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The development of motor and vocal coordination in infancy: dynamic systems approach

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'

Would you tell me, please, which way I ought to go from here?'
'That depends a good deal on where you want to get to,' said the Cat.
'I don't much care where — said Alice.
'Then it doesn't matter which way you go,' said the Cat.
,—so long as I get SOMEWHERE,' Alice added as an explanation.
'Oh, you're sure to do that,' said the Cat, 'if you only walk long enough.'

~ Lewis Caroll, *Alice’s Adventures in Wonderland*

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Abstract

The coordination of motor and vocal actions is the bedrock of social interaction, but its developmental origins are not well understood. This thesis aimed to analyze the development of motor and vocal coordination across the first year of life. Specifically, it aimed to investigate the increasing specialization of infant limb movements and vocal production to the demands of the task-driven context. It also studied the task-related differences in caregivers' vocal input and emerging differences in dyadic vocal turn-taking. Overall, the presented results show a progressive specialization of within-person and between-person coordination of motor and vocal actions of the infant.

Infant-caregiver dyads (total *N* = 104, Polish-speaking) participated in a longitudinal study with 4 meetings across the first year of infant's life (at 4-, 6-, 9-, and 12 months of age). During each visit, participants were asked to participate in three types of play that differed in task demands: book-sharing, rattle-shaking, and playing with manipulative toys. Each lab meeting consisted of a series of parent-child interaction plays during which infants' and parents' behaviors were recorded using cameras, microphones, and wearable motion trackers.

Chapter 2 showed higher entropy and longer mean line (of recurrence plots) in the Multidimensional Recurrence Quantification Analysis (MdRQA) of infant limb movements during rattle-shaking than during playing with manipulative toys (with values for book-sharing in between these two tasks), suggesting that stability and complexity of the infant's motor system become task-dependent by the end of the first year of life. This pattern indicates a significant increase in specialization for differing task demands across infancy.

Chapter 3 takes an in-depth look at the between-arm coordination of individual (arm) movements during rattle-shaking. It described developmental changes in arm movements in the context of rhythmic rattle-shaking. The results showed increases in the precision of arm movement execution, resulting in the production of more rattle-shaking arm movements at a higher frequency. The results also demonstrated an increase in between-arms coherence as arm movements became more coupled during rattle-shaking across the first year of life. Overall, the results showed increased coordination of arm movements under specific task demands by the end of the first year of life.

Chapter 4 captured a reorganization of the motor-vocal coupling during rattle-shaking across the second half of the first year of life. Limb movements were coupled with the vocalization onset at all measured time points. However, the motor-vocal coupling undergoes a reorganization in infancy. Initially, at 4 months of age there was comparable in magnitude co-activation of arms and legs, then higher co-activation of legs than arms at 6 months, followed by higher co-activation of arms than legs at 9 and 12 months. This

developmental pattern indicates that motor-vocal coupling (especially of arm movements) could be a potential precursor of the adult speech-gesture system.

Chapter 5 investigated infant speech-like production during the same tasks as in Chapter 2 (rattle-shaking, book-sharing, playing with manipulative toys), showing a similar developmental pattern of emerging task-related differences in infants' vocalizations as were previously observed for their motor system's stability and complexity (in Chapter 2). By the end of the first year of life infants were vocalizing less during playing with manipulative toys than during book-sharing and rattle-shaking.

Chapter 6 took a closer look at the caregivers' vocal input during play with their infants in different tasks. Caregivers systematically spoke more during book-sharing than during the two other tasks at all time points.

Chapter 6 also showed that dyadic vocal turn-taking between the infant and the caregiver became task-dependent at 9 months of age. Despite consistent task-related differences in caregivers' input from the age of 4 months, the dyadic patterns become context-dependent only in the second part of the first year of life. The results showed a stable tendency of caregivers to differentiate play contexts in terms of their vocal input across all measured time points. In contrast, infants learned to align their vocal behavior to the play context at a much longer timescale.

Altogether, the presented results show that the second half of the first year of life (between 6 and 12 months of age) is a window of massive reorganization of motor and vocal actions, resulting in better adjustments to task demands. These findings can help to better address the challenge of tracking atypical developmental trajectories and designing early interventions.

Streszczenie

Koordynowanie zachowań ruchowych i wokalnych jest podstawą interakcji społecznych, ale proces jej rozwoju nie został dobrze wyjaśniony. Niniejsza rozprawa miała na celu analizę rozwoju koordynacji ruchowej i wokalnej w pierwszym roku życia. W szczególności, miała ona na celu zbadanie czy niemowlęta dostosowują aktywność ruchową (ruchy kończyn) i produkcję wokalną do odmiennych wymogów zadaniowych oraz czy dokonuje się w tym zakresie zmiana rozwojowa. Ponadto, zbadane zostały różnice w mowie rodziców kierowanej do niemowląt w różnych zadaniach (zabawach rodzica z dzieckiem z różnymi przedmiotami), a także liczba naprzemiennych wokalnych wymian komunikacyjnych między rodzicem a niemowlęciem. Uzyskane wyniki wskazują na wyłanianie sie w toku rozwoju różnic między typami zabawy w zakresie koordynacji działań ruchowych i wokalnych niemowlęcia, a także wyłanianie się wokalnej koordynacji interpersonalnej (diadycznej).

W badaniu podłużnym uczestniczyły diady niemowlę-rodzic (łączne *N* = 104, polskojęzyczne). Diady uczestniczyły w czterech spotkaniach w ciągu pierwszego roku życia niemowlęcia (w wieku ok. 4., 6., 9. i 12. miesięcy). Podczas każdej wizyty uczestnicy byli proszeni o udział w trzech rodzajach zabaw, które różniły się wymaganiami: czytanie książeczek (ang. *book-sharing*), rytmiczna zabawa grzechotkami i manualne eksplorowanie zabawek. Każde spotkanie obejmowało serię interakcji rodzic-niemowlę, podczas których zachowania niemowląt i rodziców były rejestrowane za pomocą kamer, mikrofonów i ubieralnych czujników ruchu.

W rozdziale 2. w wielowymiarowej ilościowej analizie rekurencji (MdRQA) zaobserwowano wyższy poziom entropii oraz średniej długości linii (w diagramie rekurencyjnym, ang. *mean line*) dla ruchów kończyn niemowląt podczas zabawy grzechotkami niż podczas manualnej eksploracji (z pośrednimi wartościami podczas czytania książeczek). Sugeruje to, że stabilność i złożoność układu motorycznego niemowlęcia stają się zależne od zadania pod koniec pierwszego roku życia. Wzorzec ten wskazuje na znaczny wzrost specjalizacji układu motorycznego dla zróżnicowanych wymagań zadaniowych.

W rozdziale 3. opisano zmiany rozwojowe w zakresie organizacji ruchów rąk podczas rytmicznej zabawy grzechotkami. Wyniki wskazały na wzrost precyzji ruchu, co skutkowało wykonywaniem większej liczby ruchów rąk z większą częstotliwością. Wykazano również zmiany rozwojowe w zakresie spójności ruchów grzechotania pomiędzy rękami. Koherencja falkowa ruchów lewej i prawej ręki była istotnie wyższa pod koniec pierwszego roku życia, niż w poprzednich punktach czasowych. Wyniki wskazują więc na zwiększenie

poziomu koordynowania ruchów rąk, a tym samym lepszego dopasowania do wymogów zadania pod koniec pierwszego roku życia.

Rozdział 4. uchwycił reorganizację sprzężenia motoryczno-wokalnego podczas grzechotania w drugiej połowie pierwszego roku życia. Ruchy kończyn były sprzężone z początkiem wokalizacji we wszystkich mierzonych punktach czasowych. Jednak sprzężenie uległo reorganizacji w okresie niemowlęcym, z początkowo porównywalną ko-aktywacją rąk i nóg w wieku 4 miesięcy, potem wyższą ko-aktywacją nóg niż rąk w wieku 6 miesięcy, a następnie wyższą ko-aktywacją rąk niż nóg w wieku 9. i 12. miesięcy. Wzorzec ten wskazuje, że sprzężenie motoryczno-wokalne (zwłaszcza ruchów rąk) może być potencjalnym prekursorem systemu mowy i gestykulacji u dorosłych.

W rozdziale 5. zbadano podobne do mowy wokalizacje niemowląt podczas tych samych zadań, co w rozdziale 2. (grzechotki, książeczki, zabawki manipulacyjne), wykazując podobny wzorzec rozwojowy wyłaniających się różnic międzyzadaniowych w wokalizacjach niemowląt, jaki wcześniej zaobserwowano w odniesieniu do stabilności i złożoności ich układu ruchowego (rozdział 2.). Pod koniec pierwszego roku życia niemowlęta wokalizowały mniej podczas manualnej eksploracji zbawek niż podczas czytania książeczek i zabawy grzechotkami.

W rozdziale 6. przyjrzano się bliżej mowie rodziców w zależności od typu zabawy. Rodzice systematycznie mówili więcej podczas czytania książeczek niż podczas dwóch innych zadań we wszystkich mierzonych punktach czasowych.

Rozdział 6 wykazał również, że liczba diadycznych wymian komunikacyjnych między rodzicem a niemowlęciem zaczyna się różnić między zadaniami od wieku 9. miesięcy. Pomimo spójnych różnic międzyzadaniowych w mowie rodziców od 4. miesiąca życia, liczba naprzemiennych wymian komunikacyjnych stała się zależna od zadania dopiero w drugiej połowie pierwszego roku życia. Wyniki wykazały stabilną tendencję opiekunów do różnicowania kontekstu zabawy pod względem ilości mowy we wszystkich mierzonych punktach czasowych. W przeciwieństwie do tego, niemowlęta uczyły się dostosowywać swoje wokalizacje do kontekstu zabawy w znacznie dłuższej perspektywie czasowej.

Podsumowując, przedstawione wyniki pokazują, że druga połowa pierwszego roku życia (okres między 6. a 12. miesiącem życia) jest okresem znacznej reorganizacji działań motorycznych i wokalnych, co skutkuje lepszym dostosowaniem zachowań do odmiennych wymogów zadaniowych. Wyniki te mogą pomóc w zrozumieniu wyzwań związanych z badaniem atypowych trajektorii rozwojowych i projekowaniem wczesnych interwencji.

Contributions to the longitudinal project

The data included in this thesis were collected as part of a larger research project that involved multiple team members and student research assistants:

Principal Investigator: Przemysław Tomalski

Team Members: Zuzanna Laudańska, David López Pérez, Anna Malinowska-Korczak, Karolina Babis, Alicja Radkowska, Agata Kozioł, Joanna Duda-Goławska

Student Research Assistants: Jadwiga Bożek, Marta Giziewska, Diana Glebowicz, Zofia Kosowska, Monika Krefta, Katarzyna Kubik, Natalia Leszek, Weronika Pichor, Monika Podstolak, Joanna Sacharz, Karolina Sosnowska and Maja Zając

Contributions:

- Study set-up: PT, ZL, DLP, AMK, AR, KB
- Data collection T1-T4 (most sessions were co-led by two researchers or by the researcher accompanied by a student research assistant): KB 224 visits, ZL 123 visits, AMK 83 visits, AR 28 visits, WP 27 visits, AK 26 visits, MG 19 visits, MK 19 visits, NL 14 visits
- Management of study participants (including recruitment and scheduling longitudinal visits): AMK, KB & ZL (each person had a leading role at some point during the study)
- Management of student research assistants: ZL, KB & AMK
- Data management and backup: ZL, KB, AMK & PT
- Questionnaire data management: KB, ZL & AMK
- Calculation of questionnaire scores (including demographic variables): ZL
- Audio files preprocessing: ZL & KB
- Infants' vocalizations coding (including reliability coding): ZL 695 recordings, KB 337 recordings
- Caregivers' speech coding (including reliability coding): ZL 400 recordings, KB 182 recordings, Student research assistants: DG 146 recordings, NL 124 recordings, MP 65 recordings, ZK 49 recordings, KS 46 recordings, MK 26 recordings,
- Infants' rattling coding: ZL 126 recordings, AK 26 recordings (reliability coding)
- Movement data processing: DLP, JDG
- Synchronization of video recordings and movement data: JDG, DLP
- Synchronization of audio recordings and movement data: JDG
- Statistical analyses in chapters 2,3,5,6: ZL
- Statistical analysis in chapter 4: JDG

The author, Zuzanna Laudańska, asserts her right to use all of the results presented in this thesis in her doctoral dissertation proceedings. The author confirms that permission was obtained from all co-authors and contributors for use of all the results in this dissertation.

Chapter 2: The preliminary and partial version of this analysis was previously published in: **Laudańska, Z**., López Pérez, D., Radkowska, A., Babis, K., Malinowska-Korczak, A., Wallot, S., & Tomalski, P. (2022). Changes in the Complexity of Limb Movements during the First Year of Life across Different Tasks. *Entropy*, *24*(4), 552. https://doi.org/10.3390/e24040552. The chapter presents an extended version of the paper published in *Entropy,* with a larger sample, more tasks, and a modified data preprocessing pipeline. However, parts of the Introduction and Discussion sections directly quote the original text of the published manuscript.

Chapter 3 directly presents results published in: **Laudańska, Z.**, López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. *Frontiers in Psychology*, 13, 896319. https://doi.org/10.3389/fpsyg.2022.896319. The Methods and Results sections directly quote the original text of the published manuscript. The Introduction and Discussion are modified to better fit the flow of argumentation of the entire thesis.

Data presented in Chapters 4, 5, and 6 are novel and were not previously published.

Chapter 1 Introduction

Overview

Imagine that you are on a walk in a park with your friend. You are chatting about the past week and plans for the next holiday trip. At the same time, you walk, look at each other, quickly respond to each other's questions and comments, and use your hands to hold a cup of coffee and add emphasis with gestures. What is amazing about this scenario is how you coordinate your actions simultaneously at so many levels! All body parts (think here more broadly – not only arms and legs but also, for example, muscles involved in articulating speech) become organized to keep you in an upright position, walk straight, hold your coffee, and produce speech and gestures. Amazing, right? Then, let’s add another level of difficulty – on top of all these aspects of coordinating your body parts, you are also constantly involved in dyadic multimodal coordination – you walk alongside your friend, take turns while talking, look into their eyes, and exchange smiles.

Now, think about babies in their first months of life. Clearly, they are not able to coordinate their behaviors at a similarly nuanced level. They do actively participate in social exchanges, their caregivers are very excited to see their first smiles and hear babbling for the first time, but the quality of this interaction is different and not as advanced as the one between two adults. Then, the question is – how does this developmental process unfold? Does coordination within each modality (e.g., motor and vocal) emerge at a similar developmental time? What are the developmental trajectories of within-person and between-person coordination across infancy?

This thesis aimed to investigate the development of motor and vocal coordination across the first year of life. In addition, it will also provide initial evidence of developmental changes in motor-vocal coupling during vocal production. To further narrow down the multifaceted problem of early coordination patterns, I will predominantly focus on a specific aspect – the notion of multiple modalities adapting (as a whole) to the task demands. With this overarching goal in mind, this developmental change will be investigated in detail on several levels.

First, in Chapter 2, the developmental change in complexity and dynamic stability of infants' limb movements across three different types of infant-parent plays (rattle-shaking, book-sharing and playing with manipulative toys) will be examined at a high level and across the entire play duration. Then, Chapter 3 will zoom into one specific context of rattle-shaking to provide a thorough examination of rhythmic arm movements on the moment-to-moment timescale. This close look at rattle-shaking will continue in Chapter 4, where the developmental changes of motor-vocal coupling during vocal production will be analyzed, bridging two modalities of interest. Then, Chapters 5 and 6 will take a closer look at vocal production and coordination – again, across three different types of infant-parent plays. Chapter 5 will look at the infants' production of vocalizations, whereas Chapter 6 will focus on parental verbal input and dyadic vocal exchanges.

Complexity Science and Dynamic Systems Theory

The main theoretical approach of this thesis is the complexity and dynamic systems framework. Complex systems appear and are studied across many scientific domains, from physics, medicine, and biology to finance, business, and psychology. The motto of scientists interested in complex systems is that *the whole is greater than (and different from) the sum of its parts* (e.g., Kelso, 2022).

Complex systems are composed of many components that are constantly interacting with each other. Those components can spontaneously **self-organize** into higher-order structures, often without the central top-down flow of information or external interventions. Self-organization can be understood as the spontaneous emergence of coherent, higher-order structures through interactions between simpler components (e.g., Lewis, 2000). In other words, self-organization indicates the process in which a system evolves towards a more organized level (e.g., Haken, 2006; Guevara et al., 2017). The properties of these higher-order structures as a whole are very different, from the properties of their individual components. This phenomenon is often referred to as **emergence** – new properties appear through ongoing processes that are intrinsic to the system itself (e.g., Lewis, 2000).

The components of the system can also form a coordinative structure or a synergy (e.g., Turvey, 1990). The term **synergy** is used to capture the combined effects that arise from interdependence among components in a given context that are not possible or achievable by those components acting alone. The change in environment or task demands results in re-organization and formation of a new synergy (e.g., Latash, 2021). This usually happens without stable intermediate states and appears as **nonlinear phase shifts**. Some patterns would then work as **attractor states**, which means that they are relatively stable and to some degree resistant to perturbation (the more the attractor is resistant to the perturbations, the stronger it is considered; e.g., Guevara et al., 2017; see also de Jonge-Hoekstra, 2021 for an illustrative explanation of attractors).

Complex systems' behaviors are also dependent on the surrounding environment. Thus, dynamic systems theory is frequently influenced by the ideas from ecological psychology (Gibson 1979), resulting in a more multi-disciplinary theoretical framework that studies the adaptive, functional relationship between an organism and its environment. An important term that is derived from this theoretical perspective is **affordance**, which is an action possibility formed by the relationship between an agent and its environment (Gibson

1979). Therefore, all actions are the result of not only dynamic self-organization at the level of an individual (who is already a complex system) but also the environmental constraints of the environment and the task at hand. This also indicates that multiple different pathways can lead to the same result – a concept that is often referred to as **equifinality** (see Schneider & Iveron, 2023 for an example from the development of walking). Each individual can navigate functional coupling with the world in different ways (Sloan et al., 2023), which highlights the need to study individual differences to fully understand how a particular behavioral – or developmental – "endpoint" emerges.

How can this theoretical framework be useful for a developmental psychologist? Well, **infants are complex dynamic systems**: they consist of multiple components that interact over time and self-organize in order to perform actions (e.g., Kelso, 1995; Smith & Thelen, 2003; Thelen & Smith, 2007; Van Geert, 1998; 2020; Van Orden et al., 2003). Consider how many components are involved in producing each behavior (e.g., the number of muscles, bones, and neurons involved in a baby's simple grasping movement), and yet, across development, stable patterns of behaviors emerge. Those components are assembled for functional purposes in a flexible, task-specific manner, which is determined by several factors such as current environmental context, infant maturational status, and previous experiences (Fogel and Thelen, 1987; Thelen and Smith, 1994). The overall actions of the infant are then the product of the entire system of elements in the specific time and context.

In their seminal work, Esther Thelen and Linda B. Smith (1994) presented a comprehensive and detailed theory of early human development based on the principles of dynamic systems theory. They proposed that development can only be understood as multiple, bidirectional, and continuous interactions of all the levels of the developing system that unfold over many timescales from milliseconds to years. Thus, the same principles of complexity science are applicable to studying an infant as a complex, dynamic system.

For example, in the case of the development of communication, some elements (like a preference to look at faces) are already present in newborns, whereas others emerge later, nurtured by contingent responses of caregivers (like verbal dialogues). Early communicative behaviors are **unstructured** and often **involve more effectors** than adult-like behaviors (like moving multiple body parts in response to adult speech rather than responding only in a vocal manner, Condon and Sander, 1974), but they **become increasingly more stable and differentiated** with age (Thelen and Smith, 1994). This involves learning how to select appropriate (and inhibit inappropriate) responses and choose specific effectors for each task. The developmental basis of the selection of effectors is not well understood – it is thought to involve trial-and-error attempts to organize actions, which is accompanied by changes in the brain and neural circuits and many other factors.

What is coordination, and how do we measure it?

I will be using a definition of **coordination** proposed by Dumas and Fairhurst (2019), which states that coordination is *“the process of organizing components of a system so that they work together properly and well."* Similarly, **synchronization** can be described as the process in which two or more systems interact with each other resulting in temporal alignment of their actions (Dumas & Fairhurst, 2019). Perfect synchronization indicates strong **coupling** between two systems (Pikovsky et al., 2001). Two systems are said to be coupled when they interact with each other, and the coupling often refers to relational strength (Dumas & Fairhurst, 2019).

Analysis of within-person and between-person coordination can be challenging. As human behaviors occur on different time scales and happen across several modalities, the collected data can include brief, complex, and noisy time series. Many important insights into interpersonal coordination have been gained using the nonlinear, recurrence-based methods of data analysis, thus, this approach will be used to analyze motor coordination in the present thesis (see examples of this approach in Abney et al., 2014; Kamphorst et al., 2024; Vanoncini et al., 2024). Importantly, this thesis is focused on spontaneous play interactions between infants and their caregivers, as previous research has shown that parent-infant synchrony emerging in spontaneous interactions differs in time and morphology from that elicited in nonspontaneous interaction (Cuadros et al., 2020).

Coordination in social interactions in infancy

The dynamic systems approach can be especially useful for explaining the development of complex and multimodal communication patterns during parent-infant interactions. Multimodal behaviors are tightly coupled early in development: very young infants usually present disorganized and less precise actions, and these actions seem to overflow from one modality to another (D’Souza et al., 2017; Soska et al., 2012). These between-modalities relations seem to change dramatically with age as infants learn how to choose the most appropriate effectors for the task demands in various situations.

Infants spontaneously engage in social interactions from the beginning of their lives, and the temporal coordination of various behaviors is considered a bedrock of social interaction (e.g., Bernieri et al., 1988; Jasnow et al.,1988). Across the first year of life, infants learn how to adjust their behaviors to communicate with others successfully. This requires coordinating their own activity at several different levels (physical movements, eye gaze, physiological states of the body, cognitive and linguistic activity) and with precise timing to respond to the partner. Across the first years of life, infants learn to coordinate their own actions (e.g., gaze and the expression of affect, Yale et al., 2003; vocalizations and looking at objects, Lin & Green, 2009) and also to coordinate their actions with their social partners across communication modalities (e.g., movements and adult speech, Condon and Sander, 1974, vocalizations with gaze to caregiver's face, D'Odorico & Cassibba, 1995; Donnellan et al., 2020; Northrup & Iverson, 2020). Infants' actions, in turn, help caregivers to organize their reactions in a contingent way (e.g., naming more objects when vocalizing, looking at objects or the mother's face, or handling multiple objects, Chang et al., 2016). Coordination patterns change significantly throughout the course of early development (Tronic & Cohn, 1989; Harrist & Waugh, 2002), but studies yield contrasting results. For example, D'Odorico and Cassibba (1995) showed that infants develop the ability to coordinate vocalizations and gaze toward their mothers only around 10 months of age and not at 4, 6, or 8 months. In contrast, Keller and Scholomereich (1987) reported that 4-month-olds produced half of their positive vocalizations during eye contact with their parents, whereas Crown et al. (2002) showed that already 6-week-old infants coordinate their gaze with adults' vocal behavior. Overall, the developmental trajectory of multimodal coordination is unclear, and more research is needed to entangle the specialization towards adult-like communicative patterns.

The current thesis approaches this problem by investigating the infant-caregiver coordination in social interactions at two levels: the individual level (in vocal as well as motor actions) and the dyad (in vocal exchanges) in semi-naturalistic settings. Specifically, we will investigate whether the patterns of infant's motor and vocal coordination, as well as infant-caregiver vocal coordination, become task-dependent across the first year of life (see section "Research Questions" below).

Development happens in context

As introduced earlier, the actions of an individual or coordinated behaviors cannot be studied in separation from the environment. However, the term "environment" is extremely broad and there is no agreement in the field on what it actually includes. For example, the home environment of the child can mean the social environment (e.g., the caregivers and siblings), the language environment (e.g., total speech produced in the child's presence, which languages the family uses on a daily basis), the physical environment (auditory noise, Cheong et al., 2020; clutter, crowding, Evans, 2006; Weisner, 2010; what kind of toys the child has, on what kind of furniture the child can climb on) or even the broader cultural environment of a given community or country, as caregiving practices also are culturally-specific (e.g., Keller, 2013; Lubiewska, 2019). If one wants to go even deeper, then also other environmental features should be considered, such as the level of air pollution (e.g., Costa et al., 2020; Binter et al., 2022) that can affect brain development. Each of these factors can also work on multiple – and nested – timescales, either affecting moment-to-moment behaviors (due to changes in affordances) or more permanently changing the development. Thus, in any study of cognitive development in infancy, it is of utmost importance to specify what aspects of the environment are going to be controlled for and what would be measured. For this reason, this thesis will investigate the role of task demands in a systematic and longitudinal way under semi-naturalistic settings (see section “Procedure”).

Motor development and communication

Motor coordination was one of the first areas in developmental psychology that was studied through the lens of complexity science and dynamic systems theory. Learning to walk and learning to reach were both studied in detail (see Thelen & Smith, 1994 for a thorough overview), showing how they are acquired through the assembly of multiple components that are constantly interacting with each other and are affected by the task- and situational demands. These multiple interacting components form **synergies**. In the field of movement, synergy is a functional entity: it refers to a collection of relatively independent components that are temporarily constrained to act as a single functional unit. This means that multiple components self-organize to accomplish a given task or function (Kelso, 2022). In infancy, movements advance from disorganized to more recognizable adult-like patterns (Thelen & Smith, 1994). The development of motor behavior involves learning through practice as infants improve their skills over time and optimize their actions to the demands of any specific task.

Nonetheless, the developmental changes in early motor coordination are not well understood. The reason for this may be that motor development was generally overlooked in mainstream developmental psychology - as Rosenbaum (2005) described, it was the “Cinderella of Psychology”. Only recently has motor development become a topic of interest for developmental psychologists studying communication (see reviews in Campos, 2000; Iverson, 2010). Furthermore, within the last two decades, motor development turned out to be so important for multiple aspects of development that it has been postulated to be the backbone of so-called **developmental cascades**, which indicate that even small changes in one domain can have far-reaching effects on development in other domains in longer timescale (Iverson, 2010; 2023).

