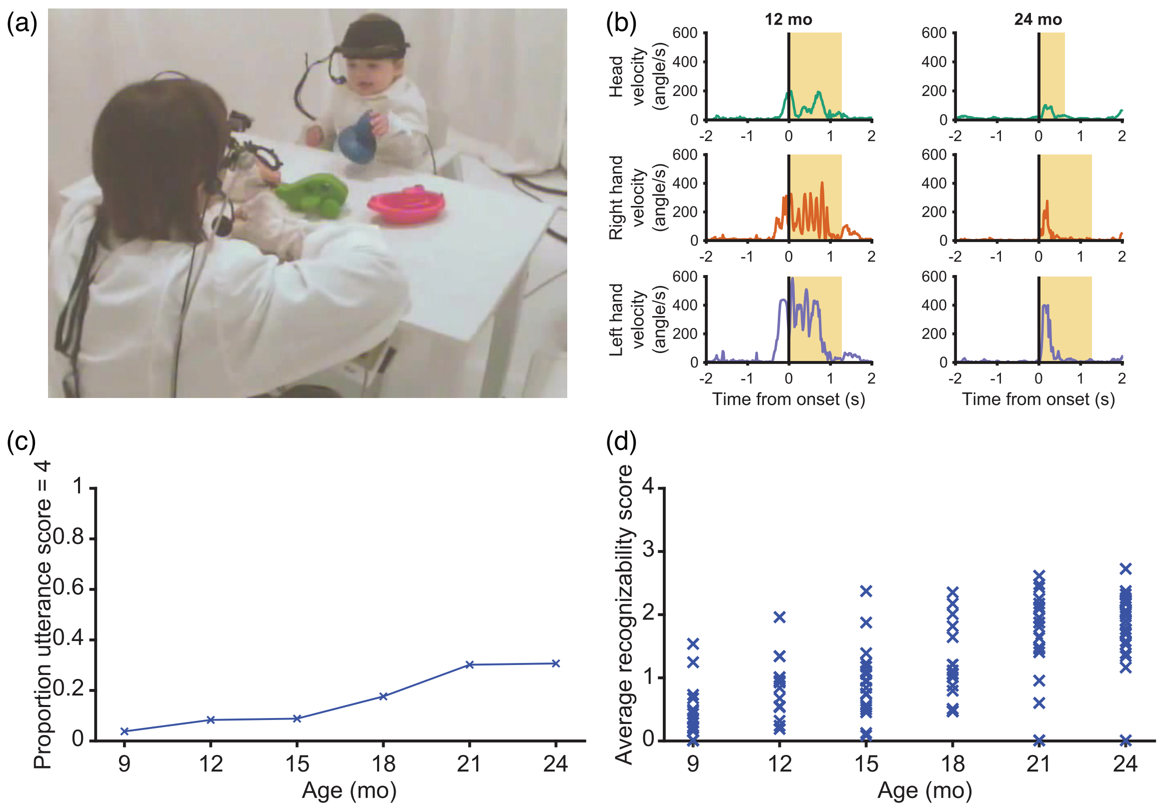

FIGURE 1 Experimental setup and exemplar data. (a) Image of the experimental setup. Note the microphone visible, mounted on the right side of the eye tracker and positioned in front of the child's mouth. (b) An exemplar demonstrating the rotational velocity of the head, left hand, and right hand beginning 2 s before the onset of a vocalization and ending 2 s after for a single individual at 12 months and at 24 months of age. The shaded region indicates the duration of the vocalization. (c) The proportion of recognizable vocalizations for each age group. (d) The average recognizability score for each individual in each age group.

medians of rotational velocity for the head, left hand, and right hand (Figure 2a). Age-related differences emerged solely in the timing of extraneous body movements and not in their occurrence (Figure 2b). To determine whether the observed movement during a vocalization was different to comparable periods of time before and after a vocalization, we defined two periods "before" and "after" each vocalization with the duration equal to that of the vocalization itself (Figure 2c). Using a flexible window to define periods of time "before" and "after" controls for the fact that vocalizations are of different durations. Wilcoxon rank sum tests comparing the median rotational velocity of the body movements before and during a vocalization revealed a significant increase for the 21-month ($Z = -6.239$, $p < 0.0001$) and 24-month ($Z = -6.630$, $p < 0.0001$) age groups, with a significant decrease in median body velocity when comparing the period during a vocalization to the period after the vocalization has ended (21-month $Z = 8.208$, $p < 0.0001$; 24-month $Z = 7.473$, $p < 0.0001$). That is, the peak velocity of hand and head movements for older children co-occurred with the vocalization while it did not for younger children. Children in these

