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Relationship between temperamental dimensions and infant limb movement complexity and dynamic stability

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ABSTRACT

Infant temperament reflects behavioral responses to stimulation, while the motor system undergoes significant developmental changes throughout infancy, influenced in part by caregivers' mental well-being. This study examines the associations between temperament and motor system organization across three distinct social interaction tasks at 6 and 12 months of age. To account for the role of the caregiver's mental well-being, we also included maternal trait anxiety in our analysis. A longitudinal sample of 83 infants at 6 months and 59 infants at 12 months participated in three caregiver-infant tasks: book-sharing, playing with manipulative toys, and rattle-shaking. Infant limb movements were recorded using wearable accelerometers, and we applied Multidimensional Recurrence Quantification Analysis (MdRQA) to extract Entropy (reflecting motor system complexity) and Mean Line (reflecting motor system stability). Using mixed-effects models, we examined the predictive effects of task and temperament variables: Negative Affectivity (NEG), Positive Affectivity or Surgency (PAS), and Orienting and Regulatory Capacity (ORC). Our results suggest that Negative Affectivity measured at 6 months predicted increased motor system Entropy and Mean Line concurrently at 6 months as well as longitudinally at 12 months. Temperamental variables measured at 12 months of age did not predict infants' motor systems' complexity and stability at the same time point. At 12 months, task conditions modulated both Entropy and Mean Line, suggesting greater sensitivity to contextual differences later in infancy. Additionally, higher maternal trait anxiety (measured at 4 months) predicted decreased motor system Entropy and Mean Line at 12 months. Our results have implications for understanding the early developmental pathways of motor system organization, its relationship with temperament, and the influence of caregiver mental well-being on infant motor development.

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1. Introduction

Cognitive and motor development are closely interconnected, with infants' bodies, environments, and experiences collectively shaping their behavioral adaptability (Adolph & Hoch, 2019). These interconnections are essential for understanding developmental trajectories and outcomes later in life. This study explores the relationship between temperament dimensions in infancy and the development of motor system features that enable flexible adaptations to environmental constraints (Aßmann et al., 2007; Abney et al., 2014).

Temperament, defined as stable individual differences in emotional and behavioral reactivity during infancy, reflects biologically and genetically influenced traits (Tang et al., 2020). These traits encompass variations in reactivity and self-regulation, focusing on emotional, motor, and attentional dimensions (Rothbart, 1981; Rothbart et al., 2004; Vonderlin et al., 2008). Reactivity refers to the responsiveness of emotional, activation, and arousal systems, while self-regulation involves processes like approach, avoidance, and attention modulation. The development of temperament arises from a dynamic interplay between genetic inheritance, maturation, and experience (e.g., Rothbart, 1981; Rothbart & Derryberry, 1981). Recognized as one of the earliest indicators of psychological differences in childhood, temperament significantly influences emotional and motor reactivity. These early traits shape subsequent social interactions, social functioning (Calkins and Swingler, 2012), and personality development across the lifespan (e.g., Tang et al., 2020; McCrae et al., 2020; Sieber & Zmyj, 2022).

Early in life, specifically the newborn and early infancy period, five primary temperament dimensions have been described: two dimensions related to negative reactivity (fearfulness/distress toward novelty and frustration/distress regarding limits), one dimension concerning positive affect (smiling and laughter), alongside distractibility/attention span (duration of orienting responses to new stimuli), and activity level (motor activity) (Rothbart et al., 1995). By the end of the first year, the child begins to exhibit effortful control and executive attention capabilities, allowing for more effective regulation and inhibition of responses. These developmental processes occur concurrently with the child's active planning skills and increasing adaptability to changing circumstances (Rothbart et al., 2004). Thus, this theoretical approach to temperament extends beyond the emotional realm by considering individual differences in reactivity and self-regulation, incorporating activity level, orienting, and executive attention into the temperament construct (Vonderlin et al., 2008).

Contemporary conceptualizations of temperament describe at least three distinct temperamental domains (Shiner et al., 2012): *1) Negative affectivity* or *negative emotionality (NEG)*; *2) Positive affectivity or surgency (PAS)*; *3) Effortful control or Orienting and Regulatory Capacity (ORC)* (Casalin et al., 2012). Negative affectivity refers to the tendency of infants to experience anger, fear, frustration, discomfort, and sadness (Shiner et al., 2012). Children with high Negative Affectivity can seem easily distressed, fearful, and shy, and they can exhibit negative facial expressions (like frowning) and demonstrate distress in behaviors like crying (Olino et al., 2011; Wittig & Rodriguez, 2019). Positive affectivity/surgency refers to the overall level of activity, impulsivity, positive anticipation, and sensation seeking in infants (Wittig & Rodriguez, 2019); and it is the developmental precursor of extraversion. High Positive Affectivity/Surgency can be expressed in laughter, smiling, and increased motor activity (Putnam & Stifter, 2008). Orienting and regulatory capacity promote the development of effortful control (Putnam & Stifter, 2008). In this sense, infants with increased Orienting and Regulatory Capacity are capable of self-soothing when they are distressed (Gartstein & Rothbart, 2003; Wittig & Rodriguez, 2019).

