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Talking Hands: Maternal Speech and Hand Movements in Mother-Infant Interactions

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***Abstract*— Caregivers' vocal production and motor behaviours play a crucial role in early social interactions with their infants, yet the links between vocalisations and arm movements remain relatively unexplored. Using a portable device, we examined the dynamics of arm movement of the caregiver before, during, and outside vocalisation events during interactions with their infants at 4, 6, 9, and 12 months of age. Our findings reveal different patterns of motor-vocal coordination, where the amplitude of caregivers' arm movements increased during vocal production, with a stronger effect observed as their infants became older. Interestingly, we also observed asymmetries in movements of the left and right arms, hinting at functional adaptations. These findings shed light on the dynamic coupling between vocal and motor behaviours in early development, providing insight into how communication emerges through coordinated multimodal interactions.**

I. INTRODUCTION

The dynamic interplay between maternal vocalisations and infant responses during free play is a crucial aspect of early developmental interactions [1]. Research has shown that infants engage in conversational exchanges, known as proto-conversations, with their caregivers as early as two months of age [2]. These interactions involve turn-taking and overlapping vocalisations, highlighting the bidirectional nature of early communication [3]. These early patterns of communication are inherently multimodal and can involve vocal production, motor coordination, reciprocated affective expression, and touch [4] [5].

Studies indicate that mothers often adjust their vocal patterns when interacting with infants, adopting higher pitch and exaggerated intonation to capture the infant's attention and convey emotional cues ("motherse" or child-directed speech). Parents also temporarily coordinate their affective behaviours (such as smiling) with their motor actions (such as pointing) in their infant-directed communication [6]. Interestingly, caregivers also tend to modulate their arm movements when demonstrating actions to their infants (also called "motionese" as a parallel to "motherse", [7]). This can include performing larger movements, adjusting the velocity of their movements and modifying the proximity to the infant [8]. Such modulation of movements may facilitate infants' learning by drawing their attention and highlighting the functions of specific actions [8]. It is currently unknown if caregivers modulate their arm movements only during infant-directed action demonstration or also during daily proto-conversations, as a way of emphasising their speech in order to capture (and maintain) infants' attention on their vocal input.

The links between motor and vocal behaviours in social interactions are particularly interesting as vocal production extends beyond the vocal apparatus itself, relying on the coordinated integration of multiple body parts through vocal-respiratory-motor biomechanical links [9]. In adults, upper limb movements are biomechanically linked to vocalisation, influencing rib cage movement and altering respiratory flow [9]–[13]. Furthermore, arm movements activate muscles connected to the rib cage, further affecting both the motion of the rib cage and the airflow [14]–[17].

The relationship between modalities of information exchange, which parents naturally employ during interactions with their children (such as exaggerated speech and movements), has not been systematically investigated. Understanding the intricate relationship between maternal speech and arm movements, particularly in the context of free play, is essential for uncovering the fundamental mechanisms of early communication and social development. This study aims to investigate how maternal speech influences caregivers' hand movements during free play by analysing accelerometer signals, focusing on differences in manual activity during speech versus non-speech periods. The findings aim to illuminate the embodied nature of early communicative exchanges.

II. EXPERIMENT

A. Participants and Data Collection

We conducted a longitudinal study of the coupling between caregivers' speech and hand movements, testing the same infant-caregiver pairs in a laboratory setting at four time points (T1–T4, at 4, 6, 9, and 12 months). Spontaneous vocal and motor activity was measured during semi-structured social interactions. A total of 104 Infant-parent dyads participated in the study. Of these, 48 dyads provided data at all four time points, while 83 missed one visit, primarily due to COVID-19-related restrictions during the 2020-2023 data collection period (see Table I for details). Additionally, 41 out of 318 visits were excluded due to issues such as the Infant refusing to wear motion trackers or technical problems with motion tracking, microphones, or synchronisation.

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TABLE I

INFANT VISITS BY AGE.