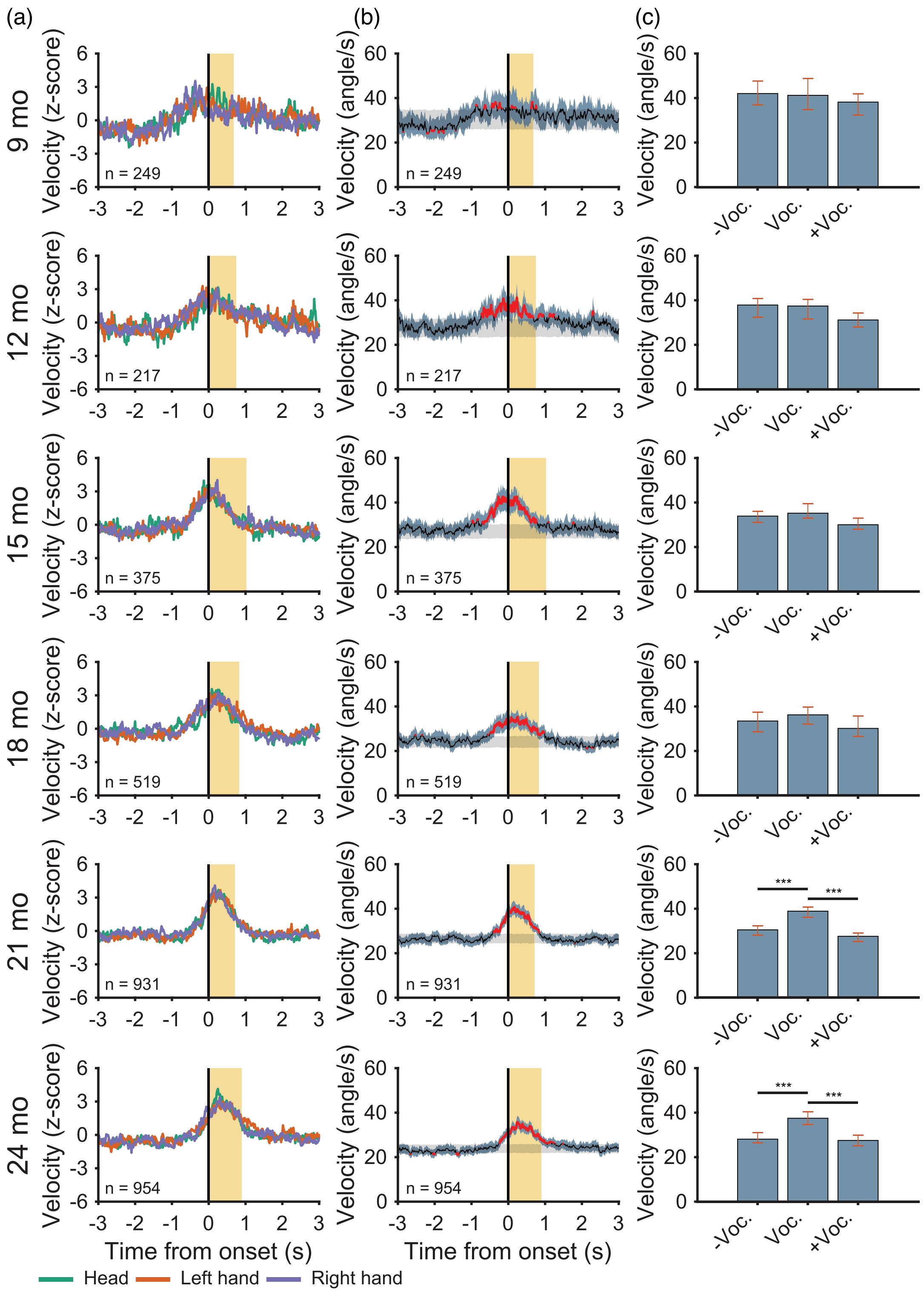

FIGURE 2 Changes in the temporal properties of movement around vocal production. (a) The z-score of the median rotational velocity for body movement beginning 3 s before the onset of a vocalization and ending 3 s after the onset for every age group observed. Vertical solid black line indicates the onset of the vocalization while the vertical shaded region indicates the median vocalization duration for that age group. (b) The median rotational velocity for body movement beginning 3 s before the onset of a vocalization and ending 3 s after the onset for every age group observed. Vertical solid black line indicates the onset of the vocalization and the vertical shaded region indicates the median vocalization duration for that age group. Horizontal shaded region indicates bootstrapped 95% confidence interval and black line indicates the median. Regions of the median in red indicated points in time when the rotational speed exceeded the bounds of a bootstrapped significance test. (c) Median body velocity before, during, and after a vocalization. Medians for the periods of time before and after the vocalization were of equal duration to the vocalization. Error bars indicate bootstrapped 95% confidence intervals. Stars indicate significance at $p < 0.0001$.

older age groups also produced the most recognizable word sounds. Younger age groups, who produce fewer recognizable words, show no significant change in body movement during a vocalization compared to a comparable duration immediately before onset (minimum $Z = -1.517$, maximum $Z = 0.040$, minimum $p = 0.266$, maximum $p = 0.968$) or after offset (minimum $Z = 1.211$, maximum $Z = 2.861$, minimum $p = 0.017$, maximum $p = 0.231$). In sum, prior to a vocalization, all infants began to move their head and hands. With increasing age, the onset of those extraneous movements and their peak velocity became more temporally tied to the onset of the vocalization.