Biological approaches have long been employed to investigate why and how individuals differ in temperament dimensions and, later, in personality (e.g., Reuter et al., 2022; Marshall et al., 2009). These studies, however, often yield contrasting results. This variability is not surprising when considering that living organisms are complex adaptive systems comprising numerous interdependent subsystems (Richardson et al., 2014). These systems engage in continuous interactions with their material and social environments (Thompson & Varela, 2001), with neuroendocrine, neural, and physiological components dynamically changing and forming a multilevel network of regulatory activities (e.g., Bashkatov & Garipova, 2022; Trofimova et al., 2016, 2018). From the perspective of the dynamic systems theoretical framework (Thelen & Smith, 1994), motor actions are conceptualized as elements assembled in a flexible, task-specific manner to serve functional purposes. This assembly is influenced by the immediate environmental context, the infant's maturational status, and prior experiences (Fogel & Thelen, 1987; Thelen & Smith, 1994). An infant's actions emerge from the entire system of interacting elements at a specific time and context, likely shaped by the child's reactivity and self-regulation patterns. In this context, motor system complexity and dynamic stability become critical for understanding how temperamental characteristics are expressed and regulated. Complexity, operationalized here as entropy values, reflects the system's capacity to adapt and respond flexibly to diverse contexts, while dynamic stability, operationalized here as mean values, ensures coherence and resilience in the face of perturbations (e.g., de Jonge-Hoekstra et al., 2020). Interestingly, entropy can be indicative of both complexity or flexibility (e.g., De Jonge-Hoekstra et al., 2020) and irregular or unpredictable dynamics of the system (Shannon, 1948). Such differences in interpretation call for a cautionary approach, especially concerning a rapidly developing system – which is the case for a motor system in infancy. Thus, factors such as the age of participants or the context in which their behaviors are embedded can affect the overall interpretation of entropy.

In developmental research, motor activity level has been a frequently studied dimension of temperament, as it is closely linked to patterns of gross and fine motor activity (e.g., Buss & Plomin, 1975; Schaffer, 1966; Thomas et al., 1963; see Rothbart & Derryberry, 1981 for a review). For example, effortful control has been shown to positively influence motor coordination (Sofologi et al., 2021), while the velocity of infants' head movements during the still-face paradigm reflects self-regulation (Hammal et al., 2015). Moreover, movement is considered a key modality for expressing temperament in infancy (Planalp et al., 2017; Lev-Encab et al., 2022). However, to the best of our knowledge, the relationship between an infant's temperament and the complexity of their motor system has yet to be explored. A notable exception is Chua et al. (2025), who utilized dynamic analyses of motor kinematics and behaviors to study emotional self-regulation, offering a promising line for further investigation.

Nonlinear approaches have been increasingly utilized in the psychology of individual differences among adults. Previous studies have shown that body motion dynamics during self-referencing tasks were significantly related to personality traits (Arellano-Véliz et al., 2024b). In particular, the relationship between personality traits and body motion dynamics varied depending on the topic participants talked about, emphasizing the critical role of situational constraints in embodied dynamics. For instance, neuroticism was associated with lower determinism (less patterned dynamics) and more variability when talking about sensory and socioemotional experiences, reduced complexity and stability during socioemotional topics, alongside heightened negative affect. Personality traits are also expressed in dyadic motor coordination. In this sense, extroversion has been linked to stronger interpersonal motor synchronization (Arellano-Véliz et al., 2024a). Here, too, context plays a crucial role: the nature of the conversation (e.g., bonding vs. argumentative) influences both the strength of bodily synchronization and the dynamic organization of body motion (Arellano-Véliz et al., 2024a).

Approaches to temperament in developmental psychology emphasize the individual's developing capacity for control over self and environment, making it an integrative view of biological and behavioral aspects of temperament by operating with terms like reactivity and self-regulation (Derryberry & Tucker, 2015). Temperament operates as an open system, which is influenced by ongoing interactions with the environment (Sofologi et al., 2021; Putnam and Stifter, 2008). Early variations in the likelihood of experiencing positive or negative moods, becoming aroused in response to environmental transactions, or self-regulating after being upset are examples of temperamental factors in the interaction with the environment in which the infants are developing (Cervone & Pervin, 2019).

As part of the environment that plays a role in infants' development, caregivers are fundamental. In this regard, maternal anxiety has been linked to various developmental and psychological outcomes in infants (Glasheen et al., 2010; Field, 2018; Del Hoyo-Bilbao and Orue, 2024). It predicted anxious-depressive symptomatology (Barker et al., 2011; O'Connor et al., 2002) and behavioral problems in children (Behrendt et al., 2020). Maternal anxiety is also associated with infants' temperament, particularly Negative Affectivity (NEG) (Spry et al., 2020). Maternal anxiety also relates to other temperament dimensions such as effortful control (ORC) and Positive Affectivity/Surgency (PAS). A longitudinal association was found between maternal anxiety in infancy and lower effortful control and higher surgency levels at 3 years of age (Behrendt et al., 2020). Similarly, various forms of maternal anxiety during prenatal and postnatal periods were individually linked to perceived difficulties in infant temperament. In particular, chronically high maternal anxiety, whether pregnancy-specific or general, predicted the highest perceived infant activity level and Negative Affectivity at 6 months postpartum (Henrichs et al., 2009). In addition, a recent study showed that the relationship between maternal anxiety and infant Negative Affectivity was explained through the mediating roles of parenting self-regulation and the child's emotional awareness (Del Hoyo-Bilbao and Orue, 2024). Similarly, the connection between maternal anxiety and infant effortful control was mediated by the caregiver's compassion and attentive listening to the child (Del Hoyo-Bilbao and Orue, 2024). In this sense, maternal anxiety after childbirth represents a critical time for the development of infant temperament and cognitive and motor development (Keim et al., 2011). Recent research suggests the existence of critical time points in which maternal mental health predicts cascading influences on child development outcomes, such as temperament across the first 6 months of life (Rigato et al., 2020).