Time Point	Mean InfantAge [months]	SE [months]	InfantAge Range	No. Visits
T1	4.36	0.29	3.90 - 5.20	61
T2	6.59	0.40	6.00 - 7.80	74
T3	09.06	0.35	8.20 - 10.02	71
T4	12.14	0.52	11.00 - 14.50	73

B. Equipment

Caregiver and infant body movements were recorded at 60 Hz using wearable motion trackers (MTw Awinda, Xsens Technologies B.V. [19] [20]) and synchronised with MT Manager Software [19]. Twelve sensors were used, with data reported here coming from one pair placed on the wrists of the caregiver.

C. Procedure

The infants and caregivers participated in a series of interactive tasks, each lasting about 5 minutes, using age-appropriate toys. The analyses focused on two tasks—Rattle-shaking and Manipulative play, each lasting approximately five minutes. The manipulative task involved more complex interactions aimed at exploring objects, whereas rattle-shaking was a simpler activity, a rhythmic activity that combined vocal and motor engagement.

The toy sets differed between the younger (4–6 months) and older (9–12 months) age groups to ensure age-appropriate engagement and alignment with their cognitive and motor abilities. The dyads had full autonomy in their play, moving freely around the room without specific instructions on how to structure the activity or what body positions to adopt.

In the rattle-shaking task, caregivers and infants played freely with a set of four rattles, which varied by age group. This task is considered the most constrained, as it elicits highly repetitive arm movements that may propagate throughout the body [21].

In the manipulative task, caregivers and infants interacted with a set of four toys, each differing in size and designed to encourage various types of engagement. Unlike rattle-shaking, manipulative play is a more open-ended activity focused on multimodal exploration. It allows for greater variability in arm and hand movements, offering almost unlimited degrees of freedom.

The specific toys used in each condition are shown in Fig. 1. Dyadic positioning was unrestricted, allowing natural movement. The interactions were recorded using three HD CCTV cameras, and audio was recorded with a high-quality microphone [22]

D. Coding of Vocalisations

Caregivers' vocalisations were coded offline using PRAAT [23] software. Coders marked the beginning and end of each vocalisation, which was defined as a sound made during a single exhalation. Vocalisations were classified into two categories: syllables and words. Inter-rater agreement

Fig. 1. Toys used during the Manipulative and Rattle-shaking tasks. Photos are provided courtesy of the Neurocognitive Development Lab (Babylab) at the Institute of Psychology, Polish Academy of Sciences.

TABLE II

NUMBER OF VOCALISATIONS DURING TASK AT DIFFERENT AGES.

InfantAge	Rattle-shaking Vocalisations	Manipulative Vocalisations
4 months	5099	5391
6 months	4995	5383
9 months	4372	4760
12 months	4995	4696

was calculated with 86 double-coded recordings, yielding a Cohen's kappa of 0.85. Table II presents the number of vocalisations produced by the caregiver while interacting with the infant during chosen tasks at different ages of the infant. The full procedure can be found in [24].

III. DATA ANALYSIS

A. Data pre-processing

Inertial Measurement Unit (IMU) data from sensors on the caregiver's wrist were processed in MATLAB [25] and EEGlab [26] using custom scripts. Missing values in the data, caused by occasional WiFi connectivity problems and internal sensor adjustments, were interpolated using MATLAB's *interp1* [25] function. The signals were then resampled when a lower sampling rate was detected. Finally, the acceleration magnitude was calculated at each time point [27]. The acceleration at time (t) is defined as the sum of the squared accelerations along the three spatial dimensions:

$$\mathrm{Acc}(t) = x(t)^2 + y(t)^2 + z(t)^2, \tag{1}$$

where $(x(t), y(t), z(t) \in \mathbb{R}^{1\times N})$, and the variables $(x(t), y(t), z(t))$ represents the accelerations along the three spatial dimensions over time.