At all ages, infants moved before beginning a vocalization. The earliest time point at which the rotational velocity exceeded the bootstrapped significance test within 1 s of the onset became closer to the onset of the vocalization with age (9 months = 917 ms, 12 months = 917 ms, 15 months = 983 ms, 18 months = 683 ms, 21 months = 416 ms, 24 months = 250 ms). To confirm the observed tightening in the timing of movement to vocalization onset, we also calculated the time from the onset of acceleration in body movement to the onset of a vocalization for every vocalization at each age group. LME models revealed a significant main effect of age ($F(5, 2572) = 3.163$, $p < 0.0004$) and an interaction between age and recognizability of word production in the duration between acceleration onset and vocalization onset ($F(5, 2572) = 4.151$, $p < 0.0009$) with no main effect of recognizability ($F(1, 2572) = 0.864$, $p = 0.353$). To determine whether the recognizability of a vocalization could be predicted from this precision in timing and the age of the infant, a logistic regression with random effects was conducted. Recognizability was defined to only include vocalizations where all four individual raters unanimously agreed the vocalization was a recognizable word. There was a main effect of age on recognizability of word production ($F(5, 2572) = 10.237$, $p < 0.0001$) with no main effect of movement precision ($F(1, 2572) = 1.179$, $p = 0.278$) and no interaction between age and precision ($F(5, 2572) = 0.825$, $p = 0.532$). A Wilcoxon rank sum test comparing the distributions of the precision in timing for all recognizable and unrecognizable words in the corpus revealed a significant difference ($Z = = 3.446$, $p < 0.0001$) whereby recognizable vocalizations were less variable in their precision than unrecognizable vocalizations; however since this analysis includes the confound of increasing age and increasingly recognizable vocal productions, it does not provide clear evidence of a link between recognizability independent of age and more temporally precise body movements.

4 | DISCUSSION

Body movements extraneous to a behavior are common in early human development (Addamo et al., 2007; D'Souza et al., 2017; Hoy et al., 2004; Soska et al., 2012). Later in life, these extraneous body movements are observed when new motor skills are learned (D'Souza et al., 2017; Gesell, 1954; Gibson & Pick, 2000; Soska et al., 2012; Sporns & Edelman, 1993; Thelen, 1985). Co-occurring extraneous body movements, such as hand movements when kicking, are often interpreted in terms of an overflow of neural motor activations and indicative of motor pathways that are not fully differentiated (Addamo et al., 2007; Hoy et al., 2004). From this perspective, the present findings suggest a protracted period extending to the second birthday when the orofacial region and other muscle groups are often co-activated preceding and during the production of vocalizations. This observation suggests a link between advances in general sensory-motor development and advances in speech production (Ejiri & Masataka, 2001; Iverson, 2010; Iverson & Goldin-Meadow, 2005; Iverson & Thelen, 1999). The increased temporal precision of co-occurring body movements with vocalizations across age suggests possible developmental changes in the precision or noise reduction of neural signals from the orofacial muscles that produce speech to the head and hands. In brief, the findings are consistent with the hypotheses of both real-time interactions and a common developmental course for different motor system components and thus a potential pathway for the predictive relations among general sensory-motor development and early language development.

Human infants can produce well over 2000 vocalizations a day (Warlaumont et al., 2014), and the cumulative effect of vocalizing over time likely strengthens neural connections between these vocalization-related muscle groups and the brain, defining motor representations distinct from those of other body parts (Johnson, 2011; Merzenich, 2001). Indeed, neurophysiological evidence from humans and other mammals supports the refinement and formation of brain areas (Cadwell et al., 2019) during the sensory feedback of muscle activity (Kanazawa et al., 2023), particularly during sleep (Blumberg et al., 2022; Dooley et al., 2021) and whole-body action planning (Gordon et al., 2023). Even in the peripheral nervous system, consistent use of a muscle facilitates the refinement and pruning of neural connections to the muscle (Lanuza et al., 2018; Lee, 2020; Thompson, 1983). The broad, imprecise movements observed during vocal production may indicate that the neural signals to the articulators are initially noisy, broad, and imprecisely timed which may be reflected in noisier and longer extraneous body movements. This conjecture is consistent with findings about diffuse activation patterns in primary motor cortex during the initial acquisition of stepping and reaching (Nishiyori et al., 2016, 2021) and poorly differentiated speech representations in primary auditory cortex having cascading impacts on children's reading and language abilities (Merzenich, 2001; Nagarajan et al., 1999).