Studies that aimed to investigate the developmental (and multimodal) cascades showed that mastering movement facilitates learning and development across a wide range of psychological domains (see review in Adolph & Hoch, 2019). The next section will review the studies investigating the relations between motor development and vocal production and communication. New motor skills create new opportunities for infants to interact with the environment (e.g., Adolph & Tamis-LeMonda, 2014; Campos, 2000; Iverson, 2010; Needham & Libertus, 2011; West & Iverson, 2021). Walking allows them to travel faster and further than crawling (Adolph & Tamis-LeMonda, 2014), it also changes their field of view –

crawlers' view is dominated by the floor right in front of them, whereas walkers have a broad view of the room as they move (Kretch et al., 2014). Crawlers prefer objects close to them and share them with caregivers while remaining stationary, whereas walking is associated with new forms of object behaviors such as accessing distant objects, carrying them and approaching mothers to share objects with them (Karasik, Tamis-LeMonda & Adolph, 2011). Having more experience in crawling and walking further affects carrying objects (Karasik et al., 2012). Similarly, sitters and non-sitters interact with objects differently (Rochat & Goubet, 1995), and the level of independent sitting proficiency further affects object exploration (Marcinowski et al., 2019; Soska et al., 2010).

Furthermore, the acquisition of new motor skills changes the way infants interact with their social environment. Walking infants make gestures, vocalize, and look to their caregivers more often than crawlers do (Clearfield, 2011; Walle, 2016; Yamamoto et al., 2020). Walking infants are more likely to form communicative bids (e.g., present an object) towards their caregivers while moving, whereas crawlers typically form their bids from stationary positions, which in turn affects the verbal responses they receive from their caregivers (Karasik et al., 2014). Infant's initiation of joint engagement with caregivers and following the parent's joint engagement cues increases as a function of the infant's walking experience (Walle, 2016). Infants produce more socially directed vocalizations and gestures while walking, compared to crawling or moving in a baby-walker (Clearfield, 2011). Even more complex social changes in development, such as the onset of stranger anxiety, seem to be related to acquiring the skills to locomote independently (Brand et al., 2020).

The discussed studies clearly show that gross motor development, and specifically, the acquisition of more upright body positions and locomotion, is related to changes in social interactions and communication. As argued by Adolph & Hoch (2019), motor development is embodied (constrained by the developing body), embedded (in the environment and situational context), enculturated (dependent on the social circumstances and cultural practices), and enabling (as advances in motor development have cascading effects on other psychological domains).

Overall, the existing results clearly suggest that studying motor development in longitudinal studies in the context of social interactions is necessary to capture the dramatic differences in affordances for interpersonal communication. In this thesis, we are jointly investigating both motor and vocal development at four time points that reflect the acquisition of novel motor skills.

Motor-vocal coupling

As described above, the acquisition of novel body postures and overall gross motor development have a cascading effect on early language and communication. The developing motor system creates novel opportunities for practicing and refining communication as the growing body of literature shows that the acquisition of sitting and walking is related to productive (e.g., Oudgenoeg-Paz, 2012; Walle and Campos, 2014; He et al., 2015) and receptive language skills (Libertus & Violi, 2016; for a review see Iverson, 2010 or Gonzalez et al., 2019). However, it is important to remember that motor actions are crucial aspects of oral language production – and these motor-vocal associations seem to be present at least at several levels.

First, learning to coordinate and control speech articulators is a core component of vocal production. Uttering even a single syllable involves over 70 muscles in the mouth and tongue, as well as respiratory, laryngeal, and pharyngeal systems (Galantucci et al., 2006; Turvey, 2007). Thus, the motor development of speech articulators is necessary for the acquisition of spoken language (Thelen, 1981).

Second, apart from the coordination of speech articulators, vocal production seems to be also affected by limb movements. Studies with adults showed that the upper limb movements biomechanically interact with vocalizing by affecting rib cage movements and changing respiratory flow (Pouw et al., 2019; Pouw, de Jonge-Hoekstra, et al., 2020; Pouw, Paxton, et al., 2020; Pouw, Harrison, et al., 2020; Werner, Selen & Pouw, 2023). Moreover, moving arms recruits muscles that insert into the rib cage (Hodges et al., 1997, 2007; 2000a, 2000b), which in turn affects the ribcage's movement and, thereby, respiratory flow. Breathing can then be considered a shared resource when speech and limb movements co-occur. What is even more intriguing, such motor-vocal-respiratory coupling can also extend to lower limb movements. A preliminary study by Serré and collaborators (2022) showed that in adults, the presence of intensity peaks in the acoustic speech signal co-occurred with the time of peak acceleration of legs' biking movements, suggesting some biomechanical entanglements between motor-vocal-respiratory systems.

The developmental origins and trajectories of this vocal-motor coupling have been scarcely studied, but the initial reports suggest that the motor-vocal coupling is present in infancy but still undergoes specialization. For example, work by Iverson and Fagan (2004) showed a developmental trend for increased coordination of manual actions with vocalizations and decreased coordination with other limbs. Furthermore, Ejiri & Masataka (2001) showed in a longitudinal case study (N=4) that vocalizations co-occurred with rhythmic actions, particularly in the period preceding the onset of canonical babbling (production of well-formed syllables, including a consonant and vowel). What is more, during this period, vocalizations that co-occurred with rhythmic actions had different acoustic features than vocalizations that did not co-occur with rhythmic actions.

Third, the co-occurrence of vocalizations and manual actions in infants has been interpreted as a precursor of the speech-gesture system (e.g., Iverson and Fagan, 2004).

Gestures seem to be integral to the speaking process itself (e.g., Bernardis & Gentilucci, 2006). Early gesture production predicts later language development (e.g., Iverson & Goldin-Meadow, 2005; Rowe & Goldin-Meadow, 2009; Goldin-Meadow et al., 2014). Even congenitally blind speakers gesture despite no previous visual experience, and they do so even when they speak to a blind listener (Iverson & Goldin-Meadow, 1998).

Overall, motor-vocal coupling seems to be an inherent feature of communication, thus, the multimodal and developmental approach applied in this thesis can contribute key information to this multifaceted problem. To this end, this developmental phenomenon will be investigated here (see Chapter 4) in a younger age group than previously (Borjon et al., 2024). Furthermore, previous results will be extended by adding limb movements into the analysis. The motor-vocal coupling will be investigated across body postures, during semi-naturalistic interactions with caregivers.

Vocal coordination in infancy

As argued in the previous paragraph, vocal production is a highly coordinated motor action, involving multiple components working in unison. Furthermore, the initial vocalization patterns observed in human infants exhibit a wide range of disorganized actions (e.g., Oller, 2010) which bears a resemblance to the exploratory behaviors seen in infants' hand and arm movements during the early months of life (Thelen, 1981). Thus, vocal production can be considered a highly precise motor skill and may then be described within the framework proposed by Adolph & Hoch (2019) as embodied (constrained by the developing body), embedded (in the environment and situational context), enculturated (dependent on the social circumstances and cultural practices) and enabling (as advances in vocal development have cascading effects on other psychological domains). However, the development of vocal production in infancy has rarely been investigated as an interplay of dynamic changes in early motor development (which create novel possibilities for toy exploration), parental speech, and infants’ own vocal production. Recent examples showcase the multimodal nature of word acquisition (e.g., Schroer et al., 2022), however, the earlier (preverbal) underpinnings of this process are not yet understood.

Infants have a strong endogenous tendency to spontaneously vocalize, exploring the sensorimotor characteristics of the vocal system (e.g., Oller et al., 2019). They produce a large variety of sounds, which are mostly unrelated to their emotional state (except for laughs and cries that are consistently related to emotions). So-called „**protophones**”, presumed precursors of articulated speech, can be produced with positive, negative, or neutral facial affect on different occasions (Oller et al., 2013), presenting **functional flexibility** (e.g., Oller and Griebel, 2008). This broad category of sounds includes sounds like squeals, growls, vowel-like sounds and canonical babbling (e.g., Buder et al., 2013;

Stark, 1981). It dominates the infant vocal landscape, vastly outnumbering cries and laughs across the first year of life (Oller et al., 2021). This stage of vocal development is related to the production of many variable and repetitive vocalizations that are not related to any specific social or functional context, which suggests their exploratory character (Stark, 1978; ter Haar et al., 2021). This is especially interesting, given that many of those sounds are directed toward no one (Long et al., 2020, 2022) or toward objects rather than people (Orr, 2022). However, these preverbal sounds are treated by caregivers as communicative sounds as they respond to them more often (Hsu and Fogel, 2003) and differently than to cries (Yoo et al., 2018).

Mastering the art of conversation is also situated socially, as conversations involve structured and coordinated interactions between the interlocutors who take turns in their roles as speakers and listeners (Fusaroli et al., 2014). Thus, this developmental process involves practicing one's own responses in temporal and contextual relations with a partner (e.g., Jaffe et al., 2001). Language development happens in the context of social exchanges (e.g., Goldstein & Schwade, 2008; Gros-Louis et al., 2006, 2014) as infants are actively participating in conversation-like vocal turn-taking (often referred to as “proto-conversations) from a very early age (e.g., Gratier et al., 2015; Harder et al., 2015; Hilbrink et al., 2015, see review in Nguyen et al., 2023). Even though early vocalizations seem to be playful indicators of an infant’s well-being directed toward no one (Long et al., 2020, 2022), the more advanced speech-like vocalizations happen more often during turn-taking than when the infant is alone (Bloom et al., 1987; Long et al., 2022), highlighting the importance of the social context for language learning. In the first six months of life, infants learn about the social efficacy of their vocalizations as they understand that their non-cry vocalizations influence others (Goldstein et al., 2009; Elmlinger et al., 2023). Moreover, by vocalizing, infants elicit the production of shorter in length utterances as well as less lexically diverse contingent speech from their caregivers, thus, they shape their own language environment (Elmlinger et al., 2019, 2023). On the other hand, mothers’ temporally contingent feedback to infants’ babbling rapidly restructures the phonological patterns of vocal production, as it elicits more complex and mature vocal behavior (Goldstein et al., 2003; Goldstein & Schwade, 2008) and shapes their vocal development (Gros-Louis et al., 2014). Patterns of parental responsiveness to prelinguistic behavior have been linked to long-term developmental outcomes (e.g., Tamis-LeMonda & Bornstein, 2002). Overall, vocalizations both influence and are influenced by interactions with social partners through the social feedback loop (e.g., Elmlinger et al., 2023; Goldstein & Schwade, 2008; Warlaumont et al., 2014).

Very few studies have investigated the **contextual aspect of emerging vocal production and dyadic exchanges** (see Nguyen et al., 2022, for a discussion). As discussed above, infants' vocalizations frequently co-occur with their rhythmic motor actions – for example, during rattle-shaking (Ejiri and Masataka, 2001; Iverson and Fagan, 2004). Rome-Flanders and Cronk (1995) also showed that infants' vocalizations were similar during peek-a-boo and play with a ball, whereas Sosa (2015) observed that infants aged 10-16 months vocalized more during play with books than electronic or traditional toys. Similarly, Hsu et al. (2014) showed form–function decoupling between vocalization types across peekaboo and tickle games between 6 and 12 months of infant's age (cross-sectionally). Finally, another line of research suggests that book-sharing is particularly beneficial for communicative development (see review in Murray et al., 2022) as it promotes shared attention and dialogic structures between the infant and the caregiver. Nonetheless, little is known about the vocal production and dyadic exchanges across different types of infant-parent interactions.

Goals, research questions and hypotheses

As reviewed in the introduction, motor and vocal actions are clearly coupled in adults and the precision of this coupling is highly important for communication. For this reason, it is highly important to take a closer look at the emergence of motor-vocal coordination. The goal of this thesis is to analyze the development of motor and vocal coordination across the first year of life. Specifically, it aims to investigate the increasing specialization of infant limb movements and vocal production to the demands of the task-driven context. It also aims to investigate the task-related differences in caregivers' vocal input and emerging differences in dyadic vocal turn-taking.

The design of this study aims to capture infant and caregiver behaviors in three types of plays that differ in task demands. Rattle-shaking is considered the most constraint task, eliciting highly repetitive arm movements – that can potentially diffuse throughout the body (e.g., Hoehl et al. 2021). In contrast, playing with manipulative toys is considered the most free-flowing interaction, focused on multimodal exploration of interesting toys, with variable arm and hand movements (and almost unlimited degrees of freedom). Finally, book-sharing elicits more visual and vocal than motor actions, as the benefits of book-sharing for speech and language development were previously reported (e.g., Clemens & Kegel, 2021; see review in Murray et al., 2022). The motor patterns during book-sharing seem to be less clearly defined than in the two other tasks due to the more stationary character of this play type.

The overarching question of this thesis focuses on the developmental changes of motor-vocal coordination in infancy. Specifically, it asks how the increasing multimodal (motor-vocal) specialization to the demands of the task-driven context unfolds with infants' age. The specific questions and predictions for each part are listed below and included in each empirical chapter.

Research Questions

Within-infant motor coordination

Research Question 1: Do the patterns of infant's between-limbs motor coordination become task-dependent across the first year of life?

Prediction: Younger infants will generate multiple coordination patterns randomly, simultaneously using all limbs. Older infants will tailor their coordination patterns to the specific task or to body-environment relations.

Research Question 2: Do infants' arm movements and between-arm coupling during rattle-shaking change across the first year of life?

Prediction 1: Infants would be able to produce more rhythmic arm movements with age.

Prediction 2: Infants would rattle at a higher frequency with age.

Prediction 3: Infants' between-arms coordination (measured with wavelet coherence) would increase with age.

Motor-vocal coupling

Research Question 3: Does the within-infant coupling between motor and vocal actions change across the first year of life?

Prediction 1: The infant's arms and legs would co-activate around the onset of vocalizations due to motor-vocal-respiratory coupling.

Prediction 2: Across the second half of the first year of life, there would be an increase in coupling between arm movements and vocalizations due to the emerging speech-gesture system around the onset of canonical babbling.

Within-infant vocal coordination

Research Question 4: Do infants' vocalizations become task-dependent across the first year of life?

Prediction: The frequency of infants' vocalizations at 4 and 6 months will be similar across all three tasks. At 9 and 12 months, infants will vocalize more during book-sharing (an activity that encourages vocal interactions) than during rattle-shaking or playing with manipulative toys. Moreover, infants will produce more vocalizations during rattle-shaking than playing with manipulative toys at 9 and 12 months, due to the co-occurrence of rhythmic vocalizations (such as canonical babbling) with rhythmic manual actions. The frequency of vocal production during play with manipulative toys will be the lowest because this type of play mostly involves manual exploration.

Dyadic vocal coordination

Research Question 5: Does parental vocal input change depending on the task and infant's age?

Prediction: The caregivers would speak more during the book-sharing task than during two other tasks at all time points due to reading and animating.

Research Question 6: Do the patterns of infant-caregiver vocal coordination become task-dependent across the first year of life?

Prediction: The highest number of conversational turns would happen during the book-sharing task (related to the parental influence of higher vocal production in this context) but only at 9 and 12 months of the infant's age, when the infant would become a more advanced conversational partner thanks to gross motor development and increased postural stability.

General methodological approach

This thesis takes an innovative methodological approach by combining analyses of infants' and caregivers' movements and vocal production in a longitudinal study with 4 meetings during the first year of life (at 4-, 6-, 9- and 12 months of age). Each lab meeting consisted of a series of parent-child interaction plays during which infants' and parents' behaviors were recorded using cameras, microphones, and wearable motion trackers. All parent-infant dyads participated in five interactive play tasks, but only three of them (that are characterized by the most distinct task demands) are the subject of this thesis: book-sharing, playing with manipulative toys and rattle-shaking.

Participants

Source of the data

The sample included in this thesis participated in a large-scale project (MOVIN) funded by the National Science Center of Poland (Sonata Bis, no. 2018/30/E/HS6/00214): *Decoupling of motor, visual and vocal activity in infancy during dyadic social interactions* led by prof. Przemysław Tomalski, supervisor of this thesis. The data collection was conducted at the Institute of Psychology, Polish Academy of Sciences, and received clearance from the Ethics Committee at the same institution. The scope of the data collected in this project exceeded the data presented in this thesis. Parts of this project's dataset were previously reported in Laudańska et al., 2022a, 2022b, 2023 (Study 2) and Kozioł et al., 2023. The author of this thesis participated in all stages of the project planning and piloting as well as data collection and planning analytical approach (see section "Contributions to the longitudinal project").

The analysis of infant vocal production was further supported by the National Science Center of Poland (Opus, no. 2022/47/B/HS6/02565): *How do parents facilitate early vocal development of infants? The role of optimizing postural stability and locomotor activity during social interactions*, also led by prof. Przemysław Tomalski.

Sample characteristics

Overall, 104 families took part in the project when infants were around 4 (T1), 6 (T2), 9 (T3) and 12 (T4) months old. 83 dyads participated in a minimum of three visits, out of them, 48 dyads contributed data at all 4 time points (missed visits are mostly due to Covid-19-related restrictions as data collection was conducted between the years 2020 and 2023). Therefore, 20 dyads contributed data at T2, T3 and T4, 7 at T1, T3, T4, and 8 at T1, T3 and T4. Participants were from predominantly middle-class families living in the Warsaw, Poland metropolitan area (>1.7 million inhabitants). The majority (90%) of the caregivers had completed higher education: 3 held a Ph.D. degree, 81 held a master's degree, 10 held a bachelor's, and 4 completed high school (6 missing data). The majority (87.5%) of infants were Polish monolinguals, but 13 infants heard other language(s) at home for min 20%. Infants received a diploma and a small gift (a baby book) for their participation.

Since some testing sessions were shortened due to the infant's fussiness (which resulted in omitting one or more of the interaction tasks) and audio or movement data were not available from several testing sessions due to technical problems, the description of the sample that provided data for each analysis is reported separately in each empirical chapter.

Procedure

Interactions were recorded in a laboratory room, on a carpeted play area. Upon the family's arrival, an experimenter explained the study protocol and obtained informed parental consent. Once the infant was familiarized with the laboratory, the wearable motion trackers and head cameras were put on the infant and caregiver. Then, a set of parent-child interaction tasks with different sets of age-appropriate toys took place. The sets for infants aged 4 and 6 months were slightly different from those for infants aged 9 and 12 months to maintain their interest in a given task as well as to adjust the size and weight of objects to infants' motor skills. At the beginning of each game, the caregivers were asked to clap several times to mark the start of the procedure to synchronize wearable sensors with video recordings.

There were 6-7 different tasks during each meeting, but in this thesis, only three of them are compared: book-sharing, playing with manipulative toys, and rattle-shaking. The order of plays was randomized between participants and testing sessions.

Book-sharing

In a book-sharing task, the dyads were provided with several baby books. At T1 and T2, there were three small picture books: one with nursery rhymes, one with big pictures of animals and people and one with pictures and onomatopoeic words. At T3 & T4, infants and parents were given one bigger book with pictures and onomatopoeic words and one smaller book with animal pictures, nursery rhymes about animals and tactile elements.

Playing with manipulative toys

In a manipulative toys task, infants and parents were given a set of toys that varied in tactile structure and provided multimodal feedback (sounds, movements). Two toys were the same at all time points: a sensory pop-it toy and a gliding, rolling and rattling sensory toy with tactile silicone elements. In addition, at T1 & T2, the set consisted of a wooden wiggly worm, a sensory toy with different tactile fabric and silicone elements, and a grasping ball with finger holes and rattling beads, whereas at T3 & T4: a spinning toy with small balls inside, a sensory-exploration toy with elements with different textures that can be pushed, spun or clicked and make different sounds

Rattle-shaking

The task lasted approx. 5 minutes. The dyads were given two maracas rattles and two rattles of different types (the barbell rattles for younger infants and teddybear rattles for older ones).

Fig. 1.1. The sets of toys used for each play. The top row indicates toys used in T1 & T2, and the bottom row indicates toys used in T3 & T4.

Motion-trackers

Infants' and caregivers' movements were recorded at 60 Hz using wearable motion trackers (MTw Awinda, Xsens Technologies B.V.), an Awinda station receiver. (Xsens Technologies B.V.) and MT Manager Software (Xsens Technologies B.V.). Overall, 12 sensors were used (on the infant's arms, legs, head, and torso; and on the caregiver's arms, head, and torso). Details about movement data preprocessing are reported separately in each empirical chapter.

Video and audio recordings

All tasks were recorded using 3 remote-controlled HD CCTV cameras (Axis) located at different heights to capture the overview of the room as well as the faces of both the parent and the infant. During the session, an experimenter operated the cameras (this included zooming in and out as well as moving them vertically and horizontally) to ensure that at least one camera captured the infant's behavior. The sound recording was synchronized with a video system and was carried out with a high-grade cardioid membrane condenser microphone (Sennheiser e914) placed underneath one of the cameras. Audio and video files were used for behavioral micro-coding. The details of each coding scheme and procedure are described separately in each empirical chapter. In addition, infants and caregivers were wearing head-mounted cameras during interaction tasks, however, these data are not reported in the present thesis.

Chapter 2: Developmental changes in limb movement coordination across the first year of life: the emergence of task-related differences

Chapter 2: Developmental changes in limb movement coordination across the first year of life: the emergence of task-related differences

The preliminary and partial version of the dataset was previously published in:
Laudańska, Z., López Pérez, D., Radkowska, A., Babis, K., Malinowska-Korczak, A., Wallot, S., & Tomalski, P. (2022). Changes in the Complexity of Limb Movements during the First Year of Life across Different Tasks. *Entropy*, *24*(4), 552. https://doi.org/10.3390/e24040552

This chapter presents an extended version of the paper published in *Entropy,* with a larger sample, more tasks, and a modified data preprocessing pipeline. However, parts of the Introduction and Discussion sections directly quote the original text of the published manuscript.

Conceptualization: ZL, DLP, AR, KB, AMK, PT
Investigation: ZL, AR, KB, AMK
Data curation: DLP, JDG, SW, ZL
Formal analysis - Movement data anlaysis: DLP, JDG
Formal analysis - Statistical analysis: ZL
Supervision: PT
Funding acquisition: PT
Visualization: ZL
Writing—original draft: ZL
Writing—review and editing: ZL, DLP, PT, SW, AR, AMK, KB
Writing - Editing paper into chapter: ZL

Introduction

The first empirical chapter of this thesis aims to provide an answer to Research Question 1: Do infants' between-limbs motor coordination patterns become task-dependent across the first year of life?

Particular situational contexts may encourage highly structured and repetitive patterns of limb movements - for example, rhythmic activities such as drumming or rattle shaking. Infants' movements during drumming become faster and more regular with age (Rocha et al., 2021), and the rhythmic synchronization is usually not limited to arm movements but diffuses throughout the body (Hoehl et al., 2021). This increase in the regularity of movements may result in a developmental decrease in the complexity of limb movements. On the other hand, the lack of structure in unconstrained play with exploratory toys may be related to a developmental increase in the complexity of limb movements, as older infants can selectively use hands in varied ways to manipulate objects while using legs to stabilize their position or move around. Finally, some types of play, such as book-sharing, promote actions in vocal, rather than motor, modality, so there may not be clearly distinguishable patterns of coordinated limb movement during this type of activity. Thus, the context and task demands are important when evaluating the complexity of limb movements.

However, the ability to adjust movements to specific task demands may depend on several factors. Firstly, during the transition to more upright body postures such as sitting and standing (which typically happens in the second half of the first year of age), infants learn to better use their arms and hands for reaching for objects and exploring them (Harbourne et al., 2013; Marcinowski et al., 2019; Soska et al., 2010), which may contribute to differential patterns of upper and lower limb movements. Secondly, the increase of postural control allows for using upper limbs for purposes other than stabilization of body position. Infants aged 6 and 7 months present trunk control mostly in the thoracic region (Greco et al., 2018), and the acquisition of trunk control in the lumbar region between 4 and 6 months of age has a positive impact on the quality of reaching behavior (Rachwani et al., 2013). Infants begin to show full trunk control from 8 to 9 months of age (Greco et al., 2018). Postural control and freeing arms from their supporting role may be key for the execution of more precise arm movements. Thus, the main hypothesis here is that task-related differences in limb movement coordination would be present from 9 months of age.

Abney et al. (2014) demonstrated that infant development can be studied as a complex system with analytical tools derived from nonlinear dynamics. Studies on motor development have traditionally focused on quantifying changes in individual limb movements (i.e., reaching hand) or in pairs (either hands or legs), but not all four together. Here, we apply the Multidimensional Recurrence Quantification Analysis (MdRQA, Wallot, 2016) to investigate the changes in movement complexity of all limbs together. MdRQA, in contrast to other methods, is a dynamical systems method that allows for quantifying the dynamics of a multidimensional system at different levels of description by combining information from multiple variables (n > 2) and can be used to infer the shared dynamics of multiple time series (Wallot, 2016) – for example, the movement time series of all four limbs. Those shared dynamics are later summarized in a series of parameters that provide information about the complexity of the time series.

Here, we combine wearable motion trackers and MdRQA to study the developmental change in the complexity of infants' limb movements across three different types of infant-parent play: rattle-shaking, playing with manipulative toys, and book-sharing. We hypothesized that the trajectories of the complexity of limb movements would differ between the tasks, with the age-related decrease in complexity in the rattles task and the increase in complexity in the play with manipulative toys, and the in-between values of complexity for the book-sharing task, related to the lack of consistent limbs' motor actions during this type of activity.

Methods

Participants

The subsample of the group described in Chapter 1, which contributed valid movement data, was included in the analysis (see Table 2.1 for an overview).

Table 2.1. Sample Characteristics

Time Point	**Book-sharing**		**Play with manipulative toys**		**Rattle-shaking**	
	N	**Mean age (SD); Range**	**N**	**Mean age (SD); Range**	**N**	**Mean age (SD); Range**
T1	64	4.32 (0.28); 3.9-5.2	67	4.31 (0.27); 3.9-5.2	64	4.33 (0.28); 3.9-5.2
T2	79	6.60 (0.37); 6.0-7.6	87	6.60 (0.39); 6.0-7.8	85	6.60 (0.40); 6.0-7.8
T3	70	9.02 (0.30); 8.3-9.8	77	9.07 (0.35); 8.3-10.2	77	9.02 (0.35); 8.3-10.2
T4	55	12.14 (0.52); 11.5-14.5	51	12.09 (0.55); 11.0-14.5	59	12.14 (0.53); 11.0-14.5

Procedure

The procedure and tasks are described in Chapter 1.