Then signals were filtered using a 2nd-order, 1Hz cut-off high-pass Butterworth filter.

B. Synchronisation of movement and audio data

The caregiver clapped five times at the beginning of each task to synchronise audio with IMU sensor data. The delay between the signals was calculated using the claps detected in the averaged acceleration data from both arms. Signals with amplitudes above 200 ms^2 were flagged as artefacts and excluded from the analysis.

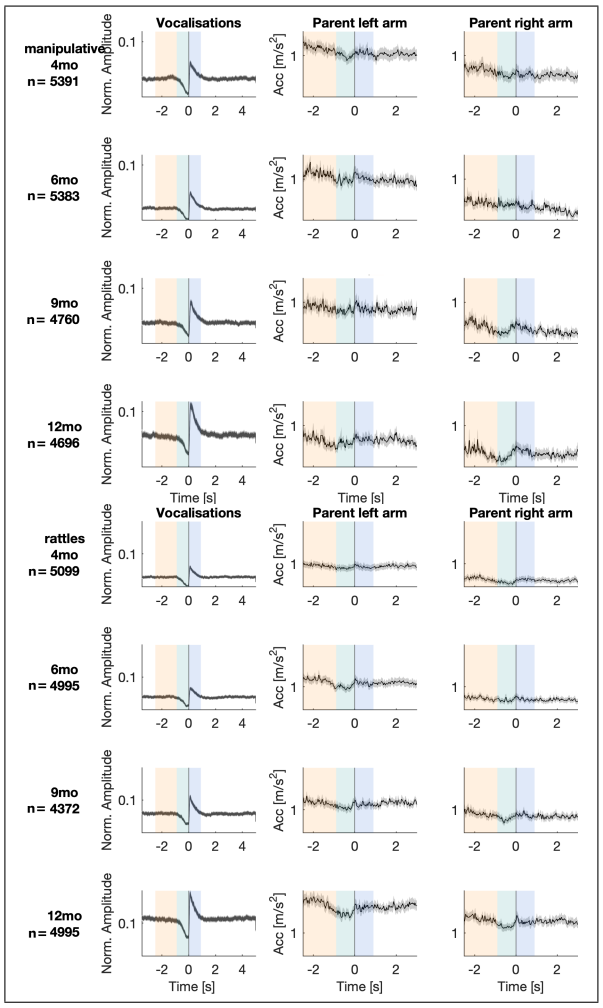

Fig. 2. Illustration of temporal dynamics of infant vocalisation and limb movement during rattle-shaking and manipulative tasks from 4 to 12 months of age. The plotted data show averaged envelope signals for vocalisation (black line) and movements of the infant's arms (magenta line) and legs (teal line). The shaded grey area represents the standard error. The *n* refers to the number of vocalisations analysed in each condition.

C. Movement data pre-processing

The wearable data was pre-processed to investigate changes in wearable signals around the onset of vocalisation, marked as 0 seconds. Audio and accelerometer (Acc) signals were segmented into time windows from -3.5 s to 5 s. To correct for the baseline of IMU accelerometer signals, we applied custom techniques based on Ouali et al. [28]. For each segment, we calculated the mean of the upper and lower envelopes within the 3.5 to 5-second range and subtracted this mean from the corresponding segment. Next, we recalculated the analytic envelope using a 12-tap FIR filter [25] applied to the baseline signal, a standard method for accelerometer data [29]. The analytic envelope was calculated using the analytic parameter, which preserves phase, thus accommodating the sinusoidal nature of IMU signals [30].

We then selected three time windows based on the magnitude change observed in the envelope of the averaged audio signal (Fig. 1. Plot panels, marked by the black line): baseline (-2.5 s to -0.9 s), pre-onset (-0.9 s to 0 s), and post-onset (0 s to 0.9 s). The average audio signal's inflexion point, visible across all age groups, defined the +/- 0.9 s window. For each limb, the median sensor data was calculated separately for the left and right sides within the chosen time window.