Importantly, psychological differences in mothers can influence their interactions with their infants and impact motor development during the first year of life. For instance, Irwin et al. (2020) found that increasing maternal prenatal anxiety was associated with lower gross motor skills at 12 months, as well as lower receptive language scores. Furthermore, maternal psychological problems, even in non-clinical samples, have been shown to influence motor development (Piallini et al., 2016). Nasreen et al. (2013) similarly reported associations between maternal ante- and postpartum depressive symptoms and infant motor development. These findings underscore the first year of life as a sensitive period during which maternal anxiety and stress can exert lasting effects on developmental trajectories (Behrendt et al., 2020). Therefore, given the link between maternal mental health and its effects on infants' developmental trajectories, identifying factors shaping this relationship and understanding other developmental consequences becomes crucial for enhancing caregiver-child interactions, interventions, and infants' mental health (Henrichs et al., 2009; Del Hoyo-Bilbao and Orue, 2024)).

1.1. The present study

In this paper, we first use traditional parent-report questionnaire measures of infant temperament at 6 and 12 months of age as well as a questionnaire measure of maternal anxiety. Second, we measure the acceleration of spontaneous infant limb movements with wearable motion trackers during three different types of infant-parent play at 6 and 12 months of age (book-sharing, playing with manipulative toys, and rattle-shaking). Third, we use a nonlinear method of data analysis to determine the infant's motor system complexity and dynamic stability. Finally, we investigate the relationship between the child's temperament and motor system complexity and dynamic stability, concurrently at 6 and 12 months and longitudinally between 6 and 12 months of age.

The selection of the 6- and 12-month age range was motivated by the significant developmental transitions that occur during this period. Between 6 and 12 months, infants undergo dramatic changes in their motor system, including the onset of independent locomotion and the acquisition of novel body postures (e.g., sitting, crawling, pulling to stand; Adolph & Berger, 2006). These advances are often accompanied by the refinement of fine motor skills, which influence how infants interact with their environment and caregivers (e.g., Libertus & Hauf, 2017). Additionally, this developmental window is marked by rapid changes in speech and communication skills, which may also affect the expression of temperamental features (Iverson, 2010). These milestones may shape the infant-caregiver dynamic and influence the patterns observed in limb movement complexity and stability. Additionally, motor responses at 6 months may not be specialized and differentiated yet (e.g., D'Souza et al., 2017). Therefore, we compared infants at 6 and 12 months of age.

Specifically, we aimed to investigate infants' motor systems' complexity and dynamic stability, which were operationalized using two key measures derived from Multidimensional Recurrence Quantification Analysis (MdRQA): Entropy and Mean Line. Entropy quantifies the variability and richness of movement patterns, reflecting how flexible and adaptive an infant's motor system is when engaging in various tasks. Higher entropy values indicate greater complexity, which may suggest a more exploratory and adaptive motor behavior. Mean Line, on the other hand, captures the temporal stability of movement patterns over time, representing the consistency of motor actions. Together, these measures provide complementary information into the dynamic properties of infant motor behavior: complexity reflects the range of possible movement states, while stability indicates how reliably those states are maintained across time (see Table 2 for detailed information). These measures were derived from accelerometric data recorded during spontaneous infant limb movements. Wearable motion trackers attached to the infants' limbs captured three-dimensional acceleration data, providing a high-resolution, continuous record of motor activity. The use of MdRQA allows for the analysis of the temporal organization of these multidimensional time series, identifying patterns that might not be evident through traditional linear methods. This approach is particularly suited for capturing the nuances of infant motor development, which often involves nonlinear and emergent changes as infants transition to more complex movement patterns and postural control (Thelen & Smith, 1994).

From a developmental perspective, motor complexity and stability are meaningful because they reflect the infant's capacity to adapt to changing environmental demands and task constraints. For instance, greater motor complexity may facilitate exploratory behavior during play, while higher stability may support goal-directed actions, such as grasping or manipulating objects. These properties are not static but evolve as the motor system matures, influenced by developmental milestones such as independent locomotion and postural control (Adolph & Berger, 2006). By investigating how these dynamic properties relate to temperament at 6 and 12 months, this study seeks to shed light on the interplay between motor and temperamental development during a period of rapid change.