Thus, individual differences in the ability to form mature word productions may partly lie in the lack of precise timing and precision in the signals needed to coordinate the articulators which may also be reflected in difficulty in the timing and precision of co-occurring and extraneous motor behaviors. A further implication of this conjecture is that infants with vocal articulation disorders may possess impairments in the ability to coordinate and time the movement of other body parts. Such an interaction is plausible; children with developmental language delay exhibit deficits in the ability to time manual actions across both hands (Vuolo et al., 2017). Discoordination of the vocal articulators, and a delay in the production of recognizable words, may then reflect immaturity or disruptions in general motor control. Indeed, children with language delay have been reported to exhibit general movement deficits (DiDonato Brumbach & Goffman, 2014; Geuze &

Kalverboer, 1994; Hill et al., 1998; Sack et al., 2022; Wolff et al., 1990) and a significant delay in several locomotor transitions, particularly the onset of walking (Trauner et al., 2000). Further, infants who exhibit a delay in babbling, the first adult-like pattern of sound production (Davis & MacNeilage, 1995; Fagan, 2009; MacNeilage & Davis, 1990; Oller, 1980), also exhibit a reduction in rhythmic manual behavior and postural stability (Iverson & Wozniak, 2007).

The present study did not distinguish between vocalization type nor movement type. More mature movements in later development, such as pointing, may coincide with the production of a vocalization. Determining whether movement type is related to the increasing precision in movement timing during vocal production is a path of future inquiry. A second line is to disentangle whether deficits in language development concurrently interact with deficits in the motor system or whether deficits across these two domains represent a larger, more general deficit.

In sum, vocal production may be intrinsically embedded within the motor system throughout development (Pouw & Fuchs, 2022). Incidental movements and actions induce short grunt vocalizations in infants, providing an early training ground for the vocal apparatus to produce sounds (McCune, 2021; McCune et al., 1996, 2021). Canonical babbling emerges during a period of rhythmic manual activity (Burkhardt-Reed et al., 2021; Cobo-Lewis et al., 1996; Ejiri & Masataka, 2001; Iverson & Wozniak, 2007; Locke et al., 1995; Thelen, 1979) and the emergence of these rhythmic arm movements precede the onset of canonical babbling (Iverson & Fagan, 2004). In adults, manual gestures can become entrained to speech patterns such that gesture and speech slow concurrently (Pouw & Dixon, 2019; Stoltmann & Fuchs, 2017) and can become entrained through visual feedback (Pouw et al., 2021; Pouw, Harrison, & Dixon, 2020; Pouw, Harrison, Esteve-Gibert, et al., 2020; Pouw, Paxton, et al., 2020).

The present results indicate that head and hand movement co-occur with vocalizations and become more temporally coordinated with vocalizations during the developmental period of 9 to 24 months, when infants increasingly produce recognizable words. Understanding the mechanisms driving this change in motor coordination has broad implications for identifying the processes that limit or promote increasingly mature word productions. This is because the articulators and orofacial region are embedded in a growing and changing body and their development is not isolated from the rest of the nervous system. Learning to produce recognizable words recruits similar processes to learning other motor skills like reaching and kicking and occurs during the same developmental time frame.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request.

ETHICS STATEMENT

All research was approved by the Human Subjects and Institutional Review Board at Indiana University (Protocol #0808000094). Caregivers volunteering their infants for the study were fully informed of the study procedures and completed written informed consent and permission forms in advance of the study.

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REFERENCES

Addamo, P. K., Farrow, M., Hoy, K. E., Bradshaw, J. L., & Georgiou-Karistianis, N. (2007). The effects of age and attention on motor overflow production—A review. *Brain Research Reviews*, *54*(1), 189–204. https://doi.org/10.1016/j.brainresrev.2007.01.004

Aoyama, T., Kaneko, F., Ohashi, Y., & Kohno, Y. (2019). Neural mechanism of selective finger movement independent of synergistic movement. *Experimental Brain Research*, *237*(12), 3485–3492. https://doi.org/10.1007/s00221-019-05693-x

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Pergamon Press.

Bloom, K., Russell, A., & Wassenberg, K. (1987). Turn taking affects the quality of infant vocalizations. *Journal of Child Language*, *14*(2), 211–227. https://doi.org/10.1017/S0305000900012897

Blumberg, M. S., Dooley, J. C., & Tiriac, A. (2022). Sleep, plasticity, and sensory neurodevelopment. *Neuron*, *110*(20), 3230–3242. https://doi.org/10.1016/j.neuron.2022.08.005

Burkhardt-Reed, M. M., Long, H. L., Bowman, D. D., Bene, E. R., & Oller, D. K. (2021). The origin of language and relative roles of voice and gesture in early communication development. *Infant Behavior and Development*, *65*, 101648. https://doi.org/10.1016/j.infbeh.2021.101648

Cadwell, C. R., Bhaduri, A., Mostajo-Radji, M. A., Keefe, M. G., & Nowakowski, T. J. (2019). Development and arealization of the cerebral cortex. *Neuron*, *103*(6), 980–1004. https://doi.org/10.1016/j.neuron.2019.07.009

Cobo-Lewis, A. B., Oller, D. K., Lynch, M. P., & Levine, S. L. (1996). Relations of motor and vocal milestones in typically developing infants and infants with Down syndrome. *American Journal of Mental Retardation: AJMR*, *100*(5), 456–467.