D. Statistical Analysis

Statistical analysis was performed in R [31] using the packages lme4, [32] emmeans [33], and lmerTest [34]. For each vocalisation, the dependent measure was calculated as the average of the median ACC values of the left and right limbs, taking into account the caregiver, limb side, the time window, and the infant's age. Linear mixed-effects models (lmer) were used to examine movement differences between limbs, time windows, and age groups. Fixed effects in the model included TimeWindow, Limb, and InfantAge, while random effects accounted for individual variability in the data. The model was specified as follows:

$$\text{median} \sim \text{TimeWindow} \times \text{InfantAge} \times \text{Limb} + (1|\text{ID}), \quad (1)$$

where InfantAge refers to the different time points in the study, TimeWindow indicates the baseline, pre-, and post-onset periods, and Limb refers to the left or right caregiver arm. After fitting the linear mixed-effects model (lmer), the next step was to perform an ANOVA [31] to assess the significance of the fixed effects (TimeWindow, Limb, and InfantAge) and their interactions. This was done using the anova() function in R to test the model for fixed effects. Next, to explore specific pairwise comparisons between levels of significant factors or interactions, post-hoc tests were conducted using the emmeans package. The estimated marginal means (EMMs) were calculated, and pairwise comparisons were performed to further interpret the results.

IV. Results

A. Key Effects on Arm Movement Amplitude

Linear mixed-effects models revealed significant effects of InfantAge, TimeWindow, and Limb on median arm movement amplitude during both the Manipulative and the Rattle-shaking tasks. Both tasks, Manipulation and Rattle-shaking, modulate arm movements in the caregiver with asymmetrical effects across limbs. Caregivers show more left-arm movement. These effects evolve with infant age, particularly between 9-12 months for caregivers. Supporting plots displaying medians for the interactions and main effects are provided in Fig. 3.

1) Rattle-shaking Task:

- InfantAge: Significant effects were observed (F = 14.22, $p < .001$), indicating developmental changes in arm movement patterns. InfantAge had a significant effect on caregiver arm movement, with differences observed between the 9- and 12-month age groups (Estimate = -0.26, $p < .001$).
- Time Window: A strong effect of time window was noted (F = 22.41, $p < .001$), highlighting distinct movement dynamics before and after vocalisation. The

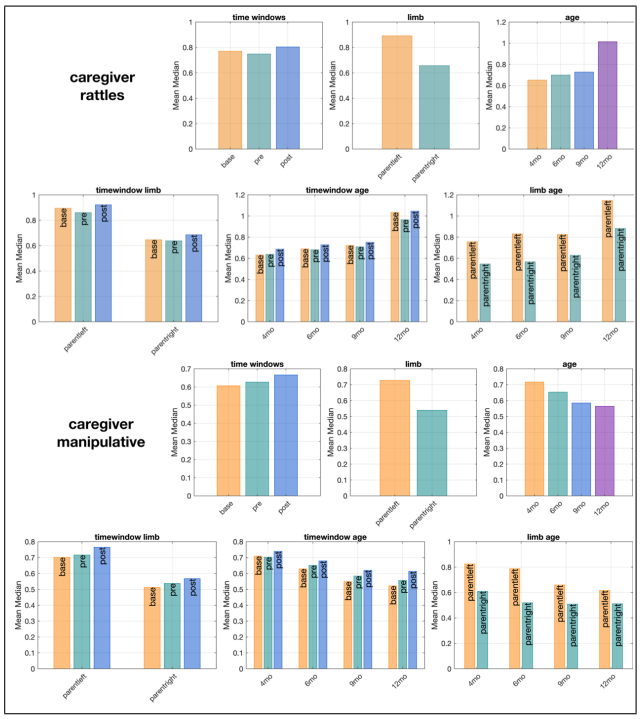

Fig. 3. Boxplot showing the main effects and the interactions for the caregiver in the Rattle-shaking and Manipulative tasks.

time window also influenced movement, with a significant increase from pre- to post-vocalisation (Estimate = 0.055, $p < .001$).