To assess the relationship between temperamental variables on infants' motor systems' complexity and dynamic stability, infants' limb movement patterns were measured across three types of infant-parent games (book-sharing, rattle-shaking, and play with manipulative toys) typically associated with different types of coordinated responses. Rattle-shaking was chosen as a highly constrained activity, characterized by repetitive arm and body movements, which are well-suited for examining rhythmic and stable motor patterns. In contrast, playing with manipulative toys was selected as the most open-ended interaction, encouraging multimodal exploration and diverse arm movement patterns, providing a broader spectrum of motor complexity and coordination. Book-sharing, on the other hand, represents a stationary activity with subtle motor patterns, such as pointing and page-turning, which are less demanding in terms of gross motor activity but may reflect fine motor skills and attentional engagement. These task variations were deliberately chosen to capture a wide range of infant movement dynamics across distinct interaction types. Detailed hypotheses are

Table 1
Summary of predictions for the effect of temperament on infant motor organization by time point and task.

Hypothesis	Description	Task effects	Longitudinal effects
H1	Lower Negative Affectivity (NEG) is hypothesized to be associated with higher motor system complexity (measured as Entropy) at concurrent time points (6 and 12 months).[a,b,c]	*H1a:* The association between NEG and complexity is expected to be stronger for tasks involving rattle-shaking and manipulative toys compared to book-sharing, as these tasks involve predominantly motor actions with less vocal input.[b,c,d]	*H1b:* Lower NEG at 6 months is expected to predict higher motor system complexity (Entropy) at 12 months.
H2	Lower Negative Affectivity (NEG) is hypothesized to be associated with higher motor dynamic stability (measured as Mean Line) at concurrent time points (6 and 12 months).[a,b,c,d]	*H2a:* The association of NEG and motor dynamic stability is expected to be stronger for tasks involving rattle-shaking and manipulative toys compared to book-sharing, due to the predominance of motor actions in the former.[b,c,d]	*H2b:* Lower NEG at 6 months is expected to predict higher motor dynamic stability (Mean Line) at 12 months.
H3	Lower Positive Affectivity/Surgency (PAS) is hypothesized to be associated with lower motor system complexity (measured as Entropy) at concurrent time points (6 and 12 months).[d,e,f,g]	*H3a:* The relationship between PAS and complexity is expected to be stronger for rattle-shaking and manipulative toy tasks compared to book-sharing due to the greater demand for motor engagement in these tasks.[b,c,d]	*H3b.* Lower PAS at 6 months is hypothesized to predict lower motor system complexity (Entropy) at 12 months.
H4	Higher Orienting/Regulatory Capacity (ORC) is hypothesized to be associated with higher motor system dynamic stability (measured as Mean Line) at concurrent time points (6 and 12 months).[c,d,e]	*H4a:* The association between ORC and motor dynamic stability is expected to be stronger for tasks involving rattle-shaking and manipulative toys compared to book-sharing, given the higher motor demands of the former.	*H4b:* Higher ORC at 6 months is hypothesized to predict higher motor dynamic stability (Mean Line) at 12 months.
H5	Exploratory analyses will examine the relationships between maternal anxiety and infant motor system complexity (Entropy) and stability (Mean Line) at 6 and 12 months.		

Note:
[a] Arellano-Véliz et al. (2024b)
[b] Rothbart and Derryberry (1981)
[c] Calkins and Fox (2002)
[d] Thelen (2005)
[e] Adolph & Hoch, 2019
[f] Buss & Goldsmith (1998)
[g] Arellano-Véliz et al. (2024a). These hypotheses were preregistered and can be accessed at https://osf.io/hsm8z

presented in Table 1. Overall, we expected task-related differences in limb movement coordination to emerge at a later age (12 months), as shown by Laudańska et al. (2022). We also expected more coordinated motor actions (e.g., stability) while exploring toys with interesting tactile structures, more rhythmic and stable patterns during rattle-shaking, and less defined motor coordination patterns during book-sharing, which involves more vocal than motor actions. The potential lack of clear motor coordination patterns in book-sharing could lead to a lack of clear relations between limb movement complexity and stability.

Moreover, considering the effects of maternal mental well-being on their perception of child behavior and temperament during the first year of life (Miller et al., 2021), we conduct exploratory analyses to investigate whether there are any relations between the caregiver's anxiety levels and infant motor system complexity and stability at 6 and 12 months.

1.1.1. Hypotheses

Table 1, presented below, outlines the study's hypotheses, examining how temperament predicts motor system organization.

2. Method

2.1. Participants

Participants were 104 infant-parent dyads who were invited to the lab 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. For the present study, we focused on T2 (6 months old, mean age = 200 days, range: 163–238 days) and T4 (12 months old, mean age = 368 days, range: 330–441 days), for which a sample of 83 and 59 infants was available, respectively. Participants were from predominantly middle-class families (indicated by the socio-economic data on income and education self-disclosed by caregiver(s)) living in Warsaw, a city with > 1.8 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). For their participation, infants received a diploma and a small gift (a baby book). The study received clearance from the Research Ethics Committee at the Institute of Psychology, Polish Academy of Sciences, Warsaw, Poland.