Davis, B. L., & MacNeilage, P. F. (1995). The articulatory basis of babbling. *Journal of Speech, Language, and Hearing Research*, *38*(6), 1199–1211. https://doi.org/10.1044/jshr.3806.1199

DiDonato Brumbach, A. C., & Goffman, L. (2014). Interaction of language processing and motor skill in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *57*(1), 158–171. https://doi.org/10.1044/1092-4388(2013/12-0215)

Dooley, J. C., Sokoloff, G., & Blumberg, M. S. (2021). Movements during sleep reveal the developmental emergence of a cerebellar-dependent internal model in motor thalamus. *Current Biology*, *31*(24), 5501–5511.e5. https://doi.org/10.1016/j.cub.2021.10.014

D'Souza, H., Cowie, D., Karmiloff-Smith, A., & Bremner, A. J. (2017). Specialization of the motor system in infancy: From broad tuning to selectively specialized purposeful actions. *Developmental Science*, *20*(4), e12409. https://doi.org/10.1111/desc.12409

Ejiri, K., & Masataka, N. (2001). Co-occurences of preverbal vocal behavior and motor action in early infancy. *Developmental Science*, *4*(1), 40–48. https://doi.org/10.1111/1467-7687.00147

Fagan, M. K. (2009). Mean Length of Utterance before words and grammar: Longitudinal trends and developmental implications of infant vocalizations. *Journal of Child Language*, *36*(3), 495–527. https://doi.org/10.1017/S0305000908009070

Flack, Z. M., & Leavens, D. A. (2018). Communication and developmental milestones. In T. Shackelford & V. Weekes-Shackelford (Eds.), *Encyclopedia of evolutionary psychological science* (pp. 1–8). Springer. https://doi.org/10.1007/978-3-319-16999-6_3634-1

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. *Frontiers in Computational Neuroscience*, *6*, https://doi.org/10.3389/fncom.2012.00099

Gavrilov, N., Hage, S. R., & Nieder, A. (2017). Functional specialization of the primate frontal lobe during cognitive control of vocalizations. *Cell Reports*, *21*(9), 2393–2406. https://doi.org/10.1016/j.celrep.2017.10.107

Gesell, A. (1954). The ontogenesis of infant behavior. In L. Carmichael (Ed.), *Manual of child psychology* (2nd ed.). Wiley.

Geuze, R. H., & Kalverboer, A. F. (1994). Tapping a rhythm: A problem of timing for children who are clumsy and dyslexic? *Adapted Physical Activity Quarterly*, *11*(2), 203–213. https://doi.org/10.1123/apaq.11.2.203

Ghazanfar, A. A., & Rendall, D. (2008). Evolution of human vocal production. *Current Biology: CB*, *18*(11), R457–R460. https://doi.org/10.1016/j.cub.2008.03.030

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development*. Oxford University Press.

Gordon, E. M., Chauvin, R. J., Van, A. N., Rajesh, A., Nielsen, A., Newbold, D. J., Lynch, C. J., Seider, N. A., Krimmel, S. R., Scheidter, K. M., Monk, J., Miller, R. L., Metoki, A., Montez, D. F., Zheng, A., Elbau, I., Madison, T., Nishino, T., Myers, M. J., … Dosenbach, N. U. F. (2023). A somato-cognitive action network alternates with effector regions in motor cortex. *Nature*, *617*(7960), 351–359. https://doi.org/10.1038/s41586-023-05964-2

Gratier, M., Devouche, E., Guellai, B., Infanti, R., Yilmaz, E., & Parlato-Oliveira, E. (2015). Early development of turn-taking in vocal interaction between mothers and infants. *Frontiers in Psychology*, *6*, https://doi.org/10.3389/fpsyg.2015.01167

Hage, S. R., Gavrilov, N., & Nieder, A. (2013). Cognitive control of distinct vocalizations in rhesus monkeys. *Journal of Cognitive Neuroscience*, *25*(10), 1692–1701. https://doi.org/10.1162/jocn_a_00428

Hill, E. L., Bishop, D. V. M., & Nimmo-Smith, I. (1998). Representational gestures in Developmental Coordination Disorder and specific language impairment: Error-types and the reliability of ratings. *Human Movement Science*, *17*(4–5), 655–678. https://doi.org/10.1016/S0167-9457(98)00017-7

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, 65–70. http://www.jstor.org/stable/4615733

Hoy, K. E., Fitzgerald, P. B., Bradshaw, J. L., Armatas, C. A., & Georgiou-Karistianis, N. (2004). Investigating the cortical origins of motor overflow. *Brain Research Reviews*, *46*(3), 315–327. https://doi.org/10.1016/j.brainresrev.2004.07.013

Iverson, J. M. (2010). Developing language in a developing body: the relationship between motor development and language development. *Journal of Child Language*, *37*(2), 229–261. https://doi.org/10.1017/S0305000909990432