- Limb: There were significant differences between left and right arm movement amplitudes for the caregiver ($F = 1209.40$, $p < .001$), suggesting asymmetry in movement. Significant differences were found between left and right hand movement (Estimate = 0.23, $p < .001$), with the left hand generally showing greater movement.
- Interactions: Significant interaction effects between age and time window were found for the caregiver ($F = 2.16$, $p = .044$), and interaction between age and limb was significant ($F = 6.81$, $p < .001$), indicating that movement patterns evolve with infant age and vary between limbs. The detailed post-hoc statistics are shown in Fig. 4.

2) Manipulative Task:

- InfantAge: Significant age effects were observed in the caregiver ($F = 3.0$, $p = .03$), further supporting developmental changes in arm movements during this task. A significant difference was found between 9 and 12 months of age (Estimate = -0.0840, $p = .035$), suggesting a decrease in caregiver's movement.
- Time Window: Time window effects were significant ($F = 73.0$, $p < .001$), with distinct patterns of movement before and during the caregiver's speech. There was a significant decrease in movement from baseline to post-onset (Estimate = -0.0414, $p < .001$), and a significant increase in movement was observed from post- to pre-vocalisation (Estimate = 0.0342, $p < .001$).
- Limb: Significant effects of limb were found in the caregiver ($F = 3200.0$, $p < .001$), reinforcing asymmetry in arm movement. There was a significant difference between left and right arm movement (Estimate = 0.1674, $p < .001$), with the left arm showing higher movement.
- Interactions: Interaction effects between age and limb was significant, ($F = 12.0$, $p < .001$), indicating age-related changes in limb-specific movement patterns. The detailed post-hoc statistics are shown in Fig. 5.

V. Discussion

This study investigated the temporal relationship between caregiver speech and their arm movement amplitudes during social interactions with their infants at 4 time points throughout the first year of life. Arm movement amplitudes before and during vocal production were compared with periods without vocal production.

A. Longitudinal Changes in Caregiver Arm Movement Patterns

Our results show that caregiver arm movements during interactions with their infants change throughout the first year of their infant's life. Caregivers showed an overall increase in movement amplitude during speech, with the effect becoming more pronounced as the infant grew older. This is in line with previous research focused specifically on "motionese", which found that some aspects of caregivers' movements during infant-directed action demonstration change with infants' age, suggesting that their main function was the organisation of infants' attention based on movement [35]. Overall, it seems that caregiver movements during social interactions with infants adapt, possibly reflecting increased engagement, more advanced object manipulation, or developing a more nuanced communicative strategy.

B. Movement Dynamics Before and During Speech Production

Examining movement changes across time windows revealed that caregivers exhibited increased amplitudes of arm movement leading to and during speech, suggesting that arm movements are an integral part of communication with infants, highlighting the multimodal nature of early social interactions. This finding aligns with research indicating that caregivers' use of gestures positively influences infants' social attention and learning. In their 2012 study, Rader and Zukow-Goldring [37] demonstrated that when caregivers synchronise dynamic gestures with speech, it effectively directs infants' attention to objects during word introduction, enhancing word learning. Furthermore, parents who gestured more at 12 months had children with larger vocabulary at 36 months than parents who gestured less [38]. Similarly, caregivers adapt their movement patterns during infant-directed demonstrations of object actions based on the complexity of the actions and the developmental level of the infant, aiming to optimise learning [8]. These findings highlight the importance of examining parent gestures - or, more

generally, arm movements - for understanding infants' socio-communicative development.