2.2. Assessment of temperament

The infant's temperament was measured using two versions of the Polish adaptation of the Infant Behavior Questionnaire-Revised (IBQ-R, Rothbart, 1981). When infants were at the age of 6 months (T2), the IBQ-R Very Short Form was used (Putnam et al., 2014), and when they were 12 months old (T4), the IBQ-R Full version was used (Gartstein & Rothbart, 2003, Polish adaptation by Dragan et al., 2011). Three dimensions were calculated for each version: Negative Affectivity (NEG), Positive Affectivity/Surgency (PAS), and Orienting/Regulatory Capacity (ORC). In the IBQ-R Very Short Form, the estimated internal consistency (Cronbach's alpha) for Negative Affectivity (NEG), Positive Affectivity (PAS), and Orienting/Regulatory Capacity ranged from.71 to.81 (Putnam et al., 2014). For the Polish adaptation of the IBQ-R Full version, the internal consistency was satisfactory, ranging in the scales from.71 to.90 (Dragan et al., 2011).

2.3. Assessment of maternal anxiety

Maternal anxiety may affect the quality of interactions with the infant (e.g., Kaitz et al., 2010). Furthermore, elevated anxiety symptoms appear to have a distinct association with maternal reports of child development and temperament (Miller et al., 2021). Thus, we measured maternal trait anxiety using the Polish version of the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983; Polish adaptation by Spielberger et al., 1987). Maternal trait anxiety was measured at the first time point of the longitudinal study (when infants were 4 months of age), so earlier than infant temperament and limb movements. The STAI has demonstrated strong internal consistency, with Cronbach's alpha coefficients from.86 to.95, and test-retest reliability coefficients between.65 and.75 over a 2-month interval (Spielberger et al., 1983). Test-retest reliability coefficients ranged from.69 to.89, which indicates substantial evidence supporting the construct and concurrent validity of the scale (Spielberger et al., 1987). The Polish version of STAI showed Cronbach's alpha coefficients from 0.76 to 0.92 (Spielberger et al., 1987).

2.4. Equipment

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 the caregiver's arms, head, and torso), but in this paper, we report data only from four sensors placed on the infant's arms and legs.

2.5. Procedure

Interactions were recorded in an infant-friendly laboratory room on a carpeted play area. Upon the family's arrival, an experimenter explained the study protocol and obtained parental consent. Once the infant was familiarized with the laboratory, the wearable motion trackers attached to the elastic bands were put on the infant's and caregiver's bodies. Then, a set of parent-child interaction tasks with different age-appropriate toys took place. The sets for infants aged 6 months were slightly different from those for infants aged 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 (see Fig. 1). There were 6–7 different tasks during each testing session, but here we report data comparing three of them: book-sharing, playing with manipulative toys, and rattle-shaking, each lasting around 5 minutes. For the present analyses, we have chosen three tasks that 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. The order of tasks was randomized between participants and testing sessions. There were no specific instructions to the caregivers, they were asked to play with their child as they usually would do, using the provided objects. The positioning of the dyads was not constrained – both infants and caregivers could position themselves in their preferred way and change their positions across the duration of each task.

2.5.1. Task 1: Book-sharing

In a book-sharing task (also referred to as "books"), the dyads were provided with several baby books. At 6 months, 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 12 months, 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.

2.5.2. Task 2: Manipulative toys

In a manipulative toys task (also referred to as "manipulative"), 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 6 months, 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 12 months: 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.

2.5.3. Task 3: Rattle-shaking

In a rattle-shaking task (also referred to as "rattles"), which lasted approximately. In 5 minutes, the dyads were given two maracas rattles and two rattles of different types (the barbell rattles for younger infants and teddy bear rattles for older ones).

2.6. Data pre-processing

IMU data from sensors placed on the infants' wrists and ankles were processed in Matlab (Mathworks, Inc, Natick, USA) using in-house scripts. The acceleration signals in three movement directions were selected for further analysis. The IMU tracking system, which measures the orientation of the user, operates wirelessly through a WiFi connection. 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. On average, there were 3.15 % (SD=10.21) missing values. 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 investigate the acceleration information, the magnitude of acceleration for each three-dimensional acceleration data point was computed and collapsed into one-dimensional time series:

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

where $x,y,z, \in \mathrm{R}^{1xN}$, and the variables $x(t),y(t),z(t)$, represent the accelerations along the three spatial dimensions over time. 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.

2.7. Time series analysis: Multidimensional Recurrence Quantification Analysis (MdRQA)

Recurrence methods such as Recurrence Quantification Analysis (RQA), which involves the study of recurrent patterns in a system's behavior, have been widely used to capture the dynamic organization of complex dynamic systems (Marwan et al., 2007; Anderson et al., 2013; Main et al., 2016; Jenkins et al., 2020). The proper assessment of a system's dynamics involves the consideration of its multidimensional nature (Wallot & Leonardi, 2018). This consideration is relevant, for example, in the assessment of 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 systems (Wallot & Leonardi, 2018).