Movement data pre-processing

IMU data from sensors placed on both wrists and ankles of an infant were processed in Matlab (Mathworks, Inc, Natick, USA) using in-house scripts. The acceleration data were selected for further analysis.

The IMU tracking system, which measures the sensor's orientation, operates wirelessly through Wi-Fi. However, occasional issues with wireless connectivity led to missing values in the IMU data. These missing values were primarily caused by internal features of the IMU sensors and automatic adjustments in the sampling rate from 60 *Hz* to 40 *Hz*. To ensure the comparability of time series data, missing values in the packages were interpolated using Matlab functions such as *fillmissing(*'linear'*)* and *interp1* with 'spline' parameter. When a lower sampling rate was detected in *.mtb* files, the signal was resampled using the *resample* Matlab function. No filtering was applied to preserve all characteristics of IMU signals. Additionally, to integrate the acceleration information, acceleration displacement $AccD$ (Equation 1) was calculated as the square root of the sum of squared displacements in each dimension:

$$AccD = \sqrt{x(t)^2 + y(t)^2 + z(t)^2} \quad (1)$$

where $x, y, z, \in \mathbb{R}^{1x\mathbb{N}}$, and the variables $x(t), y(t), z(t),$ represent the coordinates of a point at time t in three dimensions: the x, y, and z axes."

These processing steps were crucial to ensure the quality and reliability of the IMU data for further Multidimensional Recurrence Quantification Analysis and interpretation in studying infant movement patterns.

Time series analysis: Multidimensional Recurrence Quantification Analysis (MdRQA)

Recurrence methods such as the classical Recurrence Quantification Analysis (RQA), which involves the study of recurrent patterns in a system's trajectory (Marwan et al., 2007), have been widely used to capture the temporal dynamics of dynamic systems. The proper assessment of a system’s dynamics involves the consideration of its multidimensional nature – for example, by assessing different physiological, behavioral, or emotional processes – as it is generally accepted that one single modality of measurement (heart rate, movement) does not provide complete accuracy regarding the underlying processes and mechanisms of such complex system (Wallot & Leonardi, 2018).

Multidimensional Recurrence Quantification Analysis (MdRQA) is an extension of the traditional RQA developed for multidimensional time series (Wallot & Leonardi, 2018). MdRQA, like other recurrence analyses, measures how our variables of interest repeat their values or trajectories over time (Wallot et al., 2016). It can be employed to analyze multiple layers of data (time series) within individuals (multivariate/multidimensional system) or joint dynamics of a group of variables (or individuals) over time (Wallot et al., 2016). This technique extends the study of systems' trajectories to multiple dimensions and allows for the investigation of interactions between variables or levels of analysis.

Recurrence analyses are based on a phase space reconstruction employing time-delayed embedding (Wallot et al., 2016). In MdRQA, multiple recorded time series are embedded into a single phase space, where each time series provides one or more (in case time-delayed copies embed the time series) dimensions in the phase space reconstruction (Wallot & Leonardi, 2018). Thus, MdRQA quantifies the dynamics of high-dimensional signals, considering the phase space of multiple time series of a system (or systems) as the starting point (Wallot et al., 2016).

The logic of estimating the delay and embedding dimension parameters is the same as employed in RQA (Wallot et al., 2016). The parameters used in this case were delay = 1, embedding dimension = 10. In this chapter, we extracted two measures that are based on the MdRQA:

- **Entropy** (Ent): it is the Shannon entropy of the distribution of the diagonal lines on the recurrence plot, capturing repeating movement patterns.
- **Mean Line** (ML): it is the average length of repeating patterns in the system. It can be understood as a measure of the overall system's stability.

Statistical analyses

To assess the repeated-measures effects of time point (4) and task (3), we ran the General Estimating Equations (GEEs) with a Bonferroni correction for pairwise comparisons for entropy and mean line separately. GEEs are particularly useful for longitudinal data because they take into account the dependency and ordering of the data within subjects in repeated-measures designs. Furthermore, in the GEE analysis, even if a subject is missing one or more of the repeated measurements, the remaining data of that subject are used in the analysis. The statistical analysis was run in R version 4.3.1 (2023-06-16) and RStudio (2023.06.0+421) using *tidyverse*, *geepack* and *emmeans* libraries and visualized using *ggplot2*.

Results

Table 2.2. Descriptive statistics

		T1			T2			T3			T4		
		Mean (SD)	**Min**	**Max**	**Mean (SD)**	**Min**	**Max**	**Mean (SD)**	**Min**	**Max**	**Mean (SD)**	**Min**	**Max**
Book-sharing	**Ent**	4.78 (0.31)	3.94	5.56	4.99 (0.53)	3.40	6.06	2.41 (0.59)	2.41	6.26	5.05 (0.73)	2.77	6.74
	ML	13.00 (2.96)	7.37	23.22	15.70 (6.05)	5.60	35.18	16.34 (6.03)	3.72	33.15	18.53 (12.00)	4.04	68.88
Playing with manipulative toys	**Ent**	13.69 (3.49)	9.06	26.45	4.91 (0.52)	3.73	6.11	4.98 (0.58)	3.29	6.23	4.63 (0.71)	2.55	5.82
	ML	4.85 (0.30)	4.34	5.82	14.98 (6.04)	6.54	39.89	16.09 (6.51)	5.21	35.66	12.93 (5.840	3.68	30.25
Rattle-shaking	**Ent**	4.88 (0.27)	4.40	5.68	4.99 (0.50)	3.08	5.92	5.20 (0.60)	3.98	6.81	5.15 (0.60)	2.94	6.14
	ML	14.04 (3.38)	9.48	23.04	15.41 (4.93)	4.63	33.11	18.97 (8.97)	7.36	62.02	17.79 (6.40)	4.36	32.80

Entropy – the measure of the motor system's complexity

For entropy (see Fig. 2.1 and Table 2.2.), the GEE with time point (4) and task (3) as within-subject factors showed the main effects of time point (Wald $\chi 2(3) = 32.1$, $p < 0.001$) and task (Wald $\chi 2\ (2) = 18.4$, $p < 0.001$) as well as significant interaction effect (Wald $\chi 2(6) = 18.0$, $p = 0.006$). The entropy was higher during rattle-shaking than play with manipulative toys ($p=0.003$) at T4. The value of entropy during book-sharing was in between rattle-shaking and play with manipulative toys, but the differences with either task were not statistically significant. Importantly, there were no significant task differences at the earlier three time points (T1-T3), which shows the progressive emergence of specialization to task demands across the first year of life.

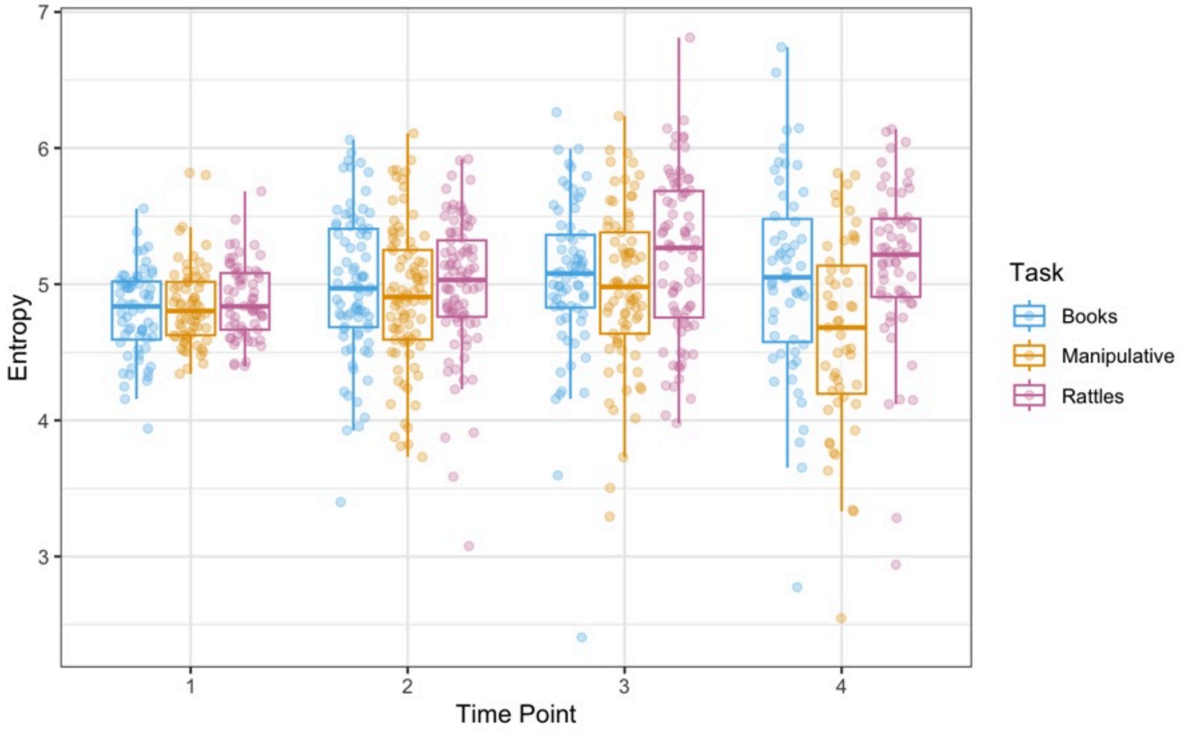

Fig. 2.1. Boxplots showing entropy at each time point during book-sharing (blue), playing with manipulative toys (orange), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

Mean Line – the measure of the motor system's dynamic stability

For the mean line (see Fig. 2.2 and Table 2.2.), the GEE with time point (4) and task (3) as within-subject factors showed the main effects of time point (Wald χ2(3) = 57.9, p < 0.001) and task (Wald χ2 (2) = 14.5, p < 0.001) as well as significant interaction effect (Wald χ2(6) = 21.9, p = 0.001). Similar to entropy, the value of the mean line was also higher during rattle-shaking than play with manipulative toys (p=0.002) at T4. The mean line value during book-sharing was between rattle-shaking and play with manipulative toys, but the differences were not statistically significant. Again, there were no significant task differences at the three earlier time points (T1-T3).

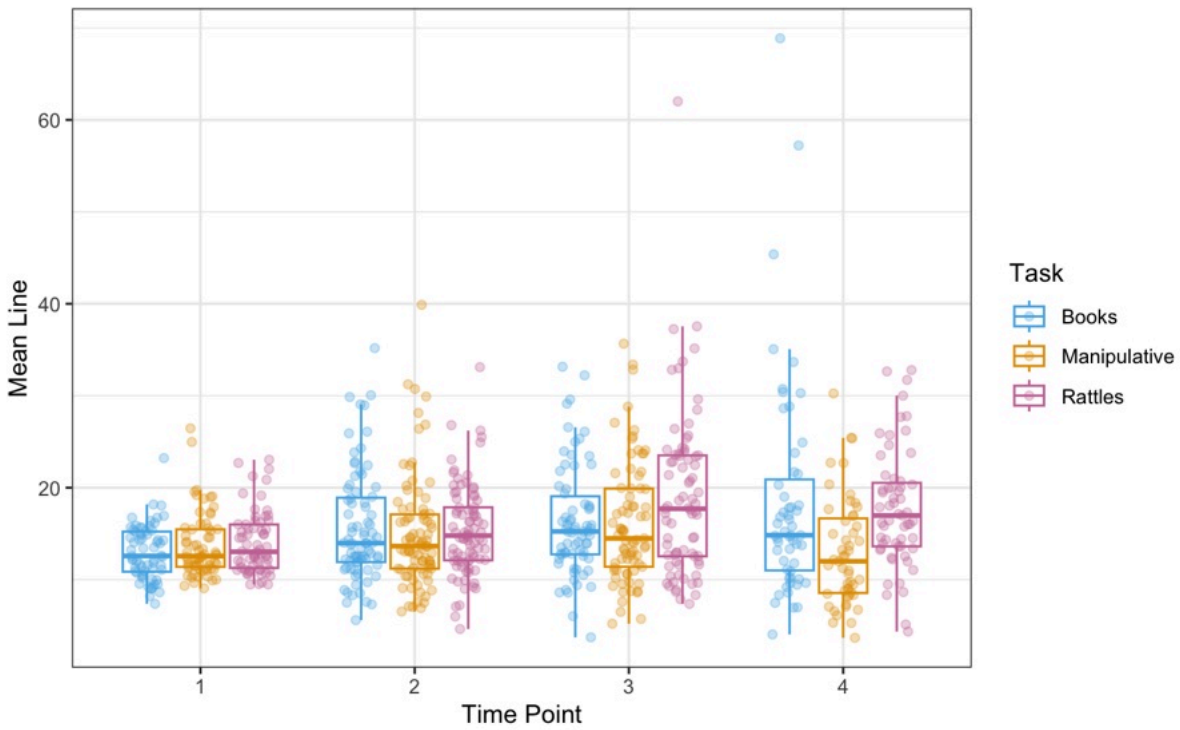

Fig. 2.2. Boxplots showing mean line values at each time point during book-sharing (blue), playing with manipulative toys (orange), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

Discussion

This chapter showed that limb movements' complexity and dynamic stability change across infancy. In a longitudinal study, infants' limb movements were recorded at around 4, 6, 9 and 12 months of age in three games that differed in task demands – with more constrained and repetitive rattle-shaking, more free-flowing object exploration during play with manipulative toys and book-sharing, which promotes vocal rather than motor interactions. To investigate the changes in the complexity of all four limbs, the Multidimensional Recurrence Quantification Analysis (MdRQA) was applied.

The results showed that the complexity measures (entropy and mean line) are modulated by the task at 12 months but not at 4, 6, or 9 months of age. These findings reflect an increase in infants' motor control, allowing for stable body positioning and easier execution of limb movements. Increased motor control is related to an overall increase in the motor system's complexity as the infant can adjust movements specifically to the task.

The results provide further insight into the early developmental organization of motor actions. Previous studies showed that the global pattern of inter-limb coordination varies with changing contexts because the behaviors are adapted and selected to fit a given task

(Thelen & Smith, 1994). The motor system continues to specialize across infancy to respond to particular environmental pressures (Goldfield, 1995). In our case, each task qualitatively required different acts – rhythmic body movements to produce the rattling sound or various reaching and holding acts to explore different objects – and infants learned how to adjust their behaviors to the specific context with age. This suggests that limb movement organization becomes context-specific by the end of the first year of life. This is in line with recent studies showing that less experienced infants generate multiple inconsistent coordination patterns, while more experienced infants tailor their coordination patterns to body–environment relations and flexibly switch solutions (e.g., Soska et al., 2012; D'Souza et al., 2017; Ossmy & Adolph, 2020). Overall, this analysis is an important step in understanding changes in the complexity of limb movements in infancy.

It showed for the first time that MdRQA measures are sensitive to changes in the dynamics of limb movements between tasks and that the observed patterns do not form randomly, as was shown in comparisons with the shuffled time series. This result is in line with previous studies suggesting that infants' development can be studied as a complex system with the tools from nonlinear dynamics (Abney et al., 2014). Moreover, MdRQA goes one step further than traditional methods as it allows for estimating the complex dynamics of multiple effectors ($n > 2$) and, therefore, characterizing the complexity of the developmental organization of motor actions in more detail. Nevertheless, MdRQA can be further extended to assess the coupling between multidimensional time series (Wallot, 2019). Therefore, methods like MdRQA offer new ways to understand how limb movements impact different areas of development, like vocal production or visual attention. They can also help with studying infant-parent interactions.

Conclusion

This chapter showed higher entropy and longer mean line during rattle-shaking than during playing with manipulative toys (with values for book-sharing in between these two tasks), suggesting that infants’ motor system’s stability and complexity become task-dependent by the end of the first year. This pattern indicates a significant increase in specialization to task demands in limb movement coordination.

Chapter 3 Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers

Chapter 3: Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers

This chapter directly presents already published results in the original form:
Laudańska, Z., López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. *Frontiers in Psychology*, 13, 896319. https://doi.org/10.3389/fpsyg.2022.896319

The Methods and Results sections almost directly quote the original text of the published manuscript. The Introduction and Discussion are modified to better fit the flow of argumentation of the present thesis.

Author Contributions

Conceptualization: ZL, DLP, AK, AR, KB, AMK, PT
Coding of infants' rattling: ZL 126 recordings, AK: 26 recordings for reliability coding
Movement data analysis: DLP
Statistical analysis: ZL
Funding acquisition: PT
Investigation (Data collection): KB, AMK, ZL, AR, AK
Project administration: PT, ZL, KB, AMK
Supervision: PT
Visualization: ZL, DLP
Writing – Original paper draft preparation: ZL
Writing – Review & Editing of the paper: ZL, DLP, AK, AR, KB, AMK, PT
Writing - Editing paper into chapter: ZL

Introduction

Chapter 2 showed that limb movement organization becomes context-dependent by the end of the first year of life. These results indicated that rhythmic play with rattles results in the most distinguishable pattern of limb movements among the three studied tasks, with the highest entropy and mean line values at 12 months of age. However, MdRQA focuses on broad and high-level coordination across the entire time series and does not allow for capturing more subtle aspects of emerging motor coordination. Thus, this chapter will examine the specific type of motor action – arm movements during rattle-shaking. Repetitive and recurrent movements are an opportunity to practice specific types of limb movements and to master their execution, so investigating them offers a unique opportunity to capture the formation of synergies.

Generally, a rhythm can be defined as a sequence of short and repeated intervals, with regularities that allow us to build expectancies when the next beat arrives (Jones, 1976), or as a recurrent nonrandom temporal pattern of actions that may not be strictly regular (Jaffe et al., 2001). Across early development, infants produce various rhythmic behaviors (e.g., kicking, rocking, waving) with a peak period of rhythmic hand-banging around 6–7 months of age (Thelen, 1979, 1981). The ability to keep a steady beat and produce a spontaneous motor tempo emerges earlier than the ability to synchronize to an external beat (Provasi and Bobin-Begue, 2003; Zentner and Eerola, 2010; Provasi et al., 2014). Infants' spontaneous motor tempo during drumming was observed from 5 months of age. It is slower than the adult one, and it becomes faster and more regular with age (Rocha et al., 2021a, 2021b).

In the present study, we investigated how infants' spontaneous rhythmic behavior in the social context of play changes across the first year of life. Our main goal was to study the developmental changes in motor coordination between arm movements during rattle-shaking. Furthermore, we also studied whether infants produce more rhythmic arm movements as they grow older and whether they do it at a higher frequency. We studied the changes in rhythmic arm movements in a naturalistic set-up: mother-infant dyads were invited to play together in the lab. Their interactions were video-recorded, which enabled us to annotate, during which episodes infants were rattling.

To this end, we first recorded infants' arm movements using wearable motion trackers (Inertial Motion Units, IMUs) in a rattle-shaking task during parent-infant interactions when infants were around 4, 6, 9 and 12 months of age. Second, we identified and manually annotated the episodes when infants were rattling to include only this type of activity in further analyses. Thirdly, we calculated the number of rattle shakes (i.e., infant arm movements with a rattle) in a data-driven way. This, in turn, allowed us to calculate the rattling frequency and the coordination between the movements of both arms. To assess the degree of coordination between the infants' two arms, we used acceleration data recorded by motion trackers to measure wavelet coherence. Wavelet coherence captures information on a range of constituent frequencies of the signal across the recorded interaction (e.g., Grinsted et al., 2004; Hale et al., 2020).

We hypothesized that 1) infants would be able to produce more rhythmic arm movements with age (Rocha et al., 2021a, 2021b), 2) they would rattle at a higher frequency with age and 3) their between-arms coordination (measured with wavelet coherence) would increase with age.

Methods

Participants

The subsample of the group described in Chapter 1, which contributed valid movement and video data, was included in the analysis (see Table 3.1 for an overview).

Table 3.1. Sample Characteristics

Time Point	N	Mean age in months (SD)	Min age in months	Max age in months
T1	31	4.35 (0.29)	3.90	5.20
T2	35	6.55 (0.36)	6.00	7.40
T3	39	9.14 (0.39)	8.60	10.20
T4	21	12.05 (0.37)	11.60	13.10

Procedure

The overall study design is described in Chapter 1 – this chapter is focused specifically on the rattle-shaking task. In this task, which lasted approximately 5 minutes, caregivers were instructed to play with their infants using the provided rattles in their preferred way. They were given two maracas rattles and two other rattles of different types (smaller and lighter barbell rattles at T1 and T2 and bigger teddy bear rattles at T3 and T4, see Fig. 3.1). At the beginning of each game, the caregivers were asked to clap several times to mark the start of the procedure to synchronize wearable sensors with video recordings. The infants' body position was not constrained and both the mother and the infant were free to move around the room. Therefore, the sitting arrangement varied between visits and could change during each visit. The most common body position at T3 and T4 was independent sitting, whereas for T1 and T2 it was lying either in a prone or a supine position.

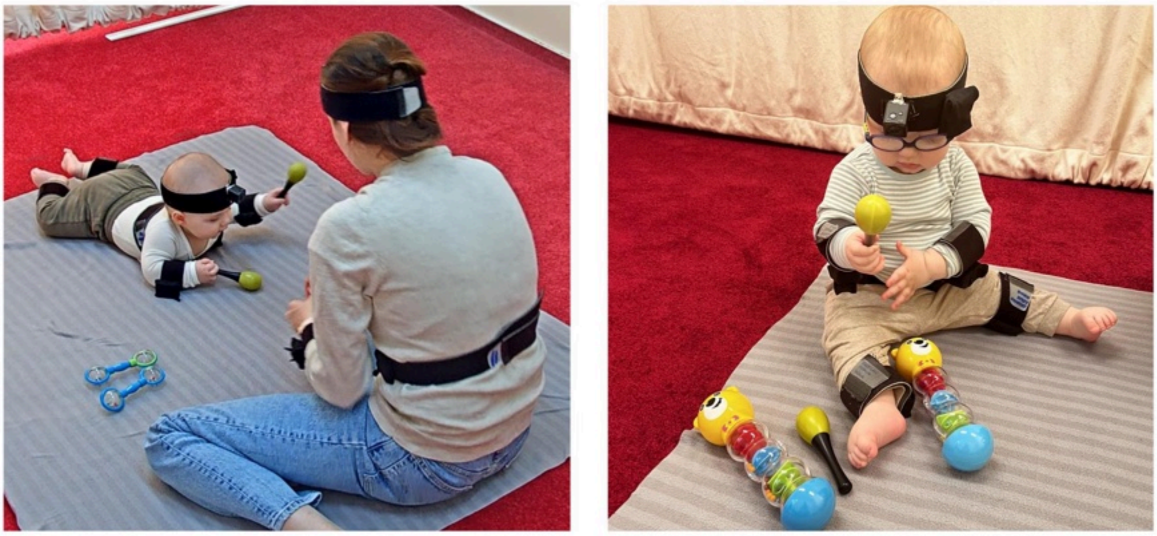

Fig. 3.1. Photos of the toys used in the rattle-shaking play at T1 and T2 (left), T3 and T4 (right). Signed permission of the caregiver was acquired for the publication of the images. Reproduced from Laudanska, Z., López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. Frontiers in Psychology, 13. https://doi.org/10.3389/fpsyg.2022.896319

Manual annotation of rattling

In each video recording, the episodes when infants were rattling as well as mothers clapping for the purpose of synchronization of videos with wearable data were manually annotated by a trained coder (ZL) in ELAN 6.3 (2022) (Sloetjes and Wittenburg, 2008). Firstly, the onset and offset of each clap were identified in a frame-by-frame manner to precisely include the moment of acceleration before joining hands. Secondly, the onset and offset of each infant rattling episode were annotated. We defined a rattling episode as a period when an infant was holding at least one rattle and made at least one movement that produced the rattling noise. Instances of an infant generating the rattling sound unintentionally (e.g., while holding a rattle during crawling or throwing it) were not annotated. Each episode ended if 1) the infant dropped the rattle or 2) was holding the rattle but not making any arm movements. Periods, when an infant did not wear motion trackers on both arms, were not annotated and excluded from the analyses. Periods when the mother was moving the infant's arms were not annotated.

In total, 126 videos were annotated. Videos during which mothers did not clap were excluded from further analyses (N = 3, two at T1, one at T3) due to problems with synchronizing motion trackers' data with video recording. Similarly, videos during which the infant did not make any rattling movements were excluded from further analyses (N = 5, two at T1, two at T2, one at T3). In order to establish the inter-rater reliability, 26 randomly selected videos (20%) were annotated separately by two trained coders (ZL & AK). Inter-rater reliability was performed in ELAN and estimated using Cohen's κ statistic, which takes into account chance agreement. Cohen's κ for rattling episodes was 0.79, which can be interpreted as substantial agreement (Landis and Koch, 1977).

Data pre-processing

Acceleration data from sensors placed on both wrists of an infant were processed in Matlab 2019 and specialist toolboxes (Mathworks, Inc, Natick, USA) using in-house scripts. First, missing samples were identified and interpolated using the interp1 function with cubic spline interpolation of the values at neighboring grid points. Then we collapsed the kinematic vectors obtained from the IMUs into a unique normalized dimension (a one-dimensional overall acceleration time series) as follows:

$$Acc = \sqrt{x(t)^2 + y(t)^2 + z(t)^2}$$

where $x, y, z, \in \mathbb{R}^{1x\mathbb{N}}$, and the variables $x(t), y(t), z(t),$ represent the coordinates of a point at time t in three dimensions: the x, y, and z axes.

Next, data were smoothed using the *medfilt1* function that applies a third-order median filter to remove one-point outliers by replacing each value with the median of three neighboring entries.