Iverson, J. M., & Fagan, M. K. (2004). Infant vocal-motor coordination: precursor to the gesture-speech system? *Child Development*, *75*(4), 1053–1066. https://doi.org/10.1111/j.1467-8624.2004.00725.x

Iverson, J. M., & Goldin-Meadow, S. (2005). Gesture paves the way for language development. *Psychological Science*, *16*(5), 367–371. https://doi.org/10.1111/j.0956-7976.2005.01542.x

Iverson, J. M., Hall, A. J., Nickel, L., & Wozniak, R. H. (2007). The relationship between reduplicated babble onset and laterality biases in infant rhythmic arm movements. *Brain and Language*, *101*(3), 198–207. https://doi.org/10.1016/j.bandl.2006.11.004

Iverson, J. M., & Thelen, E. (1999). Hand, mouth and brain: The dynamic emergence of speech and gesture. *Journal of Consciousness Studies*, *6*(11–12), 19–40.

Iverson, J. M., & Wozniak, R. H. (2007). Variation in vocal-motor development in infant siblings of children with autism. *Journal of Autism and Developmental Disorders*, *37*(1), 158–170. https://doi.org/10.1007/s10803-006-0339-z

Jo, H. J., Maenza, C., Good, D. C., Huang, X., Park, J., Sainburg, R. L., & Latash, M. L. (2016). Effects of unilateral stroke on multi-finger synergies and their feed-forward adjustments. *Neuroscience*, *319*, 194–205. https://doi.org/10.1016/j.neuroscience.2016.01.054

Johnson, M. H. (2011). Interactive Specialization: A domain-general framework for human functional brain development? *Developmental Cognitive Neuroscience*, *1*(1), 7–21. https://doi.org/10.1016/j.dcn.2010.07.003

Jürgens, U. (2002). Neural pathways underlying vocal control. *Neuroscience and Biobehavioral Reviews*, *26*(2), 235–258. https://doi.org/10.1016/S0149-7634(01)00068-9

Kanazawa, H., Yamada, Y., Tanaka, K., Kawai, M., Niwa, F., Iwanaga, K., & Kuniyoshi, Y. (2023). Open-ended movements structure sensorimotor information in early human development. *Proceedings of the National Academy of Sciences*, *120*(1). https://doi.org/10.1073/pnas.2209953120

Kent, R. D. (1992). The biology of phonological development. In C. A. Ferguson, Menn L., & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 65–90). York Press.

Kent, R. D. (2022). The maturational gradient of infant vocalizations: Developmental stages and functional modules. *Infant Behavior and Development*, *66*, 101682. https://doi.org/10.1016/j.infbeh.2021.101682

Lanuza, M. A., Tomàs, J., Garcia, N., Cilleros-Mañé, V., Just-Borràs, L., & Tomàs, M. (2018). Axonal competition and synapse elimination during neuromuscular junction development. *Current Opinion in Physiology*, *4*, 25–31. https://doi.org/10.1016/j.cophys.2018.04.001

Latash, M. L. (2020). *Bernstein's construction of movements*. Routledge.

Latash, M. L. (2021). Understanding and synergy: A single concept at different levels of analysis? *Frontiers in Systems Neuroscience*, *15:735406*, https://doi.org/10.3389/fnsys.2021.735406

Latash, M. L., & Anson, J. G. (2006). Synergies in health and disease: relations to adaptive changes in motor coordination. *Physical Therapy*, *86*(8), 1151–1160. https://doi.org/10.1093/ptj/86.8.1151

Latash, M. L., & Huang, X. (2015). Neural control of movement stability: Lessons from studies of neurological patients. *Neuroscience*, *301*, 39–48. https://doi.org/10.1016/j.neuroscience.2015.05.075

Lee, Y. il. (2020). Developmental neuromuscular synapse elimination: Activity-dependence and potential downstream effector mechanisms. *Neuroscience Letters*, *718*, 134724. https://doi.org/10.1016/j.neulet.2019.134724

Lewis, M. M. (1936). *Infant speech: A study of the beginnings of language*. Arno Press.

Locke, J. L. (1995). *The child's path to spoken language*. Harvard University Press.

Locke, J. L., Bekken, K. E., Mcminnlarson, L., & Wein, D. (1995). Emergent control of manual and vocal-motor activity in relation to the development of speech. *Brain and Language*, *51*(3), 498–508. https://doi.org/10.1006/brln.1995.1073

MacNeilage, P. F., & Davis, B. (1990). Acquisition of speech production: Frames, then content. *Attention and performance 13: Motor representation and control* (pp. 453–476). Lawrence Erlbaum Associates, Inc.