Multidimensional Recurrence Quantification Analysis (MdRQA) is a method that facilitates the analysis of multiple layers of data over time (Wallot & Leonardi, 2018). MdRQA, like other recurrence analyses, measures how our variables of interest repeat their

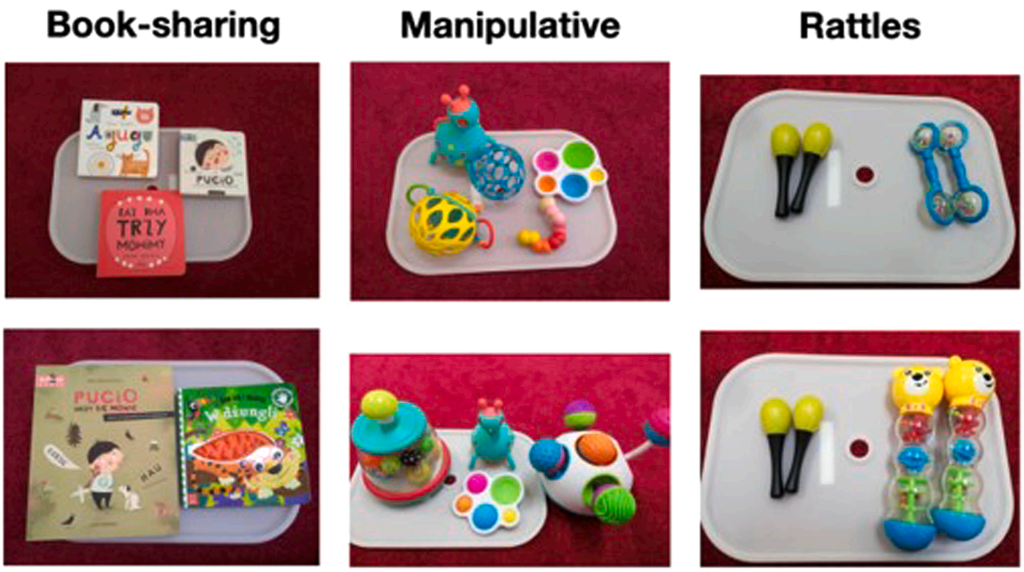

Fig. 1. *Pictures of the set of toys used on each task. Note:* The sets of toys used for each play. The top row indicates toys used during the visit at 6 months, and the bottom row indicates toys used at 12 months.

values or trajectories over time (Wallot et al., 2016). However, its particularity relies on its multidimensional approach, being able to analyze multiple layers of data (time series) within individuals (multivariate, multidimensional system) or joint dynamics of a group of variables over time (Wallot et al., 2016). MdRQA examines a singular system observed through two or more measured variables, and consequently, it assesses the auto-recurrence characteristics of a multidimensional or multivariate system (Hall et al., 2023; Wallot & Leonardi, 2018). This technique extends the study of systems' trajectories to multiple dimensions and allows for the investigation of interactions between variables or levels of analysis.

MdRQA, like other recurrence-based methods, involves reconstructing the phase space of a system using time-delayed embedding. In this process, multiple recorded time series are integrated into a single phase space, with each time series contributing one or more dimensions to the reconstruction (Wallot & Leonardi, 2018). By doing so, MdRQA enables the quantification of dynamics in 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 parameters of delay and embedding dimension is the same as is employed in RQA (see Wallot et al., 2016, for a detailed explanation). These parameters dictate how the phase space is reconstructed and influence the analysis outcomes (Wallot et al., 2016). In this study, the delay was set to 1, and the embedding dimension to 10 (similar to Laudańska et al., 2022).

We extracted the measures *Entropy* and *Mean Line*, which provide information about the systems' dynamic organization, as explained in Table 2.

2.8. Statistical analysis

To estimate the association between the temperament variables (NEG, PAS, ORC) and our MdRQA variables (Entropy and Mean Line), Maximum Likelihood (ML) linear mixed-effect models were performed using the 'lme4' R package (Bates et al., 2015). The models have a hierarchical two-level structure, where the participant scores in each task are nested within the individual structure. Level 1 corresponded to "task," the individual observations of the outcome variable (Entropy; Mean Line) by each task (book-sharing, rattle-shaking, playing with manipulative toys). Level 2 corresponded to "individuals" (infants).

Separate sets of models were conducted at 6 months, at 12 months, and longitudinally to predict motor complexity at 12 months from temperament dimensions measured at 6 months. The dependent variables for these models were Entropy and Mean Line, while the fixed-effect predictors included temperament variables and task type. To explore the unique contribution of each temperament dimension (NEG, PAS, ORC) on the outcome variables Entropy and Mean Line, separate models were run sequentially.[8] Finally, a comprehensive model was conducted, incorporating all temperament variables additively and in interaction with task type.

Our models specified three fixed-effect predictors (NEG, PAS, ORC), which were assumed to have a relatively consistent relationship with the outcome variable across the population. In addition, we have a categorical variable (task) that is also included as a fixed-effect predictor, which has three levels (tasks: book-sharing, manipulative toys, rattle-shaking), where the task "book-sharing"

[8] This is the structure of the models: Entropy ~ (NEG) * task + (1|Participant ID); Entropy ~ PAS + task + (1|Participant ID); Entropy ~ ORC + task + (1|Participant ID); Mean Line ~ NEG + task + (1|Participant ID); Mean Line ~ PAS + task + (1|Participant ID); Mean Line ~ ORC + task + (1|Participant ID).