Synchronization of sensor data and annotated videos

Video and sensor data for each infant and visit were later synchronized using the mothers' hand-clapping movements. To this end, a graphical user interface (GUI) loaded the sensor data to manually select the period when the clapping occurred. Then, we categorized the manually selected sensor periods from the GUI as "1" and "0", where 1 indicated movements that were one standard deviation above the mean acceleration in that period and 0 otherwise. Next, the time series outside the selected clapping period was set to 0. Finally, we merged those automatically detected claps separated by 50 ms or less to avoid artifactual claps due to extremely short claps or claps close together. This process resulted in a time series that contained only the mothers' claps. In the next step, this was used to find the delay between the IMUs data and the manually coded video data. To find this delay, we used diagonal cross-recurrence quantification analysis (DCRP) (e.g., Richardson and Dale, 2005) using two different time windows (a shorter window of 6 s and a longer one of 15 s). We calculated the lag profile using a Matlab version of the R function *drpdfromts* (CRQA R-package) (Coco and Dale, 2014). Generally, the experimenter initiated video and sensor recordings closely in time, so the lag between them usually was not longer than 6 s. Initially, the algorithm estimated the delay using the 6-s time window and loaded a GUI plotting both the sensor data and the manually coded data. This process asked the user to visually inspect and validate the proper alignment of the data. In 7% of cases, the lag between sensor and video data was longer than 6 s. Therefore, in these cases, we repeated the previous step, using a 15-second-long time window. Again, the alignment was visually inspected. Subsequent analyses were performed on the temporally aligned time series.

Wavelet coherence analysis of arm movements

Wavelet coherence (WC) is a relative measure of how well correlated the power and phase of two signals are at a given frequency and time (Grinsted et al., 2004) and it is defined as the squared absolute value of the smoothed cross-wavelet spectrum normalized by the product of the smoothed individual wavelet power spectra, as follows:

$$WC = \frac{\left|S(C_x^{*}(a,b)C_y(a,b))\right|^2}{S(|C_x(a,b)|^2)\cdot S(|C_y(a,b)|^2)}$$

where *Cx(a,b)* and *Cy(a,b)* denote the continuous wavelet transforms of *x* and *y* (with x and y indicating time series of an infant's left and right arm movements) at scales a in frequency and positions *b* in time. The superscript * is the complex conjugate and *S* is a smoothing operator in time and scale. The dot in the denominator indicates a product between the individual wavelet spectra of both time series.

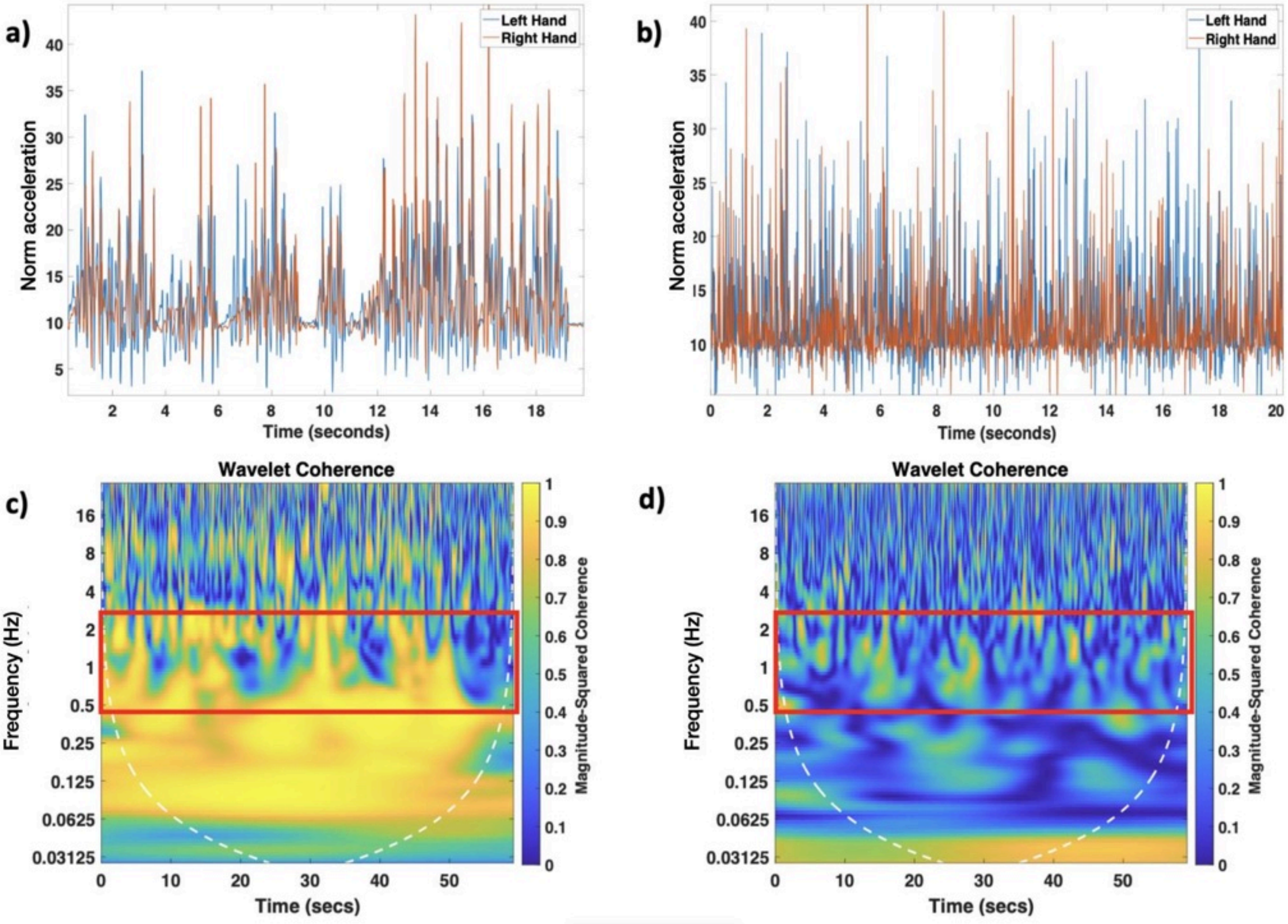

Fig. 3.2. Example of the time series created by joining together the rattling episodes of both arms using the manually annotated data (2a). Image 2b represents the randomized version of the rattling time series. Only the first 20 seconds are shown to ease representation. Images 2c and 2d represent the wavelet coherence spectra of movements of both arms using the original rattling time series and the randomized version, respectively. Highlighted with a red rectangle are the areas where the average wavelet coherence was computed. Reproduced from Laudanska, Z., López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. *Frontiers in Psychology*, 13. https://doi.org/10.3389/fpsyg.2022.896319

Wavelet coherence has a value between 0 and 1, where 0 means that no coherence is present between signals and 1 means that both signals are fully coherent at any given time and frequency. Wavelet coherence closely resembles a traditional correlation coefficient, and it can be interpreted as a localized correlation coefficient in time-frequency space (Grinsted et al., 2004).

Here, we estimated the wavelet coherence between movements of each hand using the *wcoherence* function in Matlab. To this end, manually annotated episodes of rattling were used to estimate the average duration of each rattling episode and to segment the wearable data (see Fig. 3.2a for an example and Fig. 3.2c for its computed wavelet coherence spectra) and to identify the number of rattling movements using an in-house Matlab script. We estimated rattling movement events following the same approach we used to calculate the clapping events. We categorized the rattling periods as “1” and “0”, where 1 indicated movements that were one standard deviation above the mean acceleration and 0 otherwise. Then we merged those automatically detected movements separated by 50 ms or less to avoid artifactual rattling events due to extremely short movements or movements close together. Next, the rattling frequency was calculated as the number of rattling movements divided by the total duration of rattling time derived from the video annotation data (see Table 2 for descriptives). In all but two visits, infant rattling was within the range of 0.5 and 2.5 Hz. Two cases (one at T2 and one at T4) that had a rattling frequency above 2.5 Hz were considered outliers and excluded from the analysis. Given the range of rattling frequencies, we calculated the average wavelet coherence coefficient within the range of 0.5 and 2.5 Hz for each visit.

Finally, we conducted a control analysis by calculating wavelet coherence between the right and the left arm on the shuffled time-series data from each participant and comparing the mean coherence values of the shuffled data with the original data from all participants. The procedure was iterated 1000 times. This allowed us to show that the wavelet coherence between hand movements did not arise randomly (see Figure 3.2b for an example of the randomized time series and 3.2d for its wavelet coherence spectra). In addition, to investigate developmental changes in the movements of a single hand, we calculated the continuous wavelet transform spectra.

Statistical analysis

First, to investigate the developmental changes in the number of rattling episodes, their mean duration, the number of rattling movements, the frequency of rattling and the between-hands coherence, we ran General Estimating Equations (GEEs) with a Bonferroni correction for pairwise comparisons with age as a repeated measure (T1, T2, T3, T4). GEEs are particularly adequate for longitudinal data because they take into account the dependency and ordering of the data within subjects in repeated-measures designs. Data analysis was conducted in IBM SPSS Statistics 26, figures were created using R (R Core

Team, 2020) and RStudio, version 1.4.1106 (RStudio Team, 2020), and *ggplot2* package (Wickham, 2016).

Finally, for control purposes, we ran two control analyses. In the first one, we excluded infants who had the lowest numbers of rattling episodes (7 rattling episodes or less) to see whether the infrequent rattlers affected the pattern of results. The significance of all main effects remained unchanged, apart from the effect of age on the number of rattling episodes. In the second one, we have re-coded our video data to include only those rattling episodes during which infants consecutively performed at least 4 arm movements in a row that produced a rattling sound. Again, the significance of the main effects remained unchanged, apart from the effect of age on the average duration of a rattling episode.

Results

Number of rattling episodes and the average duration of an episode

The number of rattling episodes (annotated periods when an infant was holding at least one rattle and made at least one movement that produced rattling noise) slightly increased with age (Wald $\chi2(3) = 10.448$, $p = .015$, see Fig.3.3 and Tab. 3.2 for descriptive statistics) as the number of episodes increased between T1 and T4 ($p = .026$). There was also a main effect of age in the analysis of the average duration of a rattling episode (Wald $\chi2(3) = 38.450$, $p < .001$, see Fig.3.3). The average duration was shorter at T1 than at T2, T3 and T4 (all ps < .001).

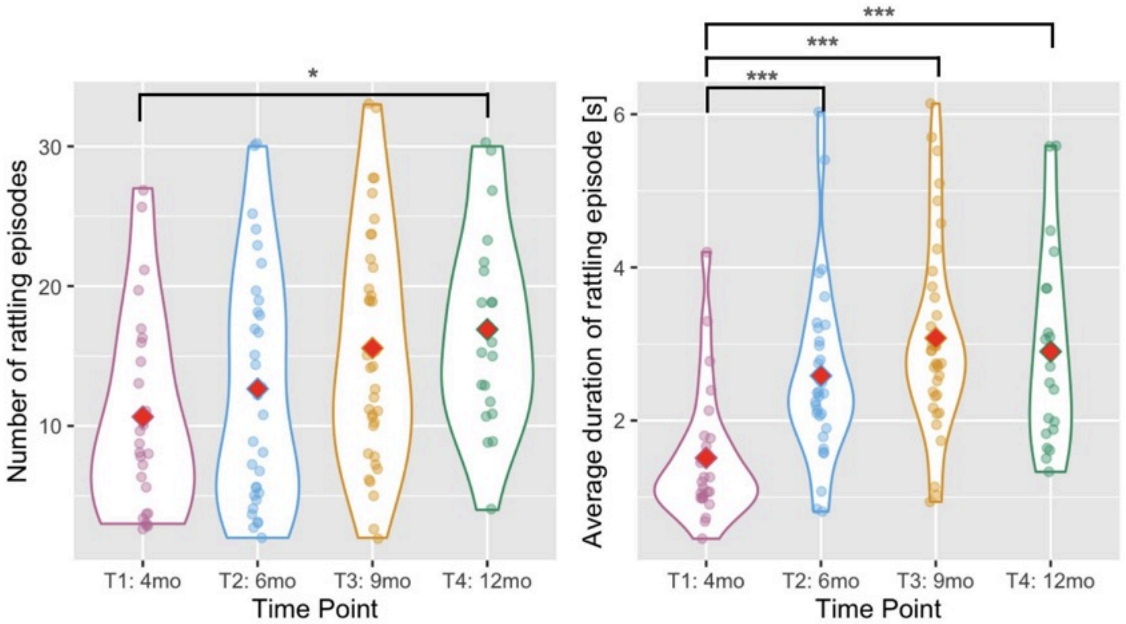

Fig. 3.3. Violin plots showing the number of rattling episodes (left) and the average duration of rattling episode (right) across time points. Red diamonds indicate mean values. A single asterisk indicates significance at p < .05, two asterisks indicate p < .01, and three indicate p < .001. Reproduced from Laudanska, Z., López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. *Frontiers in Psychology*, 13. https://doi.org/10.3389/fpsyg.2022.896319

Number of individual rattling movements

We predicted that infants would be able to produce more rhythmic arm movements with age. To test this hypothesis, we took the number of rattling movements detected automatically in the movement time series during annotated rattling episodes. The number of rattling movements increased with infants' age (Wald χ2 (3) = 129.804, p < .001, see Fig. 3.4), and pairwise comparisons showed that there were significantly fewer rattling movements at T1 than at T2 (p = .002), T3 (p < .001) and T4 (p < .001); and fewer at T2 than at T3 (p = .018) and T4 (p = .001). The difference between T3 and T4 was not significant (p = .465).

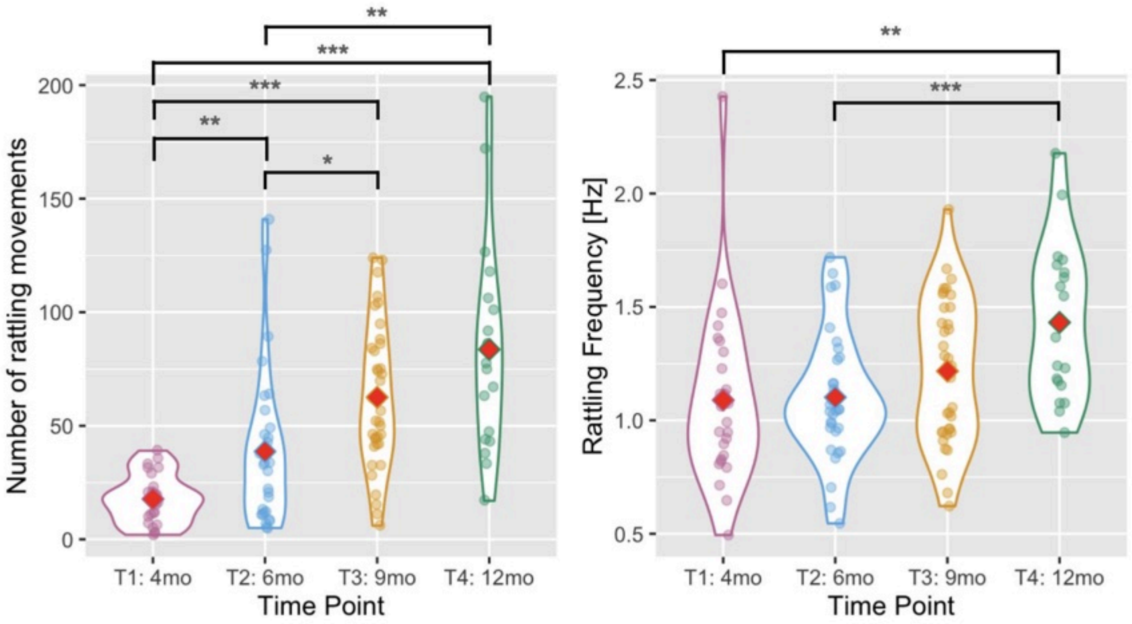

Fig. 3.4. Violin plots showing the number of rattling movements (left) and the rattling frequency (right) across time points. Red diamonds indicate mean values. A single asterisk indicates significance at p < .05, two asterisks indicate p < .01, and three indicate p < .001. Reproduced from Laudanska, Z., López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. *Frontiers in Psychology*, 13. https://doi.org/10.3389/fpsyg.2022.896319

Rattling frequency

The rattling frequency (i.e., the number of rattling movements divided by the total duration of rattling time) increased with infants' age (Wald χ2(3) = 20.498, p < .001, see Fig. 3.4) and it was higher at T4 than at T1 (p = .007) and T2 (p < .001). The difference between T4 and T3 did not reach significance (p = .058).

Between-arms coherence

Average wavelet coherence increased with age (Wald χ2(3) = 49.795, p < .001, see Fig. 3.5) between T2 and T3 (p < .001) and between T3 and T4 (p = .009). It was higher at T4 than at T1 (p = .001) or T2 (p < .001). The difference between T1 and T2 was not significant (p = .224), similarly, there was no difference between T1 and T3 (p = .725).

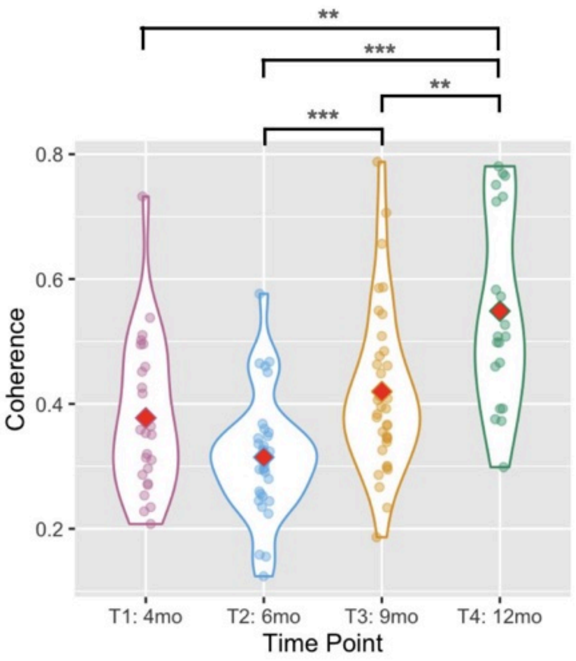

Fig. 3.5. Violin plots showing the between-arms coherence. Red diamonds indicate mean values. Two asterisks indicate p < .01, and three indicate p < .001. Reproduced from Laudanska, Z., López Pérez, D., Kozioł, A., Radkowska, A., Babis, K., Malinowska-Korczak, A., & Tomalski, P. (2022). Longitudinal changes in infants' rhythmic arm movements during rattle-shaking play with mothers. *Frontiers in Psychology,* 13. https://doi.org/10.3389/fpsyg.2022.896319

Control comparisons with shuffled time series

To show that the wavelet coherence of between-arm movements did not arise randomly, we conducted a control analysis by calculating wavelet coherence between the right and the left arm on the shuffled time-series data from each participant and comparing the mean coherence values of the shuffled data with the original data from all participants. These comparisons showed that at T2, coordination between both arms was not different from noise (T2: t(32) = 0.043; p = .966). For T1, T3, and T4, the coherence for observed data was significantly higher than their corresponding shuffled data (T1: t(25) = 2.555; p = .017; T3: t(36) = 5.800; p < .001; T4: t(20) = 6.904; p < .001). The difference between observed and shuffled data at T1 was not significant in the control analysis with excluded infrequent rattlers.

Discussion

This chapter described developmental changes in arm movements in the context of rhythmic rattle-shaking (Research Question 2). Through precise longitudinal measurements using wearable motion trackers, we showed that infants were highly motivated to produce rhythmic manual actions that generated multimodal feedback (rattle-shaking). The number of rattling episodes (periods when the infant was holding at least one rattle and made at least one movement that produced rattling noise) was similar across all visits, suggesting that infants were similarly motivated to attempt rattle-shaking. The mean duration of rattling episodes increased in subsequent months in comparison to the first visit at 4 months as infants' motor control and grasp strength increased. As infants grew older, they also made more rattling movements, and their frequency of rattling increased. Furthermore, infants' arm movements become more coupled during rattle-shaking, as shown by the age-related increase in wavelet coherence, although the developmental pattern was not linear – the coherence decreased between 4 and 6 months to increase again between 6 and 9 as well as 9 and 12. The lower coherence at 6 months and the fact that the coordination between both arms was not different from noise at this time point, may indicate a period of reorganization of the motor system.

We also observed the developmental increase in the power of wavelet spectra of movements of a single hand, with power being highest in the frequency range between 2 and 3 Hz consistently at all time points. This suggests that across the first year of life, it is not the frequency of rattling that changes, but the organization of rhythmicity within the same frequency range.

Younger infants, at 4 and 6 months of age, seem to make fewer rhythmic arm movements, which can be explained by their immature motor control (Goldfield, 1995). Motor control at the subcortical level of the central nervous system emerges and matures mainly during the first year of life, allowing for essential trunk stabilization and body positioning, a prerequisite for reaching and grasping arm movements (Westcott et al., 1997; Dusing and Harbourne, 2010; Kobesova and Kolar, 2014), both of which are necessary for the execution of rhythmic rattling. With emerging postural control, arms can also be less involved in stabilizing the body posture and used more in skilled manual reaching (Hadders-Algra, 2005). Our finding of an increase in the frequency of rattling in the second half of the first year of life suggests that older infants can execute rattling movements with more ease. This is in line with a recent study, which showed that infants' movements during drumming become faster and more regular with age (Rocha et al., 2021a). We also observed a developmental increase in the infants' between-arms coherence, which shows that arm movements become more coupled during rattle-shaking across the first year of life. On the one hand, this could be explained by the fact that older infants are able to play comfortably in a given position and do not need one hand to support themselves while sitting or lying in a prone position. On the other hand, this could be related to an increase in the overall spontaneous rhythmicity of movement. As Hoehl et al. (2021) stated in their review, rhythmic synchronization is usually not limited to a movement of a single limb, but it diffuses throughout the body.

Conclusion

All in all, our results shed more light on the development of infants' spontaneous rhythmic actions during play with the caregiver. We show that infants are motivated to play with rattles already at 4 months, and they keep trying to produce rhythmic arm movements despite constraints related to their limited muscle strength and ability to stay comfortably in a given body position. In line with our predictions, infants produced more rhythmic arm movements with age. The frequency of those movements and infants' between-arms coordination also increased across the first year of life

Chapter 4: Longitudinal Investigation of Coupling between Limb Movements and Vocalizations in Infancy

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Team members involved in the project:

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Contributions:

Conceptualization: PT, ZL, JDG, AR, DLP
Investigation: KB, ZL, AMK
Data Curation – Infants' vocalizations coding (including reliability coding): ZL 695 recordings, KB 337 recordings
Data Curation – Synchronization of audio recordings and movement data: JDG
Movement data processing: JDG
Formal Analysis (Statistical models): JDG, collaboration: PT, ZL, AR
Funding Acquisition: PT
Supervision: PT
Writing – Original Draft Preparation: ZL

Introduction

Chapter 3 characterized the longitudinal changes in infants' rhythmic arm movements during rattle-shaking play, showing their considerable refinement across the first year of life. Especially interesting was the observation that between-hand coherence significantly increases in the second half of the first year of life. Interestingly, rhythmic manual movements often co-occur with infants' vocalizations (Thelen, 1979; Locke et al., 1995; Ejiri, 1998; Ejiri & Masataka, 2001; Iverson & Fagan, 2004; Iverson & Wozniak, 2007; Burkhardt-Reed et al., 2021), suggesting some form of coupling between motor and vocal systems. In adults, arms biomechanically interact with vocalizing by affecting rib cage movements and changing respiratory flow (Pouw et al., 2019; 2020; 2023). Similar co-activations of hand and head movements were also observed in 9- to 24-month-old infants (Borjon et al., 2024). Borjon and collaborators (2024) showed that infants moved before the vocalization onset at all measured time points, as shown by the analysis of rotational velocity of hands and head movements. They also observed age-related differences in the motor-vocal coupling, however, these differences were only related to the timing of body movements and to their co-occurrence with vocalizations. Head and hand movements became more tightly coordinated with the onset of vocalization between 9 and 24 months (Borjon et al., 2024). Intriguingly, preliminary findings with adults show that such motor-vocal coupling also extends to lower limb movements (Serré et al., 2022; but see also Weston et al. 2024 for a different pattern of results).

However, it is unclear whether leg movements are also coupled with speech-like vocalizations and how the coupling between upper and lower limb movements and vocalizations changes across the first year of life (Research Question 3). We predicted that the infant's arms and legs would co-activate around the onset of a vocalization due to motor-vocal-respiratory coupling (Borjon et al., 2024) at all measured time points (4, 6, 9, and 12 months of age). Furthermore, we hypothesized that across the second half of the first year of life, there would be an increase in coupling between arm movements and vocalizations (and a decrease in leg movements coupling) due to the emerging speech-gesture system around the onset of canonical babbling (Iverson & Fagan, 2004).

Methods

Participants

The subsample of 98 infants from the group described in Chapter 1, who contributed valid movement and audio data, was included in the analysis.

Coding of infant vocalizations

For each interaction session, an audio track was extracted from videos using Audacity 2.3.3 software. Then, infants' vocalizations were coded offline from the audio track using PRAAT software (Boersma & Weenink, 2020). The coders (ZL & KB) marked the onsets and offsets of each vocalization at the utterance level. An utterance was defined as a vocalization occurring on one egress (Vihman et al., 1985; Nathani & Oller, 2001). All vocalizations were classified into four distinct, non-overlapping categories (based on Buder et al., 2013): a) reflexive sounds (laugh and cry), b) protophones (the presumed precursors to speech, e.g., squeals, vowel-like sounds, growls, whispers, yells, grunts), c) syllables, and d) words. Reflexive sounds were excluded from further analyses, whereas protophones, syllables, and words were jointly considered „speech-like vocalizations" (Warlaumont et al., 2014) in further analyses.

Movement data processing

The IMU data from sensors placed on both wrists and ankles of an infant were processed in Matlab (MathWorks, 2019) using in-house scripts. The acceleration data were selected for further analysis.

The IMU tracking system, which measures the sensor's orientation, operates wirelessly through Wi-Fi. However, occasional issues with wireless connectivity led to missing values in the IMU data. These missing values were primarily caused by internal features of the IMU sensors and automatic adjustments in the sampling rate from 60 *Hz* to 40 *Hz*. To ensure the comparability of time series data, missing values in the packages were interpolated using the Matlab function *interp1* with ‘spline' parameter. When a lower sampling rate was detected in *.mtb* files, the signal was resampled using *resample* Matlab function. Additionally, to integrate the acceleration information, acceleration displacement *Acc* (Equation 1) was calculated as the square root of the sum of squared displacements in each dimension (Abney et al., 2014):

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

where $x, y, z, \in \mathbb{R}^{1x\mathbb{N}}$, and the variables $x(t), y(t), z(t),$ represent the coordinates of a point at time t in three dimensions: the x, y, and z axes.