C. Asymmetry in Left and Right Arm Movements

A notable finding was the asymmetry in left and right arm movement amplitudes for caregivers. Caregivers exhibited greater movement in the left arm, which may reflect functional adaptations related to object handling or gestural emphasis during communication. This asymmetry could also be influenced by the typical division of labour between hands, where the left hand is often used for support while the right hand executes fine motor actions. This pattern is common when one hand is already engaged in a primary task, leaving the non-dominant hand to take on additional responsibilities or actions [39]. The non-dominant hand often helps in supporting or interacting with the child, ensuring that the caregiving activities continue smoothly without interruption.

D. Task-related differences

Our findings show that caregivers' arm movement amplitude changes during their vocal production, with effects varying by task. During the manipulative task, caregivers moved their left arm more. In the Rattle-shaking task, movement patterns were similar, but the age-related differences between 9 and 12 months of age were more pronounced.

Across both tasks, age, time window, and limb played key roles in movement differences. Caregivers consistently moved their left arm more. When the caregiver's right hand is occupied with a task (such as holding an object, guiding the child, or performing a specific action), the left hand becomes more available for movement, especially during speech. This may explain the consistent use of the left arm for gesturing or other communicative movements.

VI. CONCLUSIONS

These findings contribute to our understanding of how caregivers coordinate motor and vocal behaviours during interactions with their infants within a naturalistic context. The observed patterns suggest that caregiver vocalisations are embedded within broader multimodal interactions, where movements and speech are tightly linked. Understanding these dynamics provides valuable insights into the mechanisms underlying early communication and could inform interventions aimed at supporting parent-infant interaction in atypical developmental trajectories.

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The authors declare that they have no competing interests.

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Data and materials availability: The data and scripts that support the findings will be available upon request from the corresponding authors following an embargo period from the date of publication to allow for the finalisation of the ongoing longitudinal project. The analyses were not pre-registered.

REFERENCES

[1] Nguyen, T., Zimmer, L., & Hoehl, S. (2023). Your turn, my turn. Neural synchrony in mother–infant proto-conversation. Philosophical Transactions of the Royal Society B, 378(1875), 20210488.

[2] Van Puyvelde, M., Loots, G., Vinck, B., De Coster, L., Matthijs, L., Mouvet, K., & Pattyn, N. (2013). The interplay between tonal synchrony and social engagement in mother–infant interaction. Infancy, 18(5), 849-872.

[3] Casillas, M., & Frank, M. C. (2017). The development of children's ability to track and predict turn structure in conversation. Journal of memory and language, 92, 234-253.

[4] Feldman, R. (2007). Parent–infant synchrony: Biological foundations and developmental outcomes. Current directions in psychological science, 16(6), 340-345.https://doi.org/10.1111/j.1467-8721.2007.00532.x

[5] Northrup, J. B., & Iverson, J. M. (2020). Multimodal coordination of vocal and gaze behavior in mother–infant dyads across the first year of life. Infancy, 25(6), 952-972. doi 10.1111/infa.12369

[6] Leavens, D. A., Sansone, J., Burfield, A., Lightfoot, S., O'Hara, S., & Todd, B. K. (2014). Putting the "Joy" in joint attention: affective-gestural synchrony by parents who point for their babies. Frontiers in Psychology, 5, 879.
doi: 10.3389/fpsyg.2014.00879

[7] Brand, R. J., Baldwin, D. A., & Ashburn, L. A. (2002). Evidence for 'motionese': modifications in mothers' infant-directed action. Developmental science, 5(1), 72-83.

[8] van Schaik, J. E., Meyer, M., van Ham, C. R., & Hunnius, S. (2020). Motion tracking of parents' infant-versus adult-directed actions reveals general and action-specific modulations. Developmental Science, 23(1), e12869.

[9] Pouw, W., & Fuchs, S. (2022). Origins of vocal-entangled gesture. Neuroscience and biobehavioral reviews, 141, 104836. https://doi.org/10.1016/j.neubiorev.2022.104836

[10] Pouw, W., Harrison, S. J., & Dixon, J. A. (2019). Gesture-Speech Physics: The Biomechanical Basis for the Emergence of Gesture-Speech Synchrony. Journal of Experimental Psychology: General.