Malas, K., Trudeau, N., Giroux, M. C., Gauthier, L., Poulin, S., & McFarland, D. H. (2017). Prior history of feeding–swallowing difficulties in children with language impairment. *American Journal of Speech-Language Pathology*, *26*(1), 138–145. https://doi.org/10.1044/2016_ajslp-15-0171

McCarthy, D. (1952). Organismic Interpretation of Infant Vocalizations. *Child Development*, *23*(4), 273. https://doi.org/10.2307/1126033

McCune, L. (2021). Laryngeal vocalizations: Grunts as a gateway to language? *Lingua*, *264*, 103161. https://doi.org/10.1016/j.lingua.2021.103161

McCune, L., Lennon, E. M., & Greenwood, A. (2021). Gestures, grunts, and words: Development in a dynamic system. *First Language*, *41*(3), 243–267. https://doi.org/10.1177/0142723720966820

McCune, L., & Vihman, M. M. (2001). Early Phonetic and Lexical Development. *Journal of Speech, Language, and Hearing Research*, *44*(3), 670–684. https://doi.org/10.1044/1092-4388(2001/054)

McCune, L., Vihman, M. M., Roug-Hellichius, L., Delery, D. B., & Gogate, L. (1996). Grunt communication in human infants (Homo sapiens). *Journal of Comparative Psychology*, *110*(1), 27–37. https://doi.org/10.1037/0735-7036.110.1.27

McLeod, S., & Crowe, K. (2018). Children's consonant acquisition in 27 languages: A cross-linguistic review. *American Journal of Speech-Language Pathology*, *27*(4), 1546–1571. https://doi.org/10.1044/2018_ajslp-17-0100

Merzenich, M. M. (2001). Cortical plasticity contributing to child development. In J. L. McClelland & R. S. Siegler (Eds.), *Mechanisms of cognitive development: behavioral and neural perspectives* (1st ed). Lawrence Erlbaum Associates, Publishers.

Muceli, S., Boye, A. T., d'Avella, A., & Farina, D. (2010). Identifying representative synergy matrices for describing muscular activation patterns during multidirectional reaching in the horizontal plane. *Journal of Neurophysiology*, *103*(3), 1532–1542. https://doi.org/10.1152/jn.00559.2009

Nagarajan, S., Mahncke, H., Salz, T., Tallal, P., Roberts, T., & Merzenich, M. M. (1999). Cortical auditory signal processing in poor readers. *Proceedings of the National Academy of Sciences*, *96*(11), 6483–6488. https://doi.org/10.1073/pnas.96.11.6483

Nathani, S., Ertmer, D., & Stark, R. (2006). Assessing vocal development in infants and toddlers. *Clinical Linguistics and Phonetics*, *20*(5), 351–369. https://doi.org/10.1080/02699200500211451

Nip, I. S. B., Green, J. R., & Marx, D. B. (2011). The co-emergence of cognition, language, and speech motor control in early development: A longitudinal correlation study. *Journal of Communication Disorders*, *44*(2), 149–160. https://doi.org/10.1016/j.jcomdis.2010.08.002

Nishiyori, R., Bisconti, S., Meehan, S. K., & Ulrich, B. D. (2016). Developmental changes in motor cortex activity as infants develop functional motor skills. *Developmental Psychobiology*, *58*(6), 773–783. https://doi.org/10.1002/dev.21418

Nishiyori, R., Harris, M. K., Baur, K., & Meehan, S. K. (2021). Changes in cortical hemodynamics with the emergence of skilled motor ability in infants: An fNIRS study. *Brain Research*, *1772*, 147666. https://doi.org/10.1016/j.brainres.2021.147666

Oller, D. K. (1980). The emergence of the sounds of speech in infancy. *Child phonology* (pp. 93–112). https://doi.org/10.1016/B978-0-12-770601-6.50011-5

Oller, D. K. (2000). *The emergence of the speech capacity*. Lawrence Erlbaum. https://doi.org/10.4324/9781410602565

Pouw, W., & Dixon, J. A. (2019). Entrainment and modulation of gesture–speech synchrony under delayed auditory feedback. *Cognitive Science*, *43*(3), e12721. https://doi.org/10.1111/cogs.12721

Pouw, W., & Fuchs, S. (2022). Origins of vocal-entangled gesture. *Neuroscience & Biobehavioral Reviews*, *141*, 104836. https://doi.org/10.1016/j.neubiorev.2022.104836

Pouw, W., Harrison, S. J., & Dixon, J. A. (2020). Gesture–speech physics: The biomechanical basis for the emergence of gesture–speech synchrony. *Journal of Experimental Psychology: General*, *149*(2), 391–404. https://doi.org/10.1037/xge0000646

Pouw, W., Harrison, S. J., Esteve-Gibert, N., & Dixon, J. A. (2020). Energy flows in gesture-speech physics: The respiratory-vocal system and its coupling with hand gestures. *The Journal of the Acoustical Society of America*, *148*(3), 1231–1247. https://doi.org/10.1121/10.0001730

Pouw, W., Jonge-Hoekstra, L., Harrison, S. J., Paxton, A., & Dixon, J. A. (2021). Gesture–speech physics in fluent speech and rhythmic upper limb movements. *Annals of the New York Academy of Sciences*, *1491*(1), 89–105. https://doi.org/10.1111/nyas.14532