Next, signals were filtered with a 2nd order, *1Hz* cut-off highpass Butterworth filter (Parks & Burrus, 1987).

Synchronization of movement and audio data

To ensure that annotations are aligned with IMU sensors, at the beginning of every play, the caregiver was asked to clap with their hands 5 times. Then, the delay between the accelerometric signal and audio annotations (Fig 4.1.) was calculated based on the caregiver claps detected in averaged **Acc** wearable signals from both hands (Fig. 4.2.). Data with signal amplitude above 200 was marked as artifact with *Null* values and was not analyzed in epoched signals.

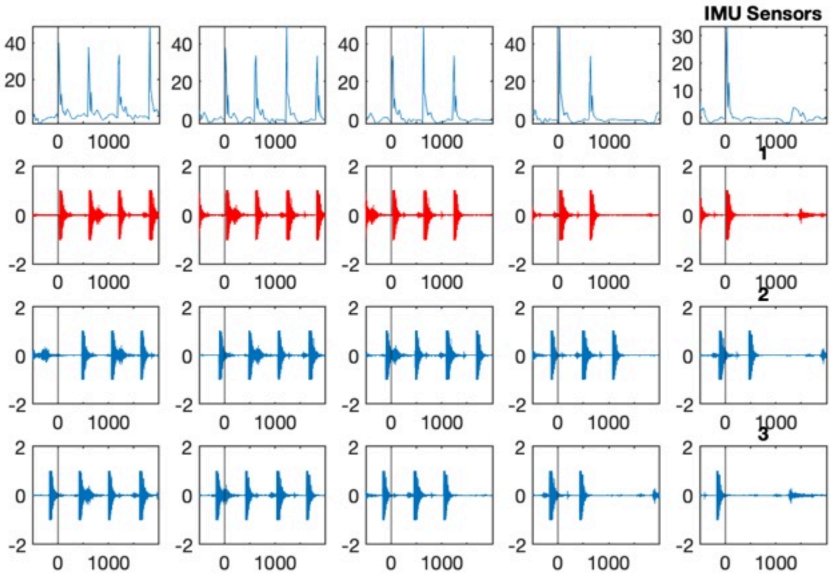


Fig. 4.1. First line: **Acc** IMU sensors signals from mothers' averaged hands representing "claps". Second - fourth line audio track. The red one is the audio that was annotated. Value 0 is the onset of vocalization.

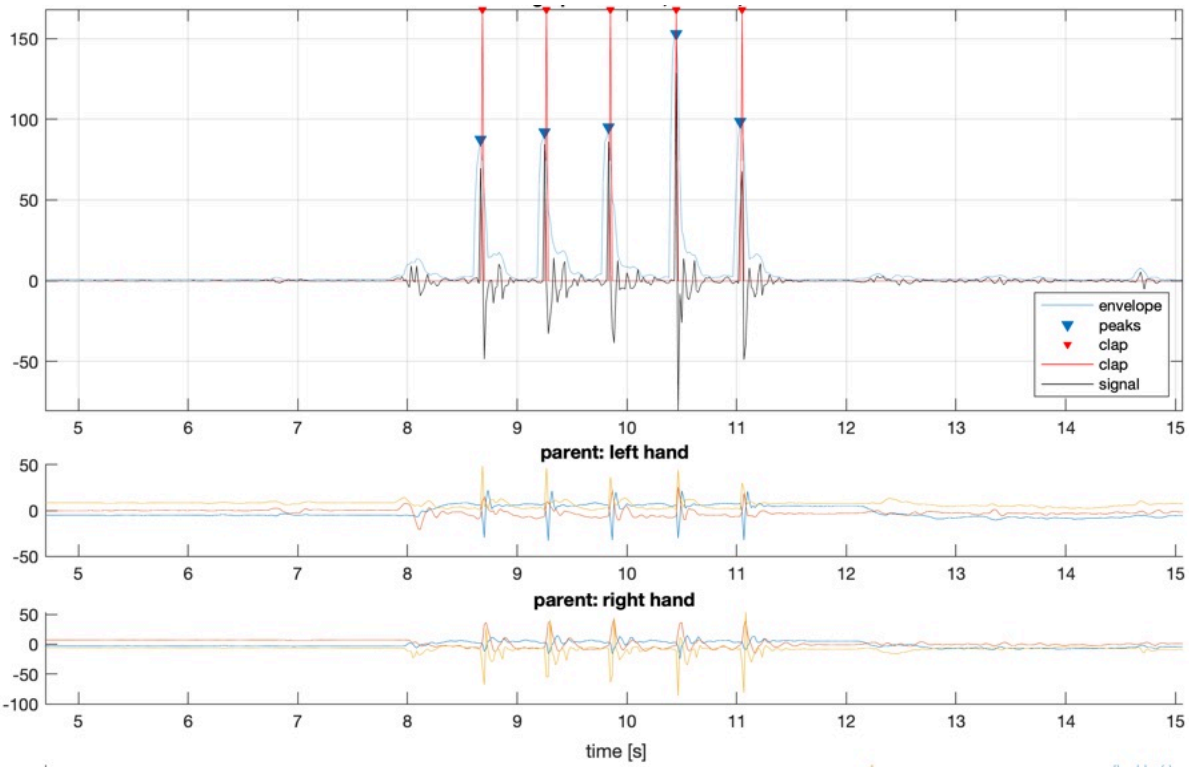


Fig. 4.2. The first line shows “claps” found in the mother averaged **AccD** hand signal. The second and third lines are the separate three-dimensional signals from IMU sensors.

The next step was to investigate changes in wearable signals around the onset of vocalization, marked as 0s. Both audio and **Acc** signals were epoched from -3.5*s* to 5*s*. Because of the nature of IMU accelerometer signals, we needed to apply unconventional baseline correction techniques based on the article by Ouali et al. (2018). For each epoch, a mean value of the upper and lower envelope was extracted from each -3.5*s* to 5*s* segment. Function *envelope*, with ‘analytic' was utilized, which returns the analytic envelope via a 12-tap FIR filter that preserves phase. Because of the sinusoidal character of IMU signals, simple averaging is not the best way to pursue analysis. Therefore, we needed to calculate the analytic envelope via a 12-tap FIR filter from the baselined signal, which is a standard technique for other kinds of accelerometer data (D’Aponte et al., 2016).

Lastly, based on the change of magnitude from the envelope of averaged audio, three time windows were chosen: baseline: -2.5*s* to -0.9*s*, before the vocalization onset: -0.9*s* to 0*s*, and after vocalization onset: 0*s* to 0.9*s*, and those windows were statistically tested.

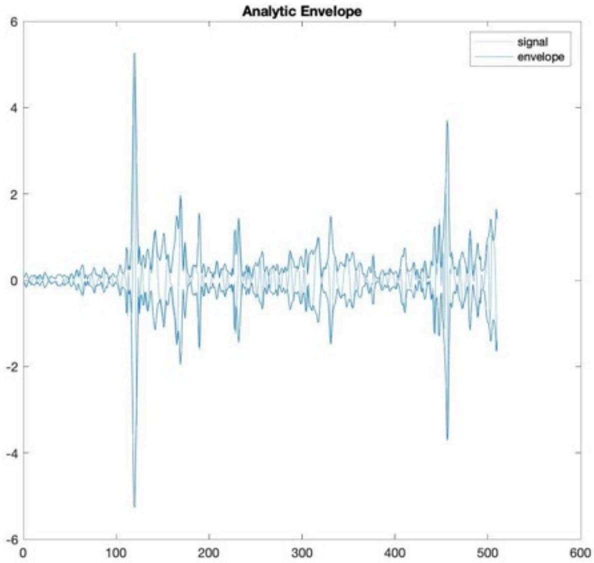


Fig 4.3. Top and bottom envelope of **Acc** signal.

Statistical Analysis

All the statistical analyses were conducted in the R environment (R Core Team). The record for a single vocalization for a given infant, time window, and limb is calculated as the mean of the medians of the signals from the left and right limbs. Data were tested with *lme4* package, which allows for fitting linear mixed (LME) models. Only the model with the best fit is reported here. The random effect was specified to acknowledge the nested structure of our data (infant's limbs nested within an individual). The time point (4, 6, 9, 12 months of age), limb (arms, legs) and time window (baseline, before vocalization onset, after vocalization onset) were included as fixed effects. The formula for the final LME model with best fit was as follows:

$$lmer\ (\, median \sim timepoint\ *\ limb\ +\ time\, window\ +\ (1|\, infant : limb\,)\ +\ (1|\, infant\,)$$

To facilitate the interpretation of results, we show four separate tables with model results, changing the reference level of the time point (T1-T4 in tables 4.1 - 4.4).

Results

We found a significant main effect of time window as both the period immediately before ($p < 0.001$) and after ($p < 0.001$) vocalization onset differed from the baseline. We also found the main effect of time point, as all four time points differed from each other (all *p*s < 0.001, see tables 4.1-4.4).

Finally, we also found a significant interaction effect between the time point and limb that captured the developmental change in the co-activation of limbs with the vocalization onset. At T1 (4 months), there was a comparable co-activation of arms and legs and the effect of limb was not significant. At T2 (6 months), the activation of legs was higher than the activation of arms (*p* < 0.001). In contrast, at T3 and T4, this pattern was reversed, as the activation of arms was higher than the activation of legs (both *p*s < 0.001).

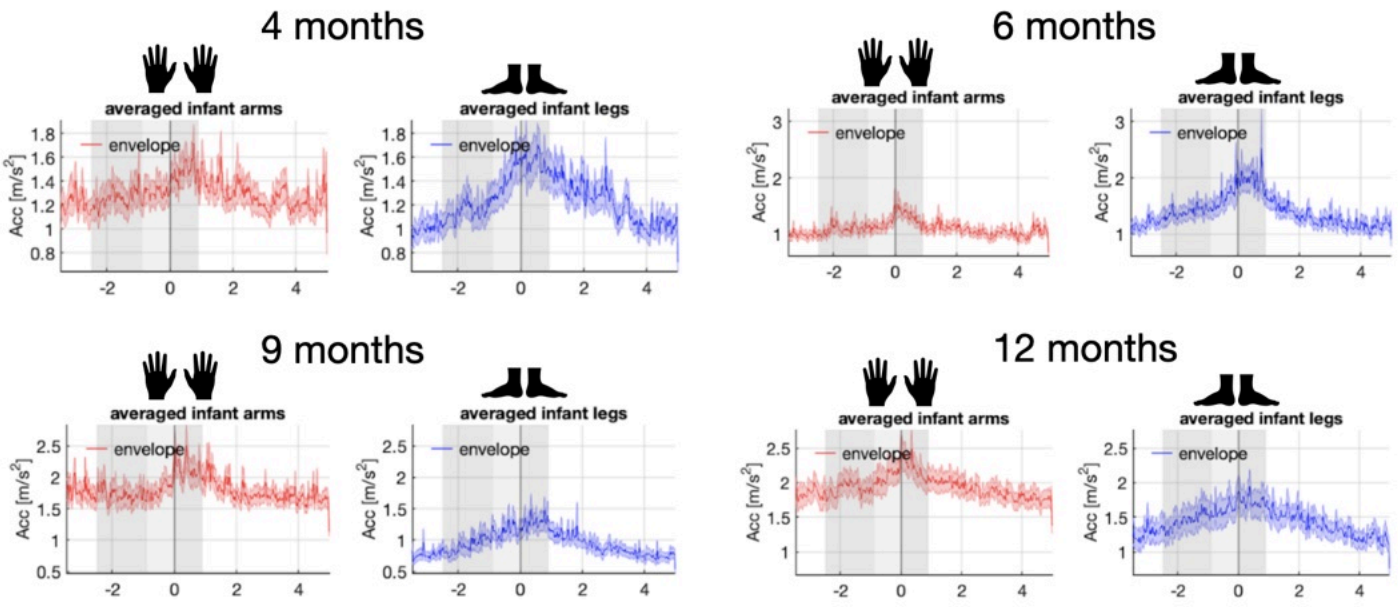


Fig. 4.4 Acceleration (m/s2) of limb movement around the vocalization onset. The X-axis shows 3.5s before and 5s after the vocalization onset (indicated by zero). The three analyzed time windows are indicated by shaded areas of the plot: baseline (-2.5s to -0.9s), period before the onset (-0.9s to 0) and period after the onset (0 to 0.9s). Please note that different scales are used on y-axes between time points to improve readability.

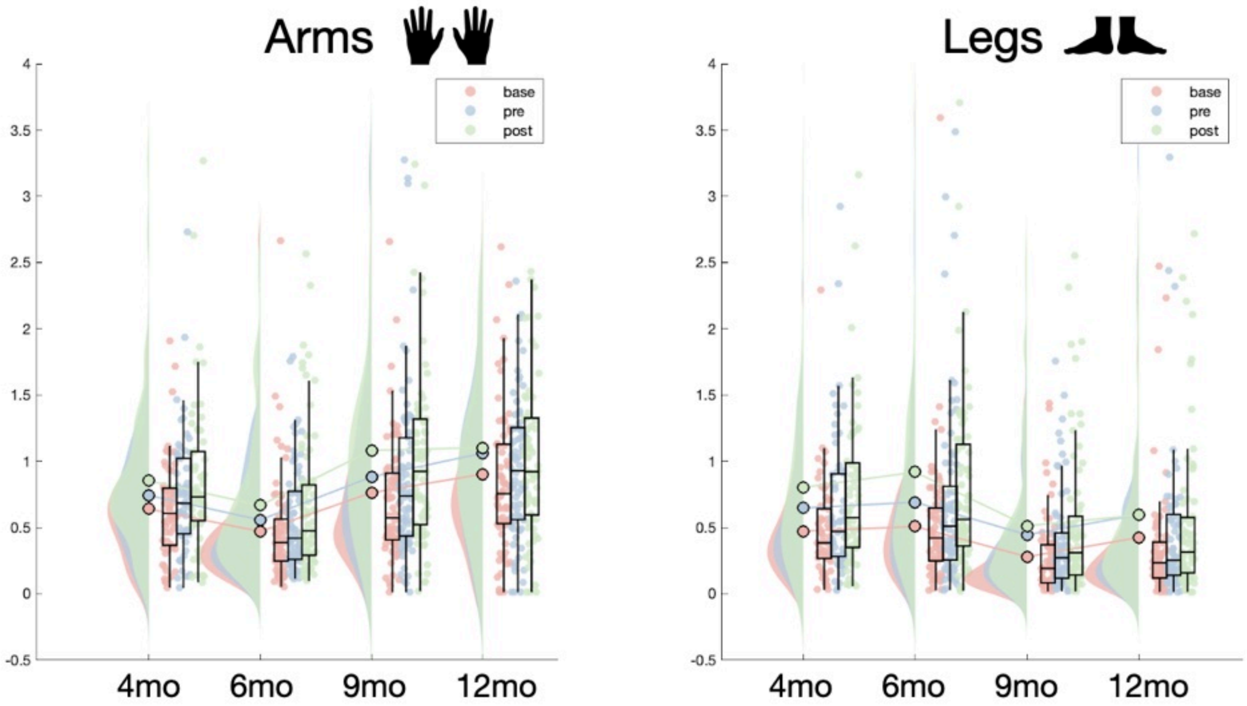
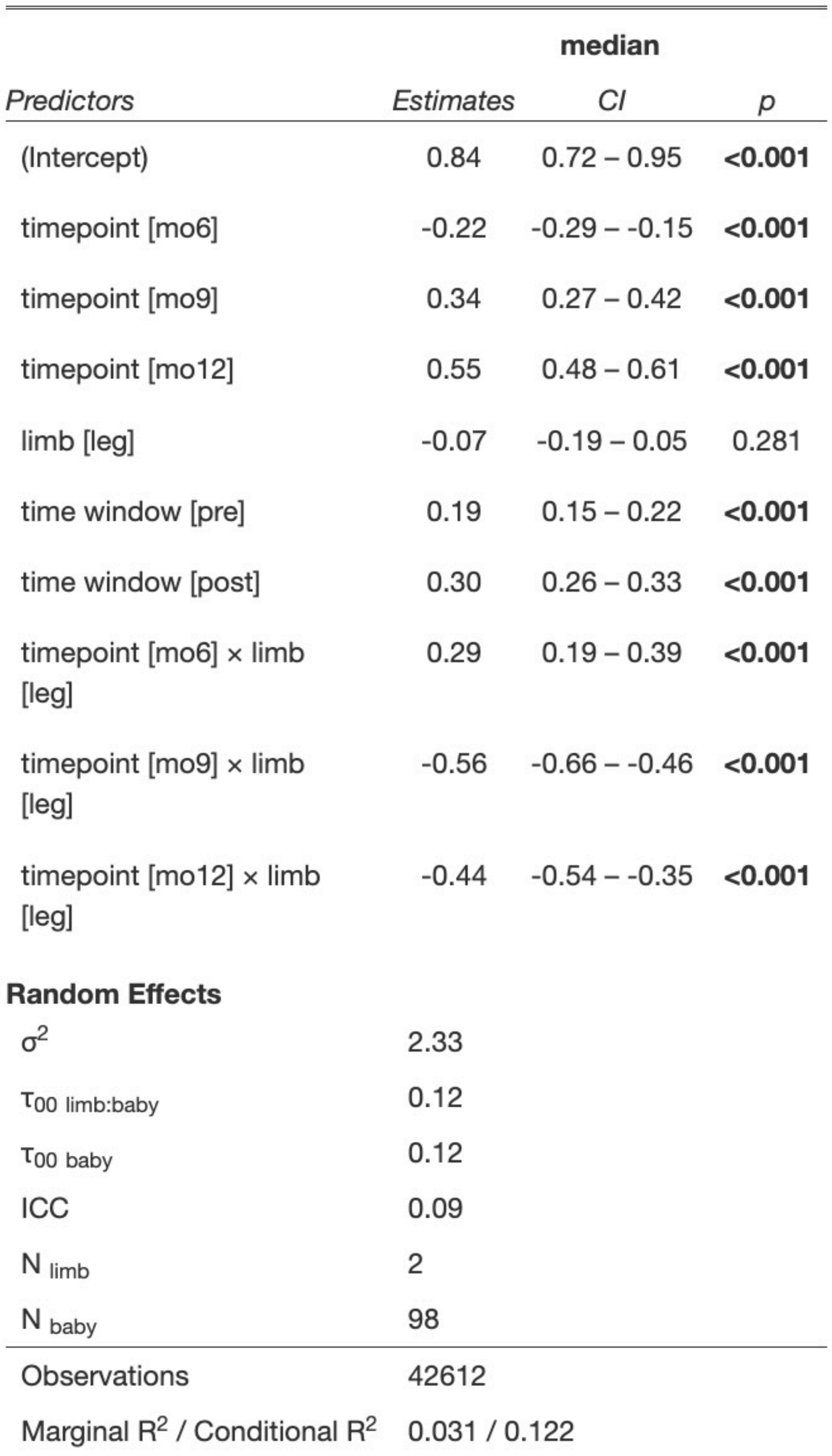


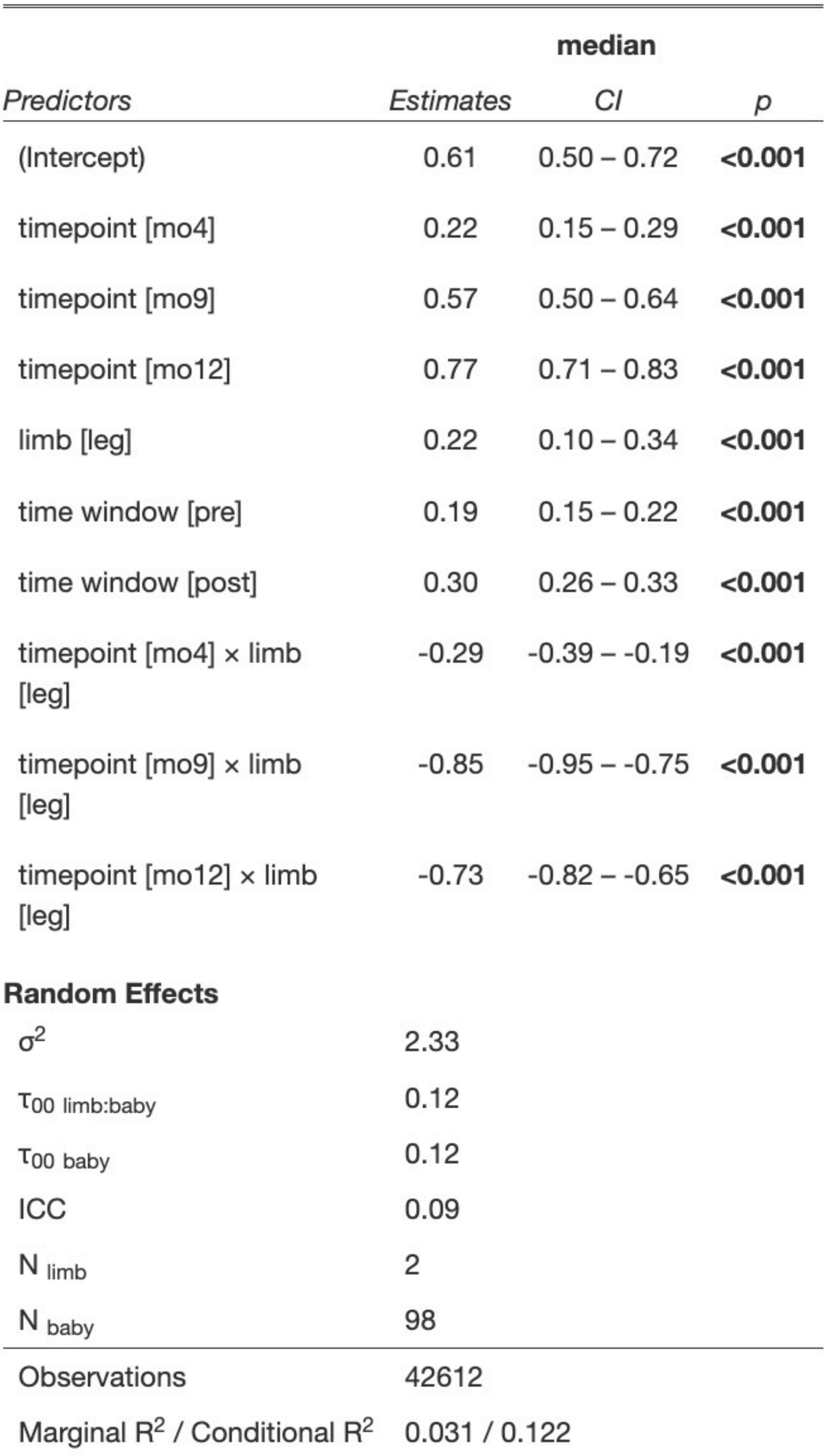
Fig. 4.5 Acceleration of limb movement in m/s2 across time points and time windows (red: baseline, blue: before vocalization onset, green: after vocalization onset) for arms (left) and legs (right). Dots indicate group-level means of individual medians, and boxplot middle lines indicate group-level medians of individual medians (hence note the disparity between medians and means for acceleration data).