Table 2
MdRQA measures' definition and interpretation.

Measure	Definition	Interpretation	Implications for Infant Motor Development
Entropy (ENT)	Shannon Entropy calculated from the distribution of diagonal line lengths in the recurrence plot, representing repeating movement patterns.[a]	- Quantifies the diversity or complexity of deterministic patterns in the multidimensional system.[a,b] - Reflects the degrees of freedom in limb movement synergies.[b] - Higher ENT values can indicate both, greater complexity and less predictability in the system's behavior.[c]	- Higher ENT may reflect greater variability in motor behavior, which can support flexibility and exploratory movements essential for developing motor coordination.[c] - Elevated ENT might also indicate irregular or less predictable dynamics within the system, reflecting potential instability or reorganization. - Such variability could signal critical changes in the system's development, with outcomes dependent on the broader context and interactions within the system.[d]
Mean Line (MnL)	The average length of diagonal lines in the recurrence plot, indicating the average duration of recurring patterns.[a]	- Measures the average duration of deterministic patterns in multidimensional time-series data.[b] - Serves as a stability indicator of the multidimensional motor system.[a,b] - Larger values of the MnL (longer average durations) suggest higher stability (longer-lasting patterns), whereas smaller values imply lower system stability.[a,b]	- Higher MnL indicates greater motor system stability, which may support smoother and more coordinated movement development over time. - Lower MnL could suggest less stable motor control, potentially reflecting challenges in sustaining or integrating movements, which may impact later developmental milestones.

Note:
[a] Wallot and Leonardi (2018)
[b] Laudańska et al. (2022);
[c] De Jonge-Hoekstra et al. (2020);
[d] Shannon, 1948

was considered the baseline. This variable allows us to investigate whether the relationship between the temperament variables of the babies and the outcome variables varies depending on the specific task. The random effect was specified as "(1|Participant ID)", which assumes that there is individual variability in the intercept of the relationship between the predictors and outcomes across different participants (for information related to the package, consult 'lme4' R package, Bates et al., 2015). This random effect accounts for the fact that different participants may have different baselines of the outcome variable (MdRQA or motor system variables), even after accounting for the fixed-effect predictors (temperament). The combination of both fixed and random effects contributes to the generalizability of the results.

Given the complexity of the mixed-effects models, which include both fixed and random effects, we performed a conservative power analysis using a simplified model that includes only the fixed effects using the R package "pwr" (Champely, 2020). This approach provides an estimate of the power to detect significant fixed effects, acknowledging that it may not fully capture the variability introduced by random effects. For the short models, including only one temperament predictor and task, the power analysis indicates a power of approximately 97.5 % to detect a medium effect size of $f2 = 0.25$ with a sample of 83 at the 0.05 significance level and 90.6 % at 12 months using the same parameters with a sample of 59. For the last step, including all temperament predictors and tasks (full models), the power to detect a medium effect size of $f2 = 0.25$ at the 0.05 significance level is 94.7 % at six months (with a sample of 83) and 81.6 % at 12 months with a sample of 59.

As an exploratory set of analyses, the effect of maternal anxiety (measured at 4 months) was assessed through mixed-effects models. In this case, the variable of maternal trait anxiety (STAI) was considered as a predictor together with the task interactively, and the response variables were Entropy and Mean Line, as in the previous models. Subsequently, the temperament variables were incorporated into separate models and a full model. This procedure was conducted with the MdRQA variables Entropy and Mean Linea at 6 and 12 months, indicating concurrent and longitudinal effects, respectively.[9]

The predictor variables (temperament scores) were centered to ensure an adequate convergence of the models. We report both estimates and standardized beta weights (β) and model estimates. This is under the reasoning that beta weights can be interpreted as effect sizes (e.g., Paxton & Dale, 2013). For linear mixed effects, all continuous predictors were standardized before being incorporated into the models to obtain beta weights. Temperament variables were centered by subtracting the mean. All statistical analyses were conducted using R (R Core Team, 2022), RStudio (RStudio Team, 2023), "lme4" R package (Bates et al., 2015), and visualized using ggplot2 (Wickham, 2016).

3. Results

3.1. IBQ-R descriptives at 6 months and 12 months of age

The descriptive statistics for temperament variables, as assessed by the IBQ-R, offer information about the dimensions of infants'

[9] Example of the model incorporating maternal anxiety and task: Entropy $\sim$ STAI * task + (1|Participant ID)

Table 3
Descriptive statistics for infants' temperament variables (IBQ-R).