Pouw, W., Paxton, A., Harrison, S. J., & Dixon, J. A. (2020). Acoustic information about upper limb movement in voicing. *Proceedings of the National Academy of Sciences*, *117*(21), 11364–11367. https://doi.org/10.1073/pnas.2004163117

Sack, L., Dollaghan, C., & Goffman, L. (2022). Contributions of early motor deficits in predicting language outcomes among preschoolers with developmental language disorder. *International Journal of Speech-Language Pathology*, *24*(4), 362–374. https://doi.org/10.1080/17549507.2021.1998629

Soska, K. C., Galeon, M. A., & Adolph, K. E. (2012). On the other hand: Overflow movements of infants' hands and legs during unimanual object exploration. *Developmental Psychobiology*, *54*(4), 372–382. https://doi.org/10.1002/dev.20595

Sporns, O., & Edelman, G. M. (1993). Solving Bernstein's problem: A proposal for the development of coordinated movement by selection. *Child Development*, *64*(4), 960–981. https://doi.org/10.1111/j.1467-8624.1993.tb04182.x

Stark, R. E. (1980). Stages of speech development in the first year of life. In G. H. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson (Eds.), *Child phonology* (Vol., 1, pp. 73–92). Academic Press. https://doi.org/10.1016/B978-0-12-770601-6.50010-3

Stoel-Gammon, C. (2011). Relationships between lexical and phonological development in young children. *Journal of Child Language*, *38*(1), 1–34. https://doi.org/10.1017/S0305000910000425

Stoltmann, K., & Fuchs, S. (2017). Syllable-pointing gesture coordination in Polish counting out rhymes: The effect of speech rate. *Journal of Multimodal Communication Studies*, *4*(1–2), 63–68.

Tamis-LeMonda, C. S., & Bornstein, M. H. (1990). Language, play, and attention at one year. *Infant Behavior and Development*, *13*(1), 85–98. https://doi.org/10.1016/0163-6383(90)90007-U

Thelen, E. (1979). Rhythmical stereotypies in normal human infants. *Animal Behaviour*, *27*(Pt 3), 699–715. https://doi.org/10.1016/0003-3472(79)90006-X

Thelen, E. (1985). Developmental origins of motor coordination: Leg movements in human infants. *Developmental Psychobiology*, *18*(1), 1–22. https://doi.org/10.1002/dev.420180102

Thelen, E. (1991). Motor aspects of emergent speech: A dynamic approach. In N. A. Krasnegor, D. M. Rumbaugh, & R. L. Schiefelbusch (Eds.), *Biological and behavioral determinants of language development* (pp. 339–362). Lawrence Erlabaum Associates.

Thompson, W. (1983). Synapse elimination in neonatal rat muscle is sensitive to pattern of muscle use. *Nature*, *302*(5909), 614–616. https://doi.org/10.1038/302614a0

Tomasello, M. (1995). Joint attention as social cognition. *Joint attention: Its origins and role in development* (pp. 103–130). Lawrence Erlbaum Associates, Inc.

Trauner, D., Wulfeck, B., Tallal, P., & Hesselink, J. (2000). Neurological and MRI profiles of children with developmental language impairment. *Developmental Medicine and Child Neurology*, *42*(7), 470–475. https://doi.org/10.1017/s0012162200000876

Vihman, M. M. (2014). *Phonological development: The first two years*. Wiley-Blackwell.

Vihman, M. M. (2017). Learning words and learning sounds: Advances in language development. *British Journal of Psychology*, *108*(1), 1–27. https://doi.org/10.1111/bjop.12207

Vihman, M. M., DePaolis, R. A., & Keren-Portnoy, T. (2009). A dynamic systems approach to babbling and words. In E. L. Bavin (Ed.), *The Cambridge Handbook of Child Language. Cambridge Handbooks in Linguisitics* (pp. 163–184). Cambridge University Press.

Vuolo, J., Goffman, L., & Zelaznik, H. N. (2017). Deficits in coordinative bimanual timing precision in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *60*(2), 393–405. https://doi.org/10.1044/2016_jslhr-l-15-0100

Walle, E. A., & Campos, J. J. (2014). Infant language development is related to the acquisition of walking. *Developmental Psychology*, *50*(2), 336–348. https://doi.org/10.1037/a0033238

Warlaumont, A. S., Richards, J. A., Gilkerson, J., & Oller, D. K. (2014). A social feedback loop for speech development and its reduction in autism. *Psychological Science*, *25*(7), 1314–1324. https://doi.org/10.1177/0956797614531023

Wolff, P. H., Michel, G. F., Ovrut, M., & Drake, C. (1990). Rate and timing precision of motor coordination in developmental dyslexia. *Developmental Psychology*, *26*(3), 349–359. https://doi.org/10.1037/0012-1649.26.3.349

Zhang, Z. (2016). Mechanics of human voice production and control. *The Journal of the Acoustical Society of America*, *140*(4), 2614–2635. https://doi.org/10.1121/1.4964509

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