[11] Pouw, W., de 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

[12] 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

[13] Pouw, W., Werner, R., Burchardt, L., & Selen, L. (2023). The human voice aligns with whole-body kinetics (p. 2023.11.28.568991). bioRxiv. https://doi.org/10.1101/2023.11.28.568991

[14] Hodges, P. W., Butler, J. E., McKenzie, D. K., & Gandevia, S. C. (1997). Contraction of the human diaphragm during rapid postural adjustments. The Journal of Physiology, 505 (Pt 2)(Pt 2), 539–548. https://doi.org/10.1111/j.1469-7793.1997.539bb.x

[15] Hodges, P. W., Cresswell, A. G., Daggfeldt, K., & Thorstensson, A. (2000). Three dimensional preparatory trunk motion precedes asymmetrical upper limb movement. Gait & Posture, 11(2), 92–101. https://doi.org/10.1016/s0966-6362(99)00055-7

[16] Hodges, P. W., & Gandevia, S. C. (2000). Activation of the human diaphragm during a repetitive postural task. The Journal of Physiology, 522 Pt 1(Pt 1), 165–175. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00165.xm

[17] Serré, H., Dohen, M., Fuchs, S., Gerber, S., & Rochet-Capellan, A. (2022). Leg movements affect speech intensity. Journal of Neurophysiology, 128(5), 1106–1116. https://doi.org/10.1152/jn.00282.2022

[18] Lindová, J., Špinka, M., & Nováková, L. (2015). Decoding of baby calls: can adult humans identify the eliciting situation from emotional vocalizations of preverbal infants?. PLoS One, 10(4), e0124317.
[19] Xsens Technologies B.V. MTw Awinda. Xsens Technologies B.V. https://www.xsens.com/products/awinda
[20] Paulich, M.; Schepers, M.; Rudigkeit, N.; Bellusci, G. Xsens MTw Awinda: Miniature Wireless Inertial-Magnetic Motion Tracker for Highly Accurate 3D Kinematic Applications. In Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM); Auckland, New Zealand, 9–12 July 2018.
[21] Hoehl, S., Fairhurst, M., & Schirmer, A. (2021). Interactional synchrony: Signals, mechanisms and benefits. Social Cognitive and Affective Neuroscience, 16(1–2), 5–18. https://doi.org/10.1093/scan/nsaa024
[22] Sennheiser. e 914. Sennheiser. https://en-us.sennheiser.com/instrument-microphone-studio-recording-music-e-914
[23] Boersma, Paul & Weenink, David (2025). Praat: doing phonetics by computer [Computer program]. Version 6.4.27,
[24] Laudańska, Z., Babis, K., Kozioł, A., Szmytke, M., Marschik, P. B., Zhang, D., ... Tomalski, P. (2025). Context Shapes (Proto) Conversations in the First Year of Life. Developmental Science, 28(3), e70018.
[25] MathWorks. (2021). MATLAB Version 9.10 (R2021a) [Software]. The MathWorks, Inc., Natick, Massachusetts, USA. Retrieved from https://www.mathworks.com/help/signal/ref/envelope.html
[26] Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of Neuroscience Methods, 134(1), 9-21.
[27] Abney, D. H., Warlaumont, A. S., Haussman, A., Ross, J. M., & Wallot, S. (2014). Using nonlinear methods to quantify changes in infant limb movements and vocalizations. Frontiers in psychology, 5, 771.
[28] Ouali, M. A., Ghanai, M., & Chafaa, K. (2018). Upper envelope detection of ECG signals for baseline wander correction: a pilot study. Turkish Journal of Electrical Engineering and Computer Sciences, 26(2), 803-816.
[29] D'Aponte, F., D'Emilia, G., Lupinetti, S., Natale, E., & Pasqualoni, P. (2016). Selective and validated data processing techniques for performance improvement of automatic lines. International Journal of Metrology and Quality Engineering, 7(1), 103
[30] Parks, T. W., & Burrus, C. S. (1987). Digital Filter Design. Wiley. Chapter 7, section 7.3.3.
[31] R Core Team. (2021). R: A language and environment for statistical computing [Software]. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/
[32] Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. https://doi.org/10.18637/jss.v067.i01
[33] Lenth, R. V. (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.7.3. https://CRAN.R-project.org/package=emmeans
[34] Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. Journal of Statistical Software, 82(13), 1-26. https://doi.org/10.18637/jss.v082.i13
[35] Rohlfing, K. J., Vollmer, A. L., Fritsch, J., & Wrede, B. (2022). Which "motionese" parameters change with children's age? Disentangling attention-getting from action-structuring modifications. Frontiers in Communication, 7, 922405.
[36] 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
[37] de Villiers Rader, N., & Zukow-Goldring, P. (2012). Caregivers' gestures direct infant attention during early word learning: The importance of dynamic synchrony. Language Sciences, 34(5), 559-568.
[38] Choi, B., Shah, P., Rowe, M. L., Nelson, C. A., & Tager-Flusberg, H. (2021). A longitudinal study of parent gestures, infant responsiveness, and vocabulary development in infants at risk for autism spectrum disorder. Journal of Autism and Developmental Disorders, 51(11), 3946-3958.
[39] Shen, H., & Sengupta, J. (2012). If you can't grab it, it won't grab you: The effect of restricting the dominant hand on target evaluations. Journal of Experimental Social Psychology, 48(2), 525-529.