Table 4.1. Model results with T1 as the reference level



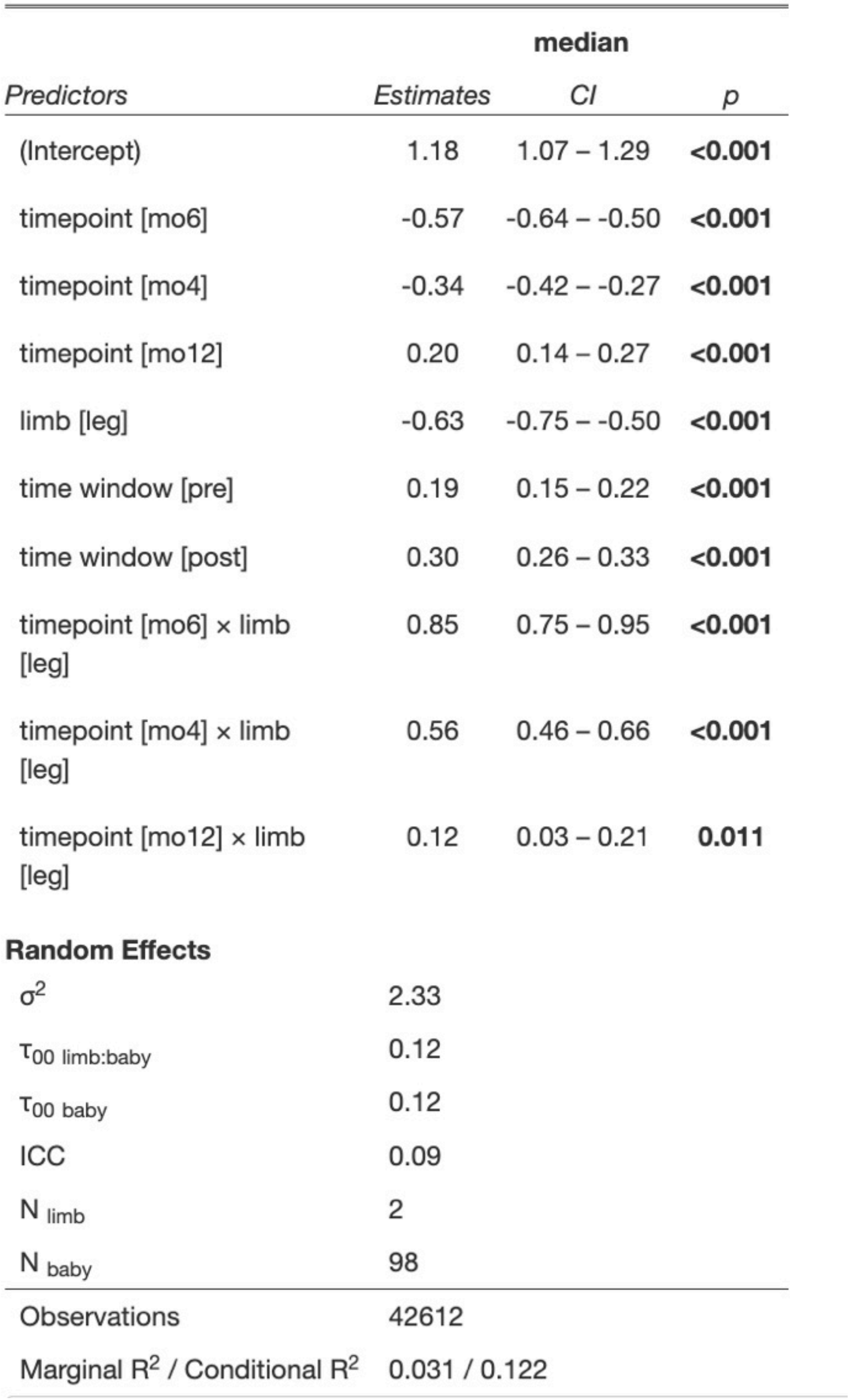
	median		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.84	0.72 – 0.95	**<0.001**
timepoint [mo6]	-0.22	-0.29 – -0.15	**<0.001**
timepoint [mo9]	0.34	0.27 – 0.42	**<0.001**
timepoint [mo12]	0.55	0.48 – 0.61	**<0.001**
limb [leg]	-0.07	-0.19 – 0.05	0.281
time window [pre]	0.19	0.15 – 0.22	**<0.001**
time window [post]	0.30	0.26 – 0.33	**<0.001**
timepoint [mo6] × limb [leg]	0.29	0.19 – 0.39	**<0.001**
timepoint [mo9] × limb [leg]	-0.56	-0.66 – -0.46	**<0.001**
timepoint [mo12] × limb [leg]	-0.44	-0.54 – -0.35	**<0.001**
Random Effects			
σ^2	2.33		
$\tau_{00\ \text{limb:baby}}$	0.12		
$\tau_{00\ \text{baby}}$	0.12		
ICC	0.09		
N_{limb}	2		
N_{baby}	98		
Observations	42612		
Marginal R^2 / Conditional R^2	0.031 / 0.122		

Table 4.2. Model results with T2 as the reference level



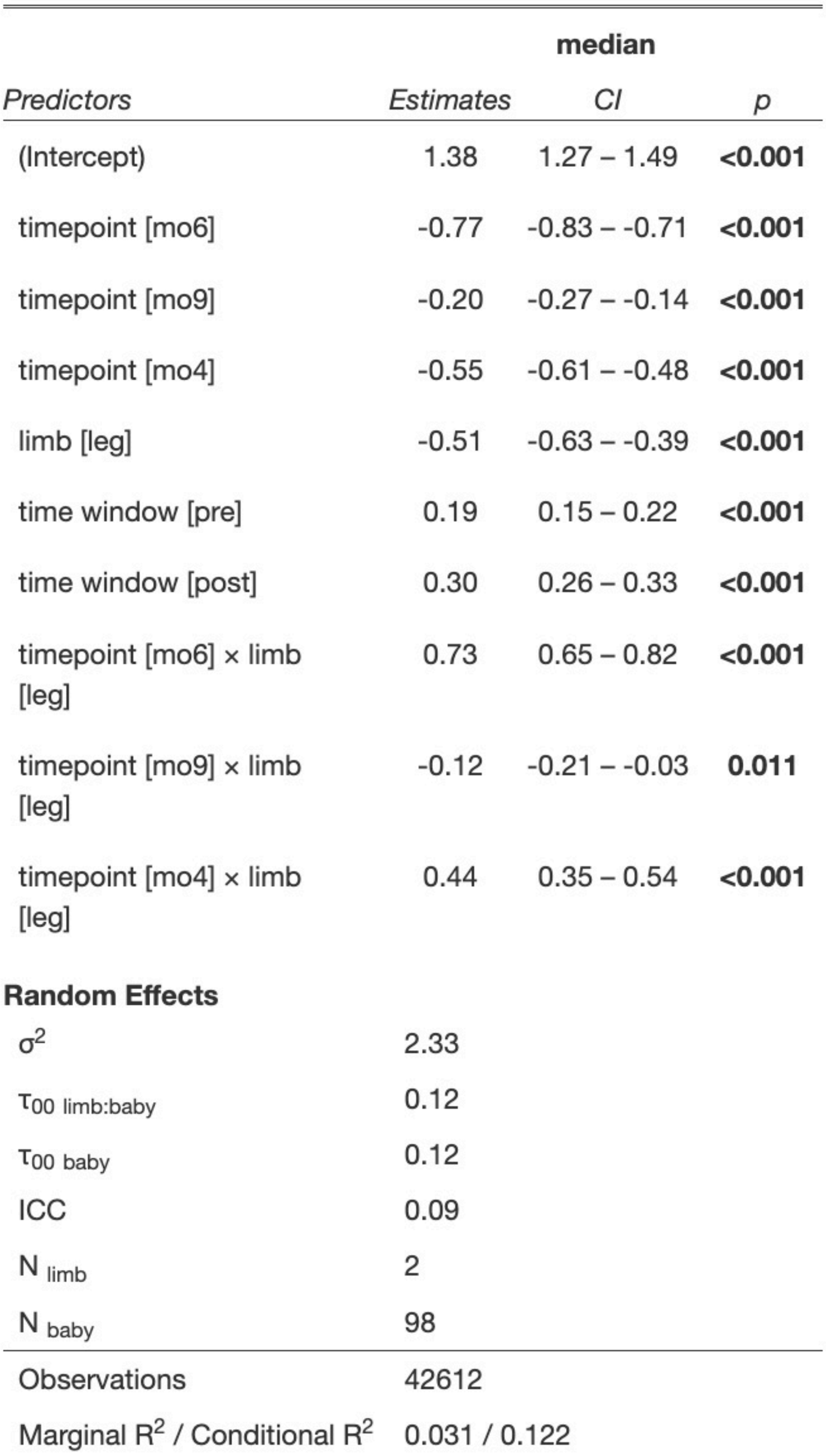
	median		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	0.61	0.50 – 0.72	**<0.001**
timepoint [mo4]	0.22	0.15 – 0.29	**<0.001**
timepoint [mo9]	0.57	0.50 – 0.64	**<0.001**
timepoint [mo12]	0.77	0.71 – 0.83	**<0.001**
limb [leg]	0.22	0.10 – 0.34	**<0.001**
time window [pre]	0.19	0.15 – 0.22	**<0.001**
time window [post]	0.30	0.26 – 0.33	**<0.001**
timepoint [mo4] × limb [leg]	-0.29	-0.39 – -0.19	**<0.001**
timepoint [mo9] × limb [leg]	-0.85	-0.95 – -0.75	**<0.001**
timepoint [mo12] × limb [leg]	-0.73	-0.82 – -0.65	**<0.001**
Random Effects			
σ^2	2.33		
$\tau_{00\ \mathrm{limb:baby}}$	0.12		
$\tau_{00\ \mathrm{baby}}$	0.12		
ICC	0.09		
N_{limb}	2		
N_{baby}	98		
Observations	42612		
Marginal R^2 / Conditional R^2	0.031 / 0.122		

Table 4.3. Model results with T3 as the reference level



	median		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	1.18	1.07 – 1.29	**<0.001**
timepoint [mo6]	-0.57	-0.64 – -0.50	**<0.001**
timepoint [mo4]	-0.34	-0.42 – -0.27	**<0.001**
timepoint [mo12]	0.20	0.14 – 0.27	**<0.001**
limb [leg]	-0.63	-0.75 – -0.50	**<0.001**
time window [pre]	0.19	0.15 – 0.22	**<0.001**
time window [post]	0.30	0.26 – 0.33	**<0.001**
timepoint [mo6] × limb [leg]	0.85	0.75 – 0.95	**<0.001**
timepoint [mo4] × limb [leg]	0.56	0.46 – 0.66	**<0.001**
timepoint [mo12] × limb [leg]	0.12	0.03 – 0.21	**0.011**
Random Effects			
σ^2	2.33		
$\tau_{00\ \text{limb:baby}}$	0.12		
$\tau_{00\ \text{baby}}$	0.12		
ICC	0.09		
N_{limb}	2		
N_{baby}	98		
Observations	42612		
Marginal R^2 / Conditional R^2	0.031 / 0.122		

Table 4.4. Model results with T4 as the reference level



	median		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	1.38	1.27 – 1.49	**<0.001**
timepoint [mo6]	-0.77	-0.83 – -0.71	**<0.001**
timepoint [mo9]	-0.20	-0.27 – -0.14	**<0.001**
timepoint [mo4]	-0.55	-0.61 – -0.48	**<0.001**
limb [leg]	-0.51	-0.63 – -0.39	**<0.001**
time window [pre]	0.19	0.15 – 0.22	**<0.001**
time window [post]	0.30	0.26 – 0.33	**<0.001**
timepoint [mo6] × limb [leg]	0.73	0.65 – 0.82	**<0.001**
timepoint [mo9] × limb [leg]	-0.12	-0.21 – -0.03	**0.011**
timepoint [mo4] × limb [leg]	0.44	0.35 – 0.54	**<0.001**
Random Effects			
σ^2	2.33		
$\tau_{00\ \text{limb:baby}}$	0.12		
$\tau_{00\ \text{baby}}$	0.12		
ICC	0.09		
N_{limb}	2		
N_{baby}	98		
Observations	42612		
Marginal R^2 / Conditional R^2	0.031 / 0.122		

Discussion

This chapter captured a reorganization of the motor-vocal coupling during rattle-shaking across the second half of the first year of life. Limb movements were coupled with the vocalization onset at all measured time points. However, the motor-vocal coupling reorganized in infancy, with initially comparable co-activation of arms and legs at 4 months, then higher co-activation of legs than arms at 6 months, followed by higher co-activation of arms than legs at both 9 and 12 months of age.

Our findings provide a conceptual replication of Borjon et al. (2024), using another, less constrained setting (tabletop play while seated in Borjon et al. vs. carpet play with unconstrained body position in ours). Both studies showed that limb movements and vocalizations are coupled in infancy and early childhood. Borjon and collaborators showed co-activations of hand and head movements before the vocalization onset in 9- to 24-month-old infants. Here, we extend these results to younger infants, adding an important finding that both leg and arm movements are coupled with vocal production – but this coupling undergoes a reorganization between 6 and 9 months of age.

As proposed by Iverson and Thelen (1999), infants' coupling between gestures and speech may be rooted in the oscillations between oral and arm movements. In particular, the repetitive, rhythmically organized movements can entrain vocal activity and facilitate the development of vocal reduplicated babbling. This could explain the increase in co-activation of arm movements (and the decrease in co-activation of leg movements) observed by us between 6 and 9 months, which is the period when infants start to produce reduplicated babbling (e.g., Buder et al., 2013).

Furthermore, the higher co-activation of arms than legs at 9 and 12 months could also indicate the emergence of vocal-entangled gestures – a potential precursor to the adult speech-gesture system (Pouw & Fuchs, 2022). Vocal-entangled gestures can be understood as arm movements that are temporally synchronized with vocalizations, resulting from the biomechanical interactions between muscles involved in arm movement, respiration, and vocal production (Pouw et al., 2019; Pouw, de Jonge-Hoekstra, et al., 2020; Pouw, Paxton, et al., 2020; Pouw, Harrison, et al., 2020). However, the developmental origins of this vocal-motor coupling require more research to understand its role in early multimodal communication.

The developmental pattern of changes in limb co-activation reported here should be interpreted with caution as there were significant changes in infants' gross motor skills and postural repertoire that we have not controlled for in the present study. Body positioning, especially the shape of the vocal tract, can affect both vocal production (Yingling, 1981, as cited in Iverson, 2010) and limb movements. For example, upper limbs are involved in a forearm support position (prone) that is a frequent body posture at 6 months of age. This dramatically changes when infants reach an independent sitting position (which usually happens between 6 and 9 months of age), which is the first upright body posture that frees arms from their role in postural support.

However, the observed increase in co-activation of leg movements and vocalizations from 4 to 6 months of age is particularly puzzling, as the repertoire of body posture skills does not change that significantly in this period. Presumably, this increase could reflect some form of postural support (with leg movements counterbalancing head movements during vocal production) that requires more postural control than is possible at 4 months of age. This idea should be investigated further in future studies, which would include analyses controlling for body position as well as measurements of head movements.

Conclusion

This chapter captured a reorganization of the motor-vocal coupling during rattle-shaking across the first year of life. Limb movements were coupled with the vocalization onset at all measured time points. However, initially, there was comparable co-activation of arms and legs at 4 months, then higher co-activation of legs than arms at 6 months, followed by higher co-activation of arms than legs at 9 and 12 months. This pattern indicates that motor-vocal coupling (especially of arm movements) could be a potential precursor of the adult speech-gesture system.

Chapter 5: Developmental changes in vocal production across the first year of life: emergence of task-related differences

Chapter 5: Developmental changes in vocal production across the first year of life: emergence of task-related differences

Team members involved in the project: Zuzanna Laudańska, Karolina Babis, Agata Kozioł, Magdalena Szmytke, Anna Malinowska-Korczak, David López Pérez, Przemysław Tomalski

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Formal Analysis: ZL
Funding Acquisition: PT
Investigation: ZL, KB, AMK
Project Administration: PT, ZL, KB, AMK
Software: AK (Python code), DLP (Matlab code), ZL (R code)
Supervision: PT, ZL, KB, AMK
Visualization: ZL
Writing – Original Draft Preparation: ZL
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Introduction

Previous chapters showed evidence that motor actions become more coordinated and specialized for task demands by the end of the first year of life. Similarly, motor-vocal coupling seems to undergo reorganization, resulting in a pattern that resembles the precursor of the adult speech-gesture system. But what about vocalizations themselves? Do we also observe increasing specialization of infants' vocal production for task demands?

As discussed in Chapter 1, infants produce a large variety of speech-like sounds (protophones), such as squeals, growls, vowel-like sounds, as well as more advanced sounds like syllables and first words (e.g., Buder et al., 2013; Stark, 1981). Very few studies investigated whether the frequency of infant vocalizations depends on the type of activity. Rome-Flanders and Cronk (1995) showed that infants' vocalizations were similar during peek-a-boo and play with a ball, whereas Sosa (2015) observed that infants aged 10-16 months vocalized more during play with books than electronic or traditional toys. Hsu et al. (2014) investigated the frequency of infant vocalizations at different stages of two common types of infant-parent play: peek-a-boo and tickle games. They observed that six- and twelve-month-old infants produced more vocalizations during the initial phase of the tickle game than during the initial phase of the peek-a-boo game. This pattern reversed during the later stage of these games when infants at both ages vocalized more during the peek-a-boo than the tickle climax stage. Furthermore, when different types of vocalizations were compared, twelve-month-old infants produced more mature canonical syllables during the peek-a-boo game than six-month-olds. Interestingly, twelve-month-olds also produced more vowel-like sounds during tickle than six-month-olds. Nonetheless, both of these games are related to dynamic changes in infants' arousal levels (across the task duration), thus, it is hard to conclude what was the role of the game structure and the positive affect and changes in arousal levels.

In order to systematically investigate the effects of infant-parent play type on infant vocalizations across the first year of life, here we analyzed three tasks (book-sharing, playing with manipulative toys, and rattle-shaking) that do not have a predictable structure of set-up and climax as in Hsu et al. (2014). Both peek-a-boo and tickle games have a predictable pattern of preparatory actions of the parent and the expected outcome that is usually related to the change in the infant's arousal level and laughter or giggles. In our study (as described in Chapter 1), we chose activities that have very different task demands but are not related to systematic changes in arousal level. Furthermore, by the end of the first year of life, these tasks have differential effects on infants' motor system's complexity and dynamic stability (see Chapter 2). We annotated and categorized all vocalizations produced by infants and calculated the frequency (rate per minute) of vocalizing and the proportion of advanced vocalizations (syllables and words) to all speech-like vocalizations (protophones, syllables, and words) produced by infants.

This chapter focuses on Research Question 4, aiming to understand whether infants' vocalizations become task-dependent across the first year of life. Based on previous research, we predicted that the frequency of infants' vocalizations at 4 and 6 months will be similar across all three tasks. At 9 and 12 months, infants will vocalize more during book-sharing (an activity that encourages vocal interactions; Clemens and Kegel, 2021; Murray et al., 2022; Sosa, 2015; Rossmanith et al. 2014) than during rattle-shaking or playing with manipulative toys. Moreover, infants will produce more vocalizations during rattle-shaking than playing with manipulative toys at 9 and 12 months, due to the co-occurrence of rhythmic vocalizations (such as canonical babbling) with rhythmic manual actions (Ejiri & Masataka, 2001; Iverson & Fagan, 2004). The frequency of vocal production during play with manipulative toys will be the lowest because this type of play mostly involves manual exploration.

In addition, to see whether some types of play may encourage infants to produce more advanced types of vocalizations rather than affect the overall frequency of vocalizations, we conducted an additional analysis focused specifically on the ratio of advanced vocalizations (syllables, words) to all speech-like vocalizations (protophones, (syllables, words). This analysis aimed to better understand the developmental pattern related to Research Question 4 but was considered exploratory.

Methods

Participants

The subsample of the group described in Chapter 1, which contributed valid audio data, was included in the analysis (see Table 5.1 for an overview).

Table 5.1. Sample Characteristics

Time Point	**Book-sharing**		**Playing with manipulative toys**		**Rattle-shaking**	
	N	**Mean age (SD); Range**	**N**	**Mean age (SD); Range**	**N**	**Mean age (SD); Range**
T1	65	4.33 (0.26); 3.9-4.9	68	4.35 (0.26); 3.9-4.9	66	4.35 (0.26); 3.9-4.9
T2	76	6.63 (0.39); 6.0-7.8	75	6.62 (0.40); 6.0-7.8	77	6.62 (0.40); 6.0-7.8
T3	69	9.07 (0.38); 8.3-9.9	71	9.07 (0.38); 8.3-9.9	69	9.08 (0.38); 8.3-9.9
T4	68	12.14 (0.53); 11.5-13.5	72	12.12 (0.52); 11.5-13.5	71	12.13 (0.52); 11.5-13.5

Procedure

The procedure and tasks are described in Chapter 1.

Coding of infant vocalizations

For each interaction session, an audio track was extracted from videos using Audacity 2.3.3 software. Then, infants' vocalizations were coded offline from the audio track using PRAAT software (Boersma & Weenink, 2020). The coders (ZL & KB) marked the onsets and offsets of each vocalization at the utterance level. An utterance was defined as a vocalization occurring on one egress (Vihman et al., 1985; Nathani & Oller, 2001). All vocalizations were classified into four distinct, non-overlapping categories (based on Buder et al., 2013): a) reflexive sounds (laugh and cry), b) protophones (the presumed precursors to speech, e.g., squeals, vowel-like sounds, growls, whispers, yells, grunts), c) syllables, and d) words. Reflexive sounds were excluded from further analyses, whereas protophones, syllables, and words were jointly considered „speech-like vocalizations" (Warlaumont et al., 2014) in further analyses. Syllables and words were jointly considered "advanced vocalizations," and the frequency ratio of advanced vocalizations to all speech-like vocalizations was calculated for an additional analysis.

Annotations were saved to TextGrid format files, and descriptive data were extracted using in-house Matlab (2019b) script using the *mPraat* toolbox (Bořil & Skarnitzl, 2016). To calculate inter-rater agreement, ~10% (N = 86) of recordings were double-coded by ZL and KB (randomly selected across tasks and time points). Cohen's κ was 0.85.

Statistical analyses

To assess the repeated-measures effects of time point (4) and task (3), we ran the General Estimating Equations (GEEs) with a Bonferroni correction for pairwise comparisons for each outcome variable separately. GEEs are particularly useful for longitudinal data because they take into account the dependency and ordering of the data within subjects in repeated-measures designs. Furthermore, in the GEE analysis, even if a subject is missing one or more of the repeated measurements, the remaining data of that subject are used in the analysis. The statistical analysis was run in R version 4.3.1 (2023-06-16) and RStudio (2023.06.0+421) using *tidyverse, geepack* and *emmeans* libraries and visualized using *ggplot2*.

Results

Frequency of infant vocalizations

To answer Research Question 4 concerning whether infants' vocalizations become task-dependent across the first year of life, we analyzed the frequency (rate per minute) of vocal production (see Fig. 5.1). The GEE with time point (4) and task (3) as within-subjects factors showed a significant difference in the frequency of infants' vocalizations between tasks (Wald $\chi2(2) = 6.7$, $p = 0.034$) and time points (Wald $\chi2\ (3) = 51.3$, $p < 0.001$), as well as the interaction effect (Wald $\chi2\ (6) = 30.2$, $p < 0.001$). Post hoc pairwise comparisons revealed that there were no task-related differences at T1, T2 and T3. At T4, infants vocalized more during book-sharing than during play with manipulative toys ($p < 0.001$) and more during rattle-shaking than play with manipulative toys ($p < 0.001$). The difference between book-sharing and rattle-shaking was not significant.

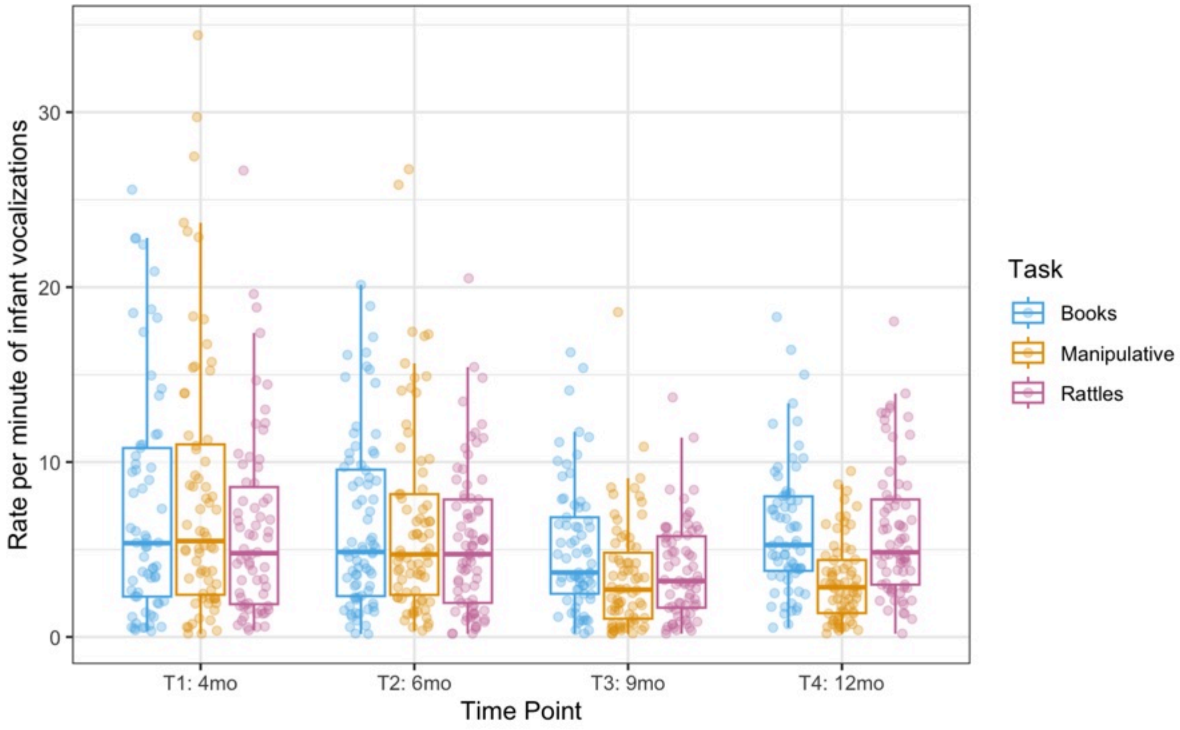

Fig. 5.1. Boxplots showing frequency (rate per minute) of infant vocalizations at each time point during book-sharing (blue), playing with manipulative toys (orange), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

The ratio of advanced vocalizations to all speech-like vocalizations

To see whether some types of activities may also encourage infants to produce more advanced types of vocalizations, we conducted an exploratory analysis on the proportion of more advanced (syllables, words) to all speech-like vocalizations (see Fig. 5.2). The GEE with time point (4) and task (3) as within-subjects factors showed a significant effect of time point in the ratio of advanced vocalizations to all speech-like vocalizations (Wald χ2 (3) = 265.7, p < 0.001). The ratio was the lowest at T1 and the highest at T4 (all ps < 0.001). The difference between T2 and T3 was not significant. There was no significant effect of task (Wald χ2(2) = 1.8, p = 0.4) or task x time point interaction (Wald χ2 (6) = 9.6, p = 0.14).

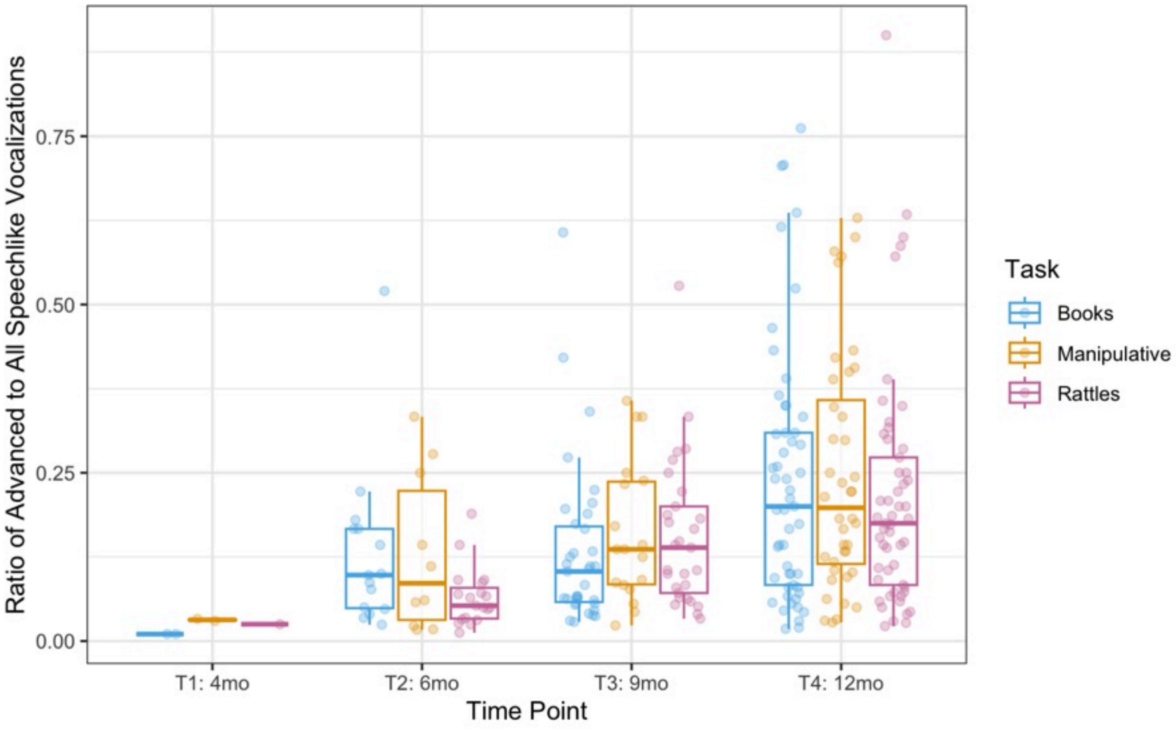

Fig. 5.2. Boxplots showing frequency ratio of advanced (syllable, word) to all (protophone, syllable, word) infant vocalizations at each time point during book-sharing (blue), playing with manipulative toys (orange), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

Discussion

This chapter investigated whether infants' vocalizations become task-dependent across the first year of life. We hypothesized that task-related differences would emerge at the age of 9 months, with more vocalizations during book-sharing than two other tasks and more vocalizations during rattle-shaking than playing with manipulative toys.