Variable	*M*	*SD*	*Range*
Negative Affectivity, NEG (6 months)	3.65	0.93	[1.58, 5.64]
Positive Affectivity/Surgency, PAS (6 months)	4.66	0.70	[3, 6.15]
Orienting/Regulatory Capacity, ORC (6 months)	4.80	0.59	[3, 6.75]
Negative Affectivity, NEG (12 months)	3.94	0.41	[3.06, 4.76]
Positive Affectivity/Surgency, PAS (12 months)	4.95	0.42	[3.99, 5.92]
Orienting/Regulatory Capacity, ORC (12 months)	4.50	0.48	[3.60, 6.02]

Note: $N_{6\ months} = 83$ participants. $N_{12\ months} = 59$ participants. M = mean, SD = standard deviation.

temperament during the first year of life (see Table 3). At 6 months, infants exhibited an average score of 3.65 ($SD = 0.93$) on Negative Emotionality (NEG). Positive Affectivity/Surgency (PAS) exhibited a mean score of 4.66 ($SD = 0.70$). And Orienting/Regulatory Capacity (ORC) showed a mean score of 4.80 ($SD = 0.59$). The internal consistency of the IBQ-R Very Short subscales and the whole scale at 6 months were assessed using Cronbach's alpha. The Positive Affectivity/Surgency (PAS) subscale had an alpha of 0.67, the Negative Affectivity (NEG) subscale had an alpha of 0.82, and the Orienting/Regulatory Capacity (ORC) subscale had an alpha of 0.67. The overall scale demonstrated good reliability, with $\alpha = 0.81$.

By 12 months, the mean score for NEG was 3.94 ($SD = 0.41$). PAS exhibited a mean score of 4.95 ($SD = 0.42$). ORC exhibited a mean score of 4.50 ($SD = 0.48$) (see Table 3). The internal consistency of the IBQ-R-Full subscales and the whole scale at 12 months was assessed using Cronbach's alpha. The Surgency/Extraversion (SUR) subscale demonstrated an alpha of 0.83, the Negative Affectivity (NEG) subscale had an alpha of 0.78, and the Regulatory Capacity/Orienting (REG) subscale showed an alpha of 0.76. The overall scale demonstrated good reliability, with $\alpha = 0.87$.

3.2. *Correlations between IBQ-R scores*

Temperament variables measured at 6 and 12 months of age were significantly correlated: Negative Affectivity (NEG) ($r = 0.59$, $p < .001$), Positive Affectivity/Surgency (PAS) ($r = 0.56$, $p < .001$), and Orienting and Regulatory Capacity (ORC) ($r = 0.57$, $p < .001$). See Table 4 for the full overview of correlations at each time point and longitudinally.

3.3. *MdRQA measures of complexity and dynamic stability of limb movements at 6 and 12 months of age*

3.3.1. *Descriptives of MdRQA*

The descriptive results indicate that at 6 months, the mean Entropy scores were slightly lower in task 2, manipulative toys ($M = 4.91$, $SD = 0.52$), and equal in task 1, book-sharing ($M = 4.99$, $SD = 0.53$) and task 3, rattle-shaking ($M = 4.99$, $SD = 0.50$). Regarding stability, at 6 months, the Mean Line scores were lower in task 2, manipulative toys ($M = 14.98$, $SD = 6.04$), and higher in task 3, rattle-shaking ($M = 15.41$, $SD = 4.93$), and task 1, book-sharing ($M = 15.7$, $SD = 6.05$) (see Fig. 2 and Table 5).

At 12 months, the mean Entropy scores were lower in task 2, manipulative toys ($M = 4.63$, $SD = 0.71$), followed by task 1, book-sharing ($M = 5.05$, $SD = 0.73$), and task 3 (rattle-shaking, $M = 5.15$, $SD = 0.60$). At 12 months, the task that showed the lowest stability was manipulative toys ($M = 12.93$, $SD = 5.84$), followed by rattle-shaking ($M = 17.79$, $SD = 6.40$), and book-sharing ($M = 18.53$, $SD = 12$) with the highest stability or Mean Line values (see Fig. 2 and Table 5).

3.4. *Predicting MdRQA from task and temperament at 6 and 12 months of age*

As detailed in the method section, linear mixed-effects models were employed to investigate the effects of task and temperament variables on infants' motor system dynamic complexity (Entropy) and dynamic stability (Mean Line). The models incorporated variations in tasks, with "Manipulative" designated as task 2 and "Rattle-shaking" as task 3, while task 1 (Book-sharing) served as the baseline (See Fig. 3 for task effects on Entropy and Mean Line at 6 and 12 months).

3.4.1. *Predicting motor system complexity (Entropy) and stability (Mean Line) concurrently at 6 months*

3.4.1.1. Entropy. To analyze the effects of task and temperament variables (Negative Affectivity, NEG, Positive Affectivity/Surgency, PAS, and Orienting and Regulatory Capacity, ORC) on Entropy – infants' motor system complexity – at 6 months of age (concurrently), we employed a sequential modeling approach. First, we examined the influence of the task alone on Entropy, employing a model with the task as the sole predictor. The mixed-effects models included task variations, with "Manipulative" as task 2, and "Rattle-shaking" as task 3, and the baseline task "Book-sharing" was denoted as task 1. Subsequently, we individually modeled the effects of each temperament variable interacting with the task (see Table 6). This step allowed us to assess how each temperament trait modulated the relationship between the task and infant motor system complexity. Finally, we constructed a comprehensive full model incorporating additively all temperament variables in interaction with the task.

The intercepts in all models were found to be statistically significant ($p < .001$). The results of the analysis are presented in Table 6. In the first model, including only the task as a predictor of Entropy at 6 months (*estimate* = 5.01, $SE = 0.