APPENDIX

	Rattles Caregiver		
Effect	**F Value**	**p-value**	**Significance**
InfantAge	14.22	<.0001	***
TimeWindow	22.41	<.0001	***
Limb	1209.40	<.0001	***
Age × TimeWindow	2.16	0.044	*
Age × Limb	6.81	<.0001	***
Contrast	**Estimate**	**SE**	**Bonferroni p-value**
mo9 - mo12	-0.2675	0.0599	<.0001
base - post	-0.0335	0.0083	<.0001
base - pre	0.0211	0.0083	0.033
post - pre	0.0546	0.0083	<.0001
parentleft - parentright	0.2344	0.0068	<.0001
mo4 parentleft - mo4 parentright	0.2104	0.0132	<.0001
mo6 parentleft - mo6 parentright	0.2650	0.0134	<.0001
mo9 parentleft - mo12 parentleft	-0.3012	0.0606	<.0001
mo9 parentleft - mo9 parentright	0.1974	0.0143	<.0001
mo12 parentleft - mo12 parentright	0.2648	0.0133	<.0001
mo9 parentright - mo12 parentright	-0.2338	0.0606	0.001

Fig. 4. Comparison of statistically significant LMER effects for the Rattle-shaking task involving caregivers.

	Manipulative Caregiver		
Effect	**F Value**	**p-value**	**Significance**
InfantAge	3.0	0.03	*
TimeWindow	73.0	< 0.001	***
Limb	3200.0	< 0.001	***
Age × Limb	12.0	< 0.001	***
Contrast	**Estimate**	**SE**	**Bonferroni p-value**
mo9 - mo12	0.0840	0.0333	0.035
base - post	-0.0414	0.0037	< 0.001
post - pre	0.0342	0.0037	< 0.001
parentleft - parentright	0.1674	0.0030	< 0.001
mo4 parentleft - mo4 parentright	0.16788	0.00595	< 0.001
mo6 parentleft - mo6 parentright	0.19359	0.00577	< 0.001
mo9 parentleft - mo9 parentright	0.14408	0.00618	< 0.001
mo12 parentleft - mo12 parentright	0.16406	0.00602	< 0.001

Fig. 5. Comparison of statistically significant LMER effects for the Manipulative task involving caregivers.