Our results partially confirm these hypotheses. We found that infants vocalize more frequently during book-sharing than playing with manipulative toys at 12 months of age, so later than predicted. We have also found that at 12 months, infants vocalized more frequently during rattle-shaking than when playing with manipulative toys, which supports our hypothesis. However, we have not found significant differences in the frequency of vocalizations between book-sharing and rattle-shaking. Music perception and production are postulated to be the most accessible forms of interpersonal communication early in infancy – preceding speech-like exchanges (Nguyen, Flaten, et al., 2023). Thus, the high level of vocal production during this task can be attributed to the beneficial role of music-making for the development of early speech-like vocalizations.

At 12 months, the frequency of vocal production during playing with manipulative toys was the lowest. This activity involves a high level of manual exploration that highly engages infants' attention, which results in a low rate of vocal production. An example of such an attentional trade-off was described by Berger et al. (2019) in the context of embodied cognition, showing a competition of resources between maintaining balance control and engaging in cognitive activity. In our case, the specific task demands related to the manual exploration of interesting objects organize infants' attention and actions in a very particular way, and differently than during book-sharing or rattle-shaking.

Furthermore, to see whether some types of play may encourage infants to produce more advanced types of vocalizations rather than affect the overall frequency of vocalizations, we conducted an additional analysis focused specifically on the ratio of advanced vocalizations (syllables, words) to all speech-like vocalizations (protophones, (syllables, words). We have not found evidence of task-specific differences in relation to the ratio of more advanced vocalizations to all vocalizations at any of the measured time points. This suggests that the process of specialization to task demands may be prolonged in development and extend beyond the first year of age.

Conclusion

Overall, we showed here that infants' vocal production becomes task-dependent by the end of the first year of age. At 12 months, infants were vocalizing less during playing with manipulative toys than during book-sharing and rattle-shaking. Thus, the developmental pattern of specialization to task demands in the vocal domain follows a similar pattern as described for the motor domain (Chapters 2 and 3).

Chapter 6: (Proto)conversations with babies: developmental relations between type of task, parental speech and infant-parent dialogue across the first year of life

Chapter 6: (Proto)conversations with babies: developmental relations between type of task, parental speech and infant-parent dialogue across the first year of life

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Author Contributions
Conceptualization: ZL, PT, DLP
Data Curation: ZL, KB
Formal Analysis: ZL
Funding Acquisition: PT
Investigation: ZL, KB, AMK
Project Administration: PT, ZL, KB, AMK
Software: AK (Python code), DLP (Matlab code), ZL (R code)
Supervision: PT, ZL, KB, AMK
Visualization: ZL
Writing – Original Draft Preparation: ZL

Infants' vocalizations coding (including reliability coding): ZL 695 recordings, KB 337 recordings

Caregivers' speech coding (including reliability coding): ZL 400 recordings, KB 182 recordings, Student research assistants: DG 146 recordings, NL 124 recordings, MP 65 recordings, ZK 49 recordings, KS 46 recordings, MK 26 recordings

Introduction

The results presented in previous empirical chapters indicate a pattern of increasing within-infant specialization in motor and vocal coordination. Task-related differences in the infant's motor coordination emerge in the second half of the first year of life (Chapter 2), accompanied by refinement in the efficiency and precision of coordinated arm movements (Chapter 3). Similarly, the motor-vocal coupling (limb movement around the onset of vocalizations) undergoes dramatic changes in infancy (Chapter 4). The frequency of infant vocal production also becomes task-dependent by the end of the first year. However, how about parental vocal input (Research Question 5)? Does it stay the same, regardless of an infant's age? Is it related to the type of play activity? Moreover, what about the between-person coordination (Research Question 6)? How does it unfold in the vocal domain?

To date, very few studies of vocal turn-taking in infancy and early childhood have been conducted (e.g., Gratier et al., 2015; Harder et al., 2015; Hilbrink et al., 2015, see review in Nguyen et al., 2023). The research investigating the role of task demands on vocal coordination is also scarce. Sosa (2015) found in a group of infants aged 10-16 months that the frequency of infant vocalizations, adult words, and conversational turns was higher during book-reading than playing with traditional or electronic toys. Furthermore, Clemens and Kegel (2021) found that in infants aged 9–18 months, book sharing resulted in a combination of more parent talk, child talk, and interactions than other types of activities such as toy play, singing songs, mealtime, or personal care. Finally, Murray et al. (2022) reviewed the literature about communication during book-sharing activities, showing that sharing picture books is an intersubjective process that frequently engages children in reciprocal interaction. Overall, it is unknown whether caregivers adjust their behaviors depending on the type of play interactions with their infants and whether dyadic coordination is task-dependent in infancy.

Thus, the final empirical chapter of this thesis will focus on parental verbal input and dyadic vocal turn-taking across the three tasks (book-sharing, playing with manipulative toys, and rattle-shaking). We hypothesized that the caregivers would speak more during the book-sharing task than during two other tasks at all time points due to reading and animating (Clemens and Kegel, 2021; Murray et al., 2022; Sosa, 2015; Rossmanith et al., 2014).

Regarding the dyadic vocal exchanges, we hypothesized that the highest number of conversational turns would happen during the book-sharing task – because a higher rate of parental vocal production provides more opportunities for the infant to respond. However, we expected these task-related differences only to emerge at 9 and 12 months, when the infant would become a more advanced conversational partner thanks to advances in vocal production and gross motor development and increased postural stability. In addition, to see whether the task demands affect not only the number of conversational turns but also the pattern of those dyadic vocal exchanges, we also included exploratory analyses of turn transition time calculated from the perspective of each speaker (infant and caregiver) to see if the latencies to respond change across tasks and time points.

Methods

Participants

The subsample of the group described in Chapter 1, which contributed valid audio data, was included in the analysis (see Table 6.1 for an overview).

Table 6.1. Sample Characteristics

Time Point	Book-sharing		Playing with manipulative toys		Rattle-shaking	
	N	**Mean age (SD); Range**	**N**	**Mean age (SD); Range**	**N**	**Mean age (SD); Range**
T1	65	4.33 (0.26); 3.9-4.9	68	4.35 (0.26); 3.9-4.9	66	4.35 (0.26); 3.9-4.9
T2	76	6.63 (0.39); 6.0-7.8	75	6.62 (0.40); 6.0-7.8	77	6.62 (0.40); 6.0-7.8
T3	69	9.07 (0.38); 8.3-9.9	71	9.07 (0.38); 8.3-9.9	69	9.08 (0.38); 8.3-9.9
T4	68	12.14 (0.53); 11.5-13.5	72	12.12 (0.52); 11.5-13.5	71	12.13 (0.52); 11.5-13.5

Procedure

The procedure and tasks are described in Chapter 1.

Coding of infant vocalizations

See the description in Chapter 5.

Coding of parental speech

For each interaction session, the parental speech was coded in a separate pass than infant's vocalizations (using the same audio files) by ZL, KB and 11 trained university students (see Acknowledgments). Four categories were formed in coding the speech produced by the caregiver: laughter, speech, vocalization, and singing. A vocalization was defined as the production of vocal sound by the caregiver that included unvoiced segments (not containing syllables). Speech was defined as the production of words (containing at least one syllable). Singing was coded if parents' produced musical tones. If the silent pause following the vocal sound was greater than 200 ms, two successive sounds were coded (Harder et al., 2015). Laughter was excluded from the analyses, whereas, speaking, vocalizing, and singing were jointly considered „caregiver’s vocal production” in several further analyses. Descriptive data were extracted analogously to the infant vocalizations (see Chapter 5). To calculate inter-rater agreement, ~10% (100 files) of recordings were double-coded (randomized across tasks, time points, and coders’ pairs). Cohen’s κ was 0.82.

Turn-taking analysis

To conduct turn-taking analysis, we adapted a Python script from Trujillo & Pouw, (2021), using *parselmouth*, *praatio*, *pympi* and *tabulate* libraries. Based on the annotations, we calculated the number of conversational turns from the perspective of an infant by taking the offset of each vocalization of an infant and finding the onset of the nearest caregiver’s vocalization within a window of 3 s (chosen on the basis of Harder et al., 2015).

Next, the time difference between the offset of the infant’s vocalization and the onset of the caregiver’s vocalization was taken as the turn transition time from the infant's perspective (which could also be understood as the caregiver’s latency to respond). Therefore, negative values indicate a temporal overlap, where the caregiver started their utterance before the infant stopped vocalizing, while positive values indicate temporal gaps. Analogously, the turn transition time from the caregiver's perspective was calculated as the time difference between the offset of the caregiver’s utterance and the onset of the infant’s vocalization (which could be understood as the infant’s latency to respond).

Statistical analyses

See the description in Chapter 5.

Results

Frequency of caregiver's vocal production

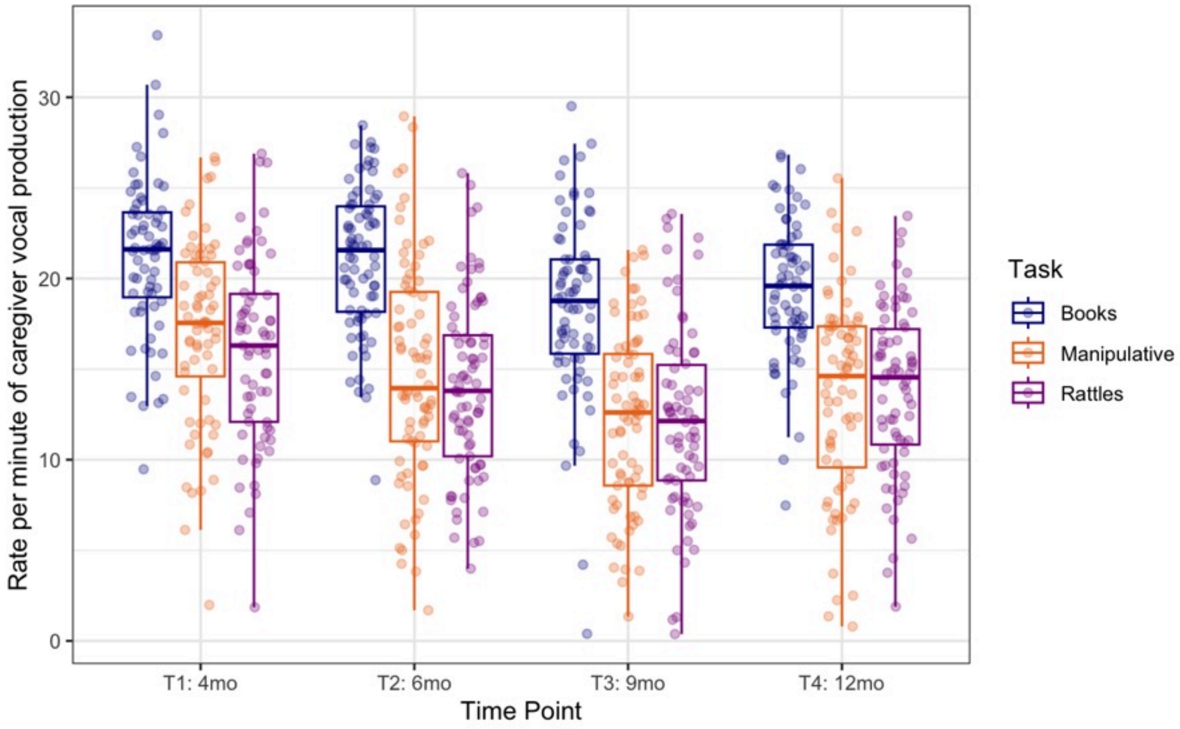

Fig. 6.1. Boxplots showing frequency (rate per minute) of caregiver vocalizations at each time point during book-sharing (dark blue), playing with manipulative toys (dark orange), and rattle-shaking (magenta). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

To answer Research Question 5 concerning whether parental vocal input changes depending on the task and infant's age, we analyzed the rate per minute of caregivers' vocal production (see Fig. 6.1). All types of vocal input, so speaking, singing and vocalizing were included. The GEE with time point (4) and task (3) as within-subject factors showed the main effects of time point (Wald $\chi2(3) = 54.1$, $p < 0.001$) and task (Wald $\chi2\ (2) = 308.6$, $p < 0.001$) in the rate per minute of caregiver's vocal production. The interaction effect was not significant (Wald $\chi2(6) = 7.1$, $p = 0.31$). Consistently across time points, caregivers provided infants with more vocal input during the book-sharing task than during the other two tasks (both ps < 0.001). The difference between rattle-shaking and playing with manipulative toys was not significant.

Dyadic vocal coordination: number of conversational turns

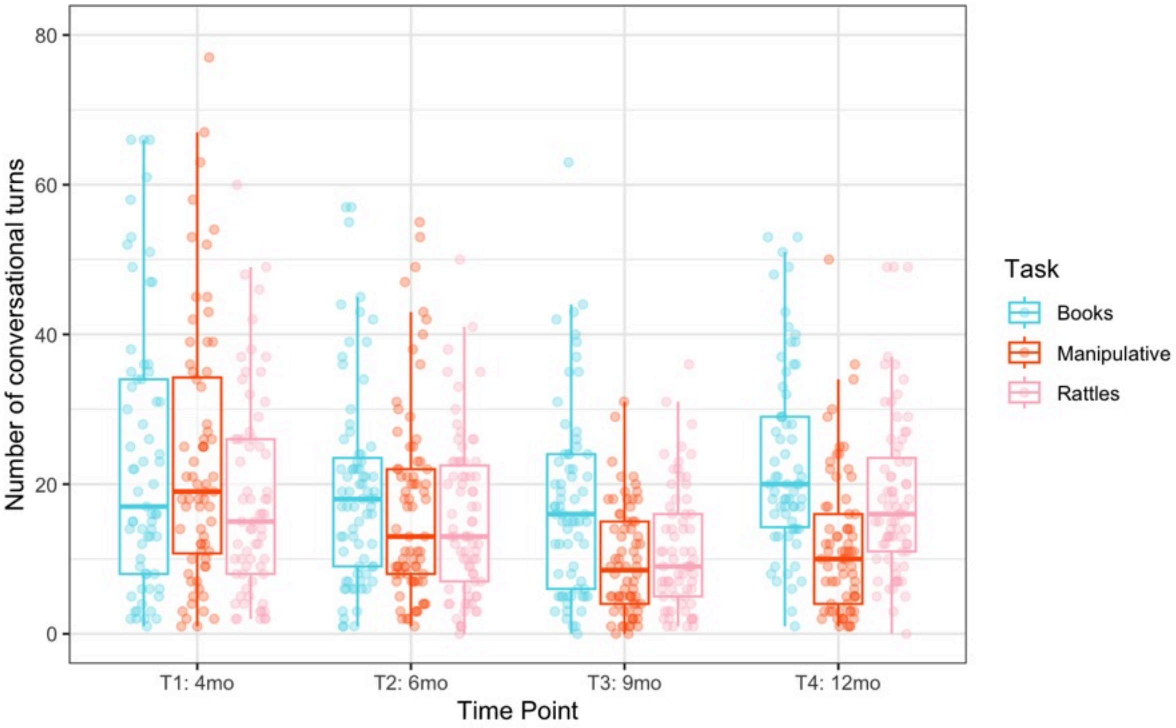

Fig. 6.2. Boxplots showing the number of conversational turns at each time point during book-sharing (blue), playing with manipulative toys (red), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

To answer Research Question 6 about task-related changes in infant-caregiver vocal coordination across the first year of life, we analyzed the number of conversational turns (see Fig. 6.2). The GEE with time point (4) and task (3) as within-subject factors showed main effects of time point (Wald $\chi2(3) = 51.4$, $p < 0.001$) and task (Wald $\chi2$ $(2) = 26.9$, $p < 0.001$) as well as a significant interaction effect (Wald $\chi2(6) = 22.2$, $p < 0.001$). At T3, there were more conversational turns during book-sharing than play with manipulative toys ($p = 0.001$) and rattle-shaking ($p = 0.027$). The difference between rattle-shaking and playing with manipulative toys was not significant. At T4, there were fewer conversational turns during play with manipulative toys than during book-sharing ($p < 0.001$) and rattle-shaking ($p = 0.013$). There were no significant differences between book-sharing and rattle-shaking at T4. Importantly, there were no significant task differences at the first two time points (T1 and T2), which shows the progressive emergence of specialization to task demands in the last three months of the first year of life.

Dyadic vocal coordination: latency to respond

Finally, to see whether the task demands affect not only the number of conversational turns but also the pattern of those dyadic vocal exchanges, we explored whether task demands would affect mean turn transition time – calculated from both the infant perspective (so the latency of caregiver's responses to infant's vocalizations) and the caregiver perspective (the latency of infant's responses to caregiver's utterances).

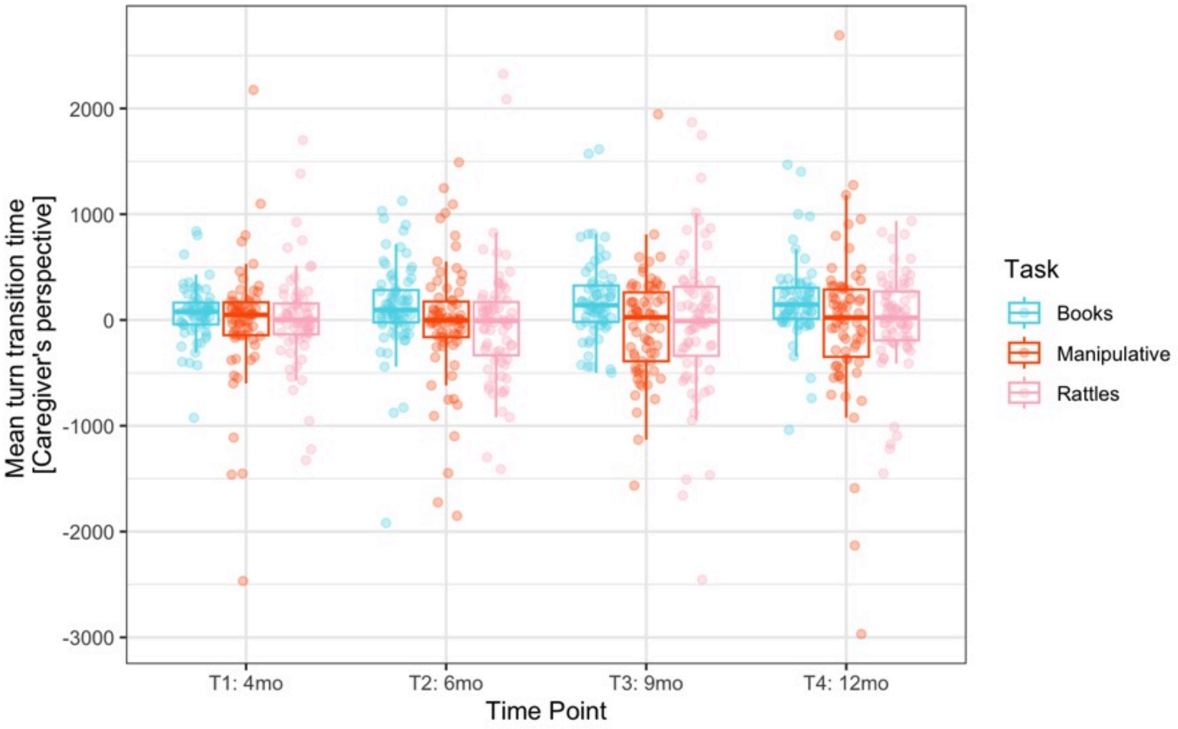

Fig. 6.3. Boxplots showing the mean turn transition time in milliseconds (the latency of infant's responses to caregiver's utterances) at each time point during book-sharing (blue), playing with manipulative toys (red), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

The GEE showed that, when calculated from the caregiver's perspective, the mean turn transition time was task-dependent (the latency of infant's responses to caregiver's utterances; see Fig. 6.3). The GEE showed a main effect of task (Wald χ2 (2) = 23.83, $p < 0.001$), with higher values during book-sharing than play with manipulative toys ($p < 0.001$) and rattle-shaking ($p < 0.001$). The mean value was above zero, indicating more gaps than overlaps. There was no significant difference between playing with manipulative toys and rattle-shaking. Neither the effect of time point (Wald χ2(3) = 0.44, p = 0.93) nor the interaction effect (Wald χ2(6) = 4.31, p = 0.64) were significant.

When calculated from the infant's perspective, the mean turn transition time was not task- or age-dependent (see Fig. 6.4). The latency of the caregiver's responses to the infant's vocalizations did not depend on the task demands or the infant's age. The GEE showed no significant effects of task (Wald χ2(2) = 0.50, p = 0.78), time point (Wald χ2(3) = 1.19, p = 0.76), or the interaction (Wald χ2(6) = 8.29, p = 0.22), which indicates a constant level of response latency on the caregiver's side.

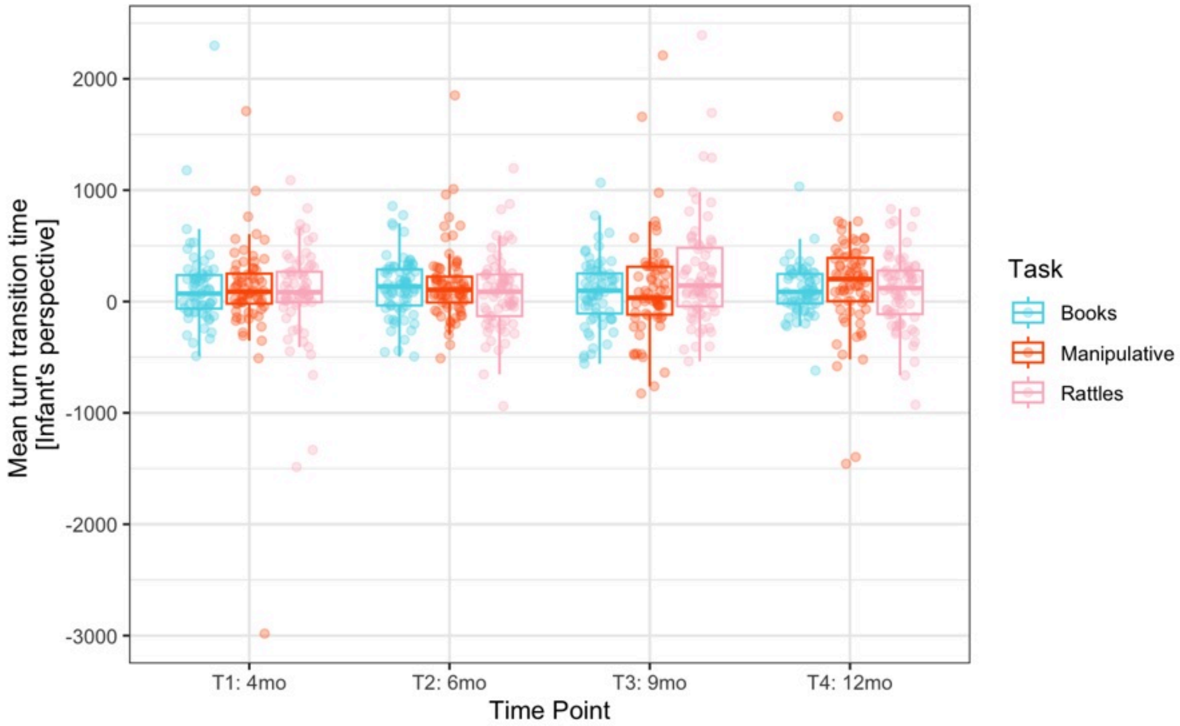

Fig. 6.4. Boxplots showing the mean turn transition time in milliseconds (the latency of caregiver's responses to infant's utterances) at each time point during book-sharing (blue), playing with manipulative toys (red), and rattle-shaking (pink). Horizontal lines represent the median value, boxes are drawn from the first quartile to the third quartile, and whiskers indicate min and max values.

Discussion

This chapter showed that caregivers talked significantly more to their infants during book-sharing than two other tasks consistently across all time points. This highlights that caregivers associate this type of play activity with verbal communication already when their infants are only 4 months old! Despite these consistent task-related differences in caregivers' input from the age of 4 months, infant vocal production becomes context-dependent only in the second part of the first year of life (Chapter 5).

We have found that task-related differences emerge not only at the individual level of infants and caregivers but also at the level of a dyad. Both conversation partners (infants and caregivers) are coordinating their vocal activity. Vocal turn-taking happened more often during book-sharing than two other types of infant-parent interaction at 9 months of age. At 12 months of age, there was no significant difference in vocal turn-taking between book-sharing and rattle-shaking (and in both tasks, turn-taking happened more frequently than during playing with manipulative toys. This supports previous findings about the positive role of book-sharing activities on early communication but also showcases an additional context of rhythmic music-making as a similarly positive type of activity around the end of the first year of life.

Furthermore, in our study, caregivers were responding to their infants' vocalizations at a similar latency across all time points and tasks. In infants, however, the mean turn transition time was different during book-sharing than play with manipulative toys and rattle-shaking (regardless of infants' age). The mean value of turn transition time during book-sharing was above zero, indicating more gaps than overlaps during vocal exchanges, so book-sharing seems to elicit more adult-like patterns of conversations. Interestingly, in infants, we have not observed any developmental changes in turn transition time. This is not in line with previous research (Hilbrink et al., 2015), which showed a non-linear developmental trajectory, with infants being relatively fast at timing their turn early in infancy but slower toward the end of the first year. These discrepancies may be related either to the language background of participants or to our manipulation of the context of the interaction (in comparison to free play used in Hilbrink et al., 2015).

The measurement of early vocalizations and turn-taking exchanges, as well as the knowledge about the best type of play to encourage them, may be important for understanding the developmental trajectories of language development and planning early interventions. More frequent turn-taking face-to-face during infant-parent interactions at 4-6 months of age were shown to be related to interpersonal neural synchrony, highlighting the importance of emerging turn-taking for child brain and language development (Nguyen, Zimmer, et al., 2023). The number of infants' conversational turns has been shown to be a predictor of language outcomes (e.g., Gilkerson et al., 2018; Romeo et al., 2018; Donnelly & Kidd, 2021).

Conclusion

This chapter took a closer look at the caregivers' vocal input and dyadic vocal turn-taking during different plays with their infants. Caregivers systematically spoke more during the book-sharing than during two other tasks at all time points. However, despite consistent task-related differences in caregivers' input from the age of 4 months, the dyadic turn-taking became context-dependent only from 9 months of age.

Chapter 7: General Discussion

Chapter 7: General Discussion

Summary of results

The goal of this thesis was to analyze the development of motor and vocal coordination across the first year of life. Specifically, it aimed to investigate the increasing specialization of infant limb movements and vocal production to the demands of the task-driven context. It also studied the task-related differences in caregivers' vocal input and emerging differences in dyadic vocal turn-taking. Overall, the presented results show a progressive specialization of within-person and between-person coordination of motor and vocal actions of the infant. Below is a summary of the research questions and main findings.

Research Question 1: Do the patterns of infants' between-limbs motor coordination become task-dependent across the first year of life?

Chapter 2 showed higher entropy and longer mean line during rattle-shaking than during playing with manipulative toys (with values for book-sharing in between these two tasks), suggesting that stability and complexity of the infant's motor system become task-dependent by the end of the first year of life. This pattern indicates a significant increase in specialization for differing task demands.

Research Question 2: Do infants' arm movements and between-arm coupling during rattle-shaking change across the first year of life?

Chapter 3 described developmental changes in arm movements in the context of rhythmic rattle-shaking. The results showed an increase in the precision of arm movement execution, resulting in the production of more rattle-shaking arm movements at a higher frequency. It also demonstrated an increase in between-arms coherence as arm movements became more coupled during rattle-shaking across the first year of life. Overall, the results showed increased coordination of arm movements to task demands by the end of the first year of life.

Research Question 3: Does the within-infant coupling between motor and vocal actions change across the first year of life?

Chapter 4 captured a reorganization of the motor-vocal coupling during rattle-shaking across the second half of the first year of life. Limb movements were coupled with the vocalization onset at all measured time points. However, the motor-vocal coupling undergoes a reorganization in infancy, with initially comparable co-activation of arms and legs at 4 months, then higher co-activation of legs than arms at 6 months, followed by higher co-activation of arms than legs at 9 and 12 months. This pattern indicates that motor-vocal coupling (especially of arm movements) could be a potential precursor of the adult speech-gesture system.

Research Question 4: Do infants' vocalizations become task-dependent across the first year of life?

Chapter 5 investigated infant vocal production during the same tasks as in Chapter 2 (rattle-shaking, booksharing, playing with manipulative toys), showing a similar developmental pattern of emerging task-related differences in infants' vocalizations as were previously observed for their motor system's stability and complexity (in Chapter 2). By the end of the first year of life infants were vocalizing less during playing with manipulative toys than during book-sharing and rattle-shaking.

Research Question 5: Does parental vocal input change depending on the task and the infant's age?

Chapter 6 took a closer look at the caregivers' vocal input during play with their infants in different tasks. Caregivers systematically spoke more during book-sharing than during the two other tasks at all time points.

Research Question 6: Do the patterns of infant-caregiver vocal coordination become task-dependent across the first year of life?

Chapter 6 showed that dyadic vocal turn-taking became task-dependent at 9 months of age. Despite consistent task-related differences in caregivers' input from the age of 4 months, the dyadic patterns become context-dependent only in the second part of the first year of life. The results showed a stable tendency of caregivers to differentiate play contexts in terms of their vocal input across all measured time points. In contrast, infants learned to align their vocal behavior to the play context at a much longer timescale.

Individual (within-infant) motor coordination

Coordination, which is a key characteristic of biological systems, involves bringing into proper relation multiple different components that are often defined over multiple scales of space and time (e.g., Turvey, 1990). Previous studies showed that movements advance from disorganized to more coordinated and resembling adult-like patterns across infancy (Thelen & Smith, 1994). The results presented in Chapters 2 and 3 provide more details about this developmental process. Chapter 2 showed that the stability and complexity of an infant's motor system become task-dependent by the end of the first year, indicating a significant increase in specialization to task demands. In our study, each task required qualitatively different actions – rhythmic body movements to produce the rattling sound, various reaching, holding, pushing and pulling actions to explore manipulative objects, or more vocal actions during book-sharing. Higher entropy in the rattle-shaking task combined with a longer mean line suggests that infants' motor system is more stable during rattle-shaking, as the pattern of arm movements is more constrained than during playing with manipulative toys. This is further supported by the results of Chapter 3, which show an increase in the number of rattling movements and between-arms coherence. Combined, this pattern of results suggests that rattle-shaking activity elicits less variable types of movements than, for example, free exploration of manipulative toys. During rattling, the group of muscles and other components of the motor system seem to become functionally linked so that they behave as a single task-specific unit. Thus, these components are forming a coordinative structure or a synergy (e.g., Turvey, 1990).

The concept of synergy formation is crucial for understanding how complex biological systems achieve their task-specific stability (Latash, 2021). According to Bernstein (1967), the formation of synergies organizes numerous elements into groups, allowing for the elimination of redundant degrees of freedom. He pointed out the problem of motor redundancy, which highlights that the number of motor systems' components is larger than the number of constraints associated with typical tasks. Thus, an infinite number of solutions exist. For this reason, the formation of synergies is a way of finding solutions for typical problems of motor redundancy. Synergic control allows then for the formation of dynamic stability of actions at levels ranging from groups of motor units to the whole body (Latash, 2010, 2019, 2021).

Recently, in academic discourse, the principle of abundance was proposed (Latash, 2012, 2021), which reformulates the problem of motor redundancy and focuses on the importance of variability in motor processes. Such variability is not conceptualized as a source of computational problems for the motor and nervous systems but as an evolutionary advantageous design that ensures both stability and flexibility of actions. The abundance of elements is used to ensure the desired dynamical stability of motor solutions to improve efficiency, supporting the adjustments to an ever-changing environment (Latash, 2012, 2021).

In relation to the results reported in Chapters 2 and 3, the notions of abundance and synergy-formation help to conceptualize the developmental process of specialization to task demands. Infants – as complex biological systems – refine their movement patterns to better organize the effectors to the task at hand. However, our results show that the protracted period of practice throughout infancy is necessary to do it efficiently. As Hadders-Algra (2018) described in her review, early in development (up to 3-4 months of age), movement variation serves mainly the purpose of exploration and refinement of the nervous system. Then, across the next months, there is a period of trial-and-error exploration and of age-related changes (accompanied by changes at multiple levels of neural organization) when movement variation starts to serve as an adaptation to environmental constraints. For example, reaching movements become more efficient as infants become able to execute more straightforward movements toward the desired object (Von Hofsten, 1991), without co-activating other effectors (Soska et al., 2012; D'Souza et al., 2017). Similar changes can be observed in other types of movements, like cruising over a handrail, during which less experienced infants generate multiple inconsistent coordination patterns, while same-age but more experienced with a given type of movement infants tailor their coordination patterns to body-environment relations and flexibly switch solutions (Ossmy & Adolph, 2020). The task-related differences at 12 months of age described in Chapter 2 likely reflect this process of increasing adaptation of movements to environmental constraints.

Furthermore, the increased between-arm coherence (Chapter 3) and high level of complexity and dynamic stability (Chapter 2) during rattle-shaking may also be related to a more confined attractor state (see de Jonge-Hoekstra, 2021 for an illustrative explanation of attractor states). The differences in movement variability are related to the differences in attractor strength (Richardson et al., 2007). During a repetitive and rhythmic activity such as rattle-shaking, individual components of the motor system (limbs, but also muscles, bones, joints on a lower scale of organization, etc.) organize themselves into groups. The coupling between those elements is strong, so the overall state of the motor system is stable – the attractor is more confined. For this reason, the attractor is, to some degree, able to resist perturbations – so the rattling movements may be similar regardless of the infant's body position or the size of the rattle. During playing with manipulative toys, entropy, and mean line were lower than during rattle-shaking, which suggests less constrained movement types and higher flexibility that helps with more fine-grained object manipulation and exploration. The values of entropy and mean line during book-sharing are placed in between those for rattle-shaking and playing with manipulative toys, suggesting a middle level of constraints and less clearly distinguishable motor patterns.

Overall, our results further show that limb movement organization becomes context-dependent across infancy, reflecting a better capacity to flexibly adapt behaviors to environmental demands. It takes infants multiple months and endless attempts before they grasp the correct configuration of all components to efficiently interact with the environment.

Individual (within-infant) motor-vocal coupling

As discussed in Chapter 1, speech production is a highly complex motor action requiring the coordination of multiple articulators. It is also accompanied by hand movements that, in adults, form a speech-gesture system (e.g., Pouw & Fuchs, 2022). Gestures tightly align with speech production on multiple levels: temporal, semantic, pragmatic, and emotive (see review in Wagner et al., 2014), but here, we will only focus on the biomechanical aspects of the precursors to the speech-gesture system. According to Iverson and Thelen (1999), infants' coupling between gestures and speech is rooted in the oscillations between oral and arm movements. They proposed that the production of repetitive, rhythmically organized movements entrains vocal activity, which facilitates the development of vocal reduplicated babbling. Pouw and Fuchs (2022) proposed a revision of this idea, arguing that the exploratory limb movements that co-occur with vocalizations affect these vocal productions through respiration. Thus, vocal-motor babbling is rooted in the biomechanical links between upper limb movements, postural muscles, and the respiratory system. Such a pattern of vocal-motor-respiratory coupling is present in adults. When adults vocalize while moving their arms with acceleration or deceleration pulses, some of the muscles recruited for arm movements also affect respiratory control. This, in turn, affects vocal production (Hodges and Gandevia, 2000a, 2000b; Pouw et al., 2023). Thus, gesture-vocal coupling partly arises due to muscle activity related to arm movements and body posture (Pouw et al., 2023).

Such synergistic co-activations of hand and head movements were also observed in 9- to 24-month-old infants (Borjon et al., 2024). Borjon and colleagues presented evidence that hand and head movements co-activate with spontaneous vocalizations during a tabletop dyadic play. This temporal precision tightened as infants became older. Here, in Chapter 4, we extended these results to a younger developmental period, less constrained setting, and simultaneous recording of upper and lower limb movements during vocal production. We showed that limb movements are coupled with the vocalization onset at all measured time points. However, the motor-vocal coupling undergoes a reorganization in infancy, with initially comparable co-activation of arms and legs at 4 months, then higher co-activation of legs than arms at 6 months, followed by higher co-activation of arms than legs at 9 and 12 months. High co-activation of arm movements from 9 months of age is in line with previous research on motor-vocal babbling, which peaks around the onset of reduplicated babbling

(Thelen, 1979; Locke et al., 1995; Ejiri, 1998; Ejiri & Masataka, 2001; Iverson & Fagan, 2004; Iverson & Wozniak, 2007; Burkhardt-Reed et al., 2021). However, the higher co-activation of the leg than arm movements at 6 months of age is more puzzling. It may be related to the intensity of kicking that may affect vocal production through changes in respiration. Another possibility is that leg movements provide postural stability during arm movements – a form of counterbalancing effect during rattle-shaking while prone or supine, which may affect rib cage muscles (and other parts of the articulatory or respiratory systems). Iverson and Fagan (2004) also showed a developmental trend for increased coordination of manual actions with vocalizations while observing decreases in coordination with other limbs. This pattern, combined with our results, suggests a progressive decoupling between upper and lower limb movements and vocal production. However, Serré and collaborators (2022) reported that the biomechanical entanglements between the respiratory-vocal-motor systems may also extend to lower limbs in adults. They showed that during simultaneous biking and telling short stories, intensity peaks in the acoustic signal co-occurred with the peak acceleration of the legs' biking movements. This was not corroborated by Weston et al. (2024), who found no evidence of correlations between leg cycling rate and speech tempo. Altogether, the biomechanical links between leg movements and speech need further research across the lifespan.

Individual (within-infant) vocal coordination

Results discussed so far show compelling evidence that motor and motor-vocal actions become more coordinated in terms of components of the motor and vocal systems across the first year of life. The next section will focus specifically on the vocal domain. At 12 months of age, infants vocalized less during playing with manipulative toys than during book-sharing or rattle-shaking (Chapter 5). These task-related differences were observed only by the end of the first year, despite consistent differences in caregivers' verbal input from the age of 4 months, with more parental speech during book-sharing than the two other tasks (Chapter 6).

The developmental pattern of specialization to task demands in the vocal domain (Chapter 5) follows a similar pattern as described for the motor domain (Chapters 2 and 3). If we continue the idea described above that vocal production is a highly specialized motor action – affected and frequently accompanied by other types of body movements – then it may be useful to continue with the idea of the formation of synergies as a way to describe the emergence of task-related differences. As discussed by Latash (2008), synergy formation is inherently related to working toward a particular goal – the components of the system "work together" to achieve a common goal. The system's synergies are then task-dependent, so the same set of components forms a different synergy for a different purpose. Therefore, if we jointly consider the results in the motor domain obtained in Chapters 2-3 and in the vocal domain (Chapter 5) at 12 months of age, we can hypothesize that the system forms different synergies for different purposes. During tasks that require motor actions (rattle-shaking and playing with manipulative toys), we see more distinguishable patterns of motor coordination. In contrast, during book-sharing, which is a type of activity mostly focused on vocal exchanges (accompanied by sporadic manual actions such as turning pages or pointing), we see more vocal actions (and, of course, shifts in visual attention, but this aspect is outside the scope of this thesis). Thus, a given task is accomplished by solutions that allow a performance best suited to the task demands. This suggests that by the end of the first year of life, infants become more able to tailor their actions towards task demands, which emphasizes the development of flexibility (so the ability to choose from variable solutions the most effective one) and stability (so the solution that allows for the most stable performance, best suitable to the task demands). To our knowledge, infant vocal production has not been investigated so far in the context of synergy formation, and our results do not allow for definite conclusions. However, the similarities in developmental trajectories between task-related changes in infant motor and vocal actions suggest that this low-level approach may be useful for studying the precursors to speech and language.

Dyadic vocal coordination

The results described in Chapter 6 present the first systematic and longitudinal report on the role of task demands on dyadic vocal turn-taking. We showed a novel finding that there were more conversational exchanges between infants and their caregivers during book-sharing than during rattle-shaking and playing with manipulative toys at 9 and 12 months of age. Our results support the notion that dyadic book-sharing activities are beneficial for early communicative development, as more vocal turn-taking can lead to better language outcomes (Clemens and Kegel, 2021; Murray et al., 2022; Sosa, 2015; Rossmanith et al., 2014). Moreover, we also extend previous findings by showing the positive effects of rhythmic musical activities on early vocal production. Interestingly, music production may be the most accessible form of interpersonal communication early in infancy – preceding speech-like exchanges (e.g., Trevarthen, 2015; Nguyen, Flaten, et al., 2023). Thus, the high level of vocal production in this task can be attributed to the beneficial role of music-making for the development of early communication. However, it is worth noting that in our study, rattle-shaking at 9 months of age was related to infants' more frequent vocal production but not to more vocal conversational turns. It is possible that turn-taking exchanges in this type of play were multimodal – sometimes happening through speech and at other times through motor synchrony or taking turns at rattle-shaking. Alternatively, this could be related to the rhythmic nature of reduplicated babbling that frequently co-occurs with arm movements (Iverson and Thelen, 1999) at this age, rather than the strictly communicative nature of vocal production. These possibilities should be investigated separately in future studies.

Furthermore, we observed task-driven differences in dyadic turn-taking earlier in development (already at 9 months) than in individual measures of infant vocal production (observed only at 12 months). This is a particularly puzzling result, however, it should be interpreted with caution until it becomes replicated in another sample. One possible explanation could be that dyadic interactions drive communicative development – thus, the role of task demands is observed earlier at the level of a dyad than at the level of an individual infant (see similar idea in Rochat & Striano, 2002; Reddy, 2003). More detailed follow-up analysis of the moment-to-moment organization of communicative exchanges should be considered as a way to understand this developmental process better.

Finally, Chapters 5 and 6 present the first longitudinal report of vocal production and turn-taking of infants learning Polish language. Research focused on infants speaking Slavic languages is scarce, and the developmental results from English-speaking populations may not generalize to this group (see Gratier, 2003 and Bornstein et al., 2015 for reports of cross-language differences). There is preliminary evidence from Rescorla et al. (2017) suggesting that the rate of vocabulary acquisition at the age of two years may be slower in Polish than in English, possibly due to the complexity of Polish language (see Haman, 2002, 2003 for more details). Generally, it is not yet clear how the production of speech-like vocalizations relates to later vocabulary size and other language outcomes across langauges, but considering the high level of difficulty of Polish (and other Slavic languages) pronunciation, with fricative consonants such as “sz” and complex consonant clusters (as in „chrząszcz” - „beetle”), mastering the articulation of first words may require more practice with sound production.

Multimodal coordination and task demands

As described in Chapter 1, the design of this study aimed to capture infant and caregiver behaviors in three types of play that differed in demands: book-sharing, rattle-shaking, and playing with manipulative toys. Our results presented in the empirical chapters show that tasks have differential effects on infants’ motor and vocal actions at 12 months of age. Book-sharing encourages more vocal production and dyadic vocal turn-taking, rattle-shaking elicits more rhythmic arm movements, often coupled with vocalizations (but not dyadic turn-taking), and playing with manipulative toys promotes various reaching, grasping, and holding actions and least frequently – vocalizations. The infant – as a complex dynamic system – becomes increasingly capable of forming task-dependent solutions (possible synergies). The period of late infancy seems to be a window of intense and complex reorganization across modalities, with emerging gross motor skills that change the affordances for interactions with objects and social partners, enabling an increase in specialization to task demands. The similarities between developmental trajectories of the emergence of task-related differences further emphasize that vocal production is intrinsically embedded within the motor system (Pouw & Fuchs, 2022), and early speech and language development should be analyzed jointly with the changes in gross and fine motor development.

Furthermore, at the dyadic level, the infant (as a dynamic system) co-organizes its actions with the actions of another system - the caregiver. So, the "synergy of synergies" should emerge during dyadic interactions. Or, in another way – the infant-parent dyad should be considered an even more complex system that needs to form a synergy to accomplish a dyadic task – a similar idea of dialog as interpersonal synergy was proposed by Fusaroli et al. (2014). However, in our case, it is crucial to note that in contrast to the caregiver, the infant is still the system "under construction," undergoing dynamic changes related to changes in body size and neural reorganization (to name a few). It seems that the infant needs to reach a certain level of skills through multiple trial-and-error attempts to adjust his/her own actions to the actions of the interaction partner (the caregiver) and to the changes in his/her environment. In our study, the caregivers acted in a task-dependent manner during all time points – for example, during book-sharing, they were providing their infants with a high level of vocal input from the age of 4 months onwards. Nonetheless, the task-related differences in both infant's and dyadic actions were only observed from 9-12 months of age.

Our results from infant research resemble, in a way, findings with the elderly population (> 70 years of age) reviewed and discussed by Latash (2008). The elderly had problems with creating motor synergies quickly, showing strong synergies, and adjusting the synergies in anticipation of a planned action. Latash argued that the changed motor synergies may be a way for the system to perform the actions at an acceptable level despite the suboptimal properties of the elements, the neuronal apparatus, and the muscles at an older age. Thus, the process of synergy formation that was partially captured in this thesis may provide a useful way of thinking about interactions between an agent (infant, child, adult) and their environment across the lifespan.

Contribution to the discipline

The results presented here highlight the need for a multimodal approach to studying speech and language development. Multimodal theoretical and research frameworks are necessary to capture the development of early within-infant and between-person coordination in communicative contexts. However, choosing appropriate methods and setup to study this research question is not easy. Collecting and analyzing multimodal datasets poses many difficulties – from choosing the right equipment and deciding on the duration and setting of the recordings to finding creative approaches to better understand phenomena that unfold across different timescales. This thesis systematically investigated several aspects of this process across the first year of life. First, we chose a semi-naturalistic design of infant-parent interactions in the lab to control some aspects of the environment (size of the room, surface, minimal visual clutter, similar level of background noise, the same number of available objects for all participants to interact with), but also allowing for free-flowing play without constrained body position or instructions for the caregiver. Next, we chose three types of play that are characterized by different demands. Rattle-shaking prompts rhythmic body movements and vocalizations, book-sharing encourages vocal communication, and playing with manipulative toys promotes manual sampling through differentiated hand movements. For the infant, we found no task-related differences at 4 or 6 months of age, but across the second half of the first year of life, infants' motor, vocal, and motor-vocal actions became increasingly more adapted to task demands. Furthermore, we found similarities in the developmental timeline of emerging motor and vocal specialization for task demands, with a period of massive reorganization between 6 and 12 months of age visible across all analyses. Since vocal production requires a highly specialized motor skill, it makes sense that the increase in specialization across both domains emerges around the same time. Jointly, the presented results can be interpreted as a progressive specialization to task demands, with increasingly more vocal production and conversational turns (and less distinguishable pattern of motor coordination in comparison to two other tasks) during book-sharing, more motor-vocal coupling during rhythmic rattle-shaking and more free-flowing motor actions during object exploration.

Overall, this thesis presents an in-depth analysis of the role of task demands on coordination patterns in the motor and the vocal domain. However, further interdisciplinary discussions about theoretical and methodological aspects of multimodal interpersonal interactions are necessary to disentangle this complex developmental process. Novel frameworks should account for developmental changes in the phonatory and articulatory vocal system (e.g., Thelen, 1981; Oller, 2010), together with gross motor development (e.g., Iverson, 2010) as well as parental verbal input and responsiveness, that jointly shape advances in communicative development.

Potential applicability of the results in clinical populations

As Anette Karmiloff-Smith (1998) wrote, "development itself is the key to understanding developmental disorders". Thus, the results discussed here have the potential for applicability in studying atypical development. Atypical motor deficits are present in many neurodevelopmental disorders, such as Down syndrome (D’Souza & D’Souza, 2022), Williams syndrome (Mayall et al., 2020), and autism spectrum disorder (Iverson & Wozniak, 2007). Similarly, an atypical pattern of vocal production in infancy may be a marker for the early detection of infants at risk of developmental disorders such as autism spectrum disorder, Rett syndrome, and fragile X syndrome (e.g., Iverson & Wozniak, 2007; Pokorny et al., 2022, Roche et al. 2019; Tenenbaum et al., 2020; see review in Lang et al. 2019). Thus, understanding the development of motor and vocal coordination (as well as coupling of limb movements and onsets of vocalizations) in the general population can help to better address the challenge of tracking atypical developmental cascades and designing early interventions.

It has been shown previously that interventions focused on parent-child turn-taking can improve children’s language skills (Ferjan Ramírez et al., 2020). Our results further suggest that the type of activity during which the vocalizations and turn-taking are happening should be taken into consideration when planning early interventions focused on vocal development. For example, the positive impact of book-sharing on the production of vocalizations and conversational turns highlights the potential of this type of activity to be included in early intervention programs developed for children at risk of language delay (see examples in Tsybina & Eriks-Brophy, 2010; Myrberg & Hammarström, 2022). Furthermore, our results suggest that rhythmic activities such as rattle-shaking may also be a promising type of task that can be included in early interventions focused on motor-vocal deficits.

Study limitations

This research has some limitations. First, our semi-naturalistic design resulted in a variety of infant body positions during each task and time point. Stable or unstable body positioning may affect the execution of limb movements and vocal production, so future research should investigate the patterns of motor, vocal, and motor-vocal coordination across all body postures to better understand its effects. Similarly, we have not controlled for dyadic positioning – infants and caregivers were unconstrained and could choose their positioning as they wished (and change it at any point of each play). As Schneider et al. (2023) showed, dyadic co-orientation and infants’ postural skills influence the way in which the interactions unfold during play with objects, so this aspect could definitely influence the results observed by us in this study. Second, we have not investigated dyadic coordination in a systematic way. Future research should measure dyadic coordination in the motor domain as well as infants' motor-vocal responses to parental motor-vocal actions – ideally, also adding other modalities such as visual attention and touch to fully grasp the early dyadic multimodal communication across play types. Third, in order to simplify the statistical modeling, the control analyses regarding gross and fine motor development at each time point were not included in this thesis. For this reason, we cannot draw definitive conclusions related to the impact of motor control or proficiency on the development of task-related specialization. Fourth, the studied sample was not representative in terms of socioeconomic status. Due to the need to commute to the lab on multiple occasions, all families were recruited from the Warsaw metropolitan area and came from highly educated middle-class backgrounds.

Conclusions

The current multi-faceted research was focused on developmental changes of motor-vocal coordination in infancy. Specifically, it showed that multimodal (motor-vocal) specialization to the demands of the task-driven context of social interactions emerges across infancy. Infant – as a complex dynamic system – starts to adjust his/her motor and vocal actions (or form synergies) to perform a given task from around 12 months of age. The development of motor and vocal coordination follows similar trajectories, emphasizing that vocal production is an example of a highly specialized motor action. The coupling between limb movements and vocalizations further highlights the close link between these two modalities, potentially showing an early precursor of the speech-gesture system from 9 months of age. Altogether, the presented results show that the second half of the first year of life (between 6 and 12 months of age) is a window of massive reorganization of motor and vocal actions, resulting in better adjustments to task demands. This process of reorganization provides a basis for the development of social communication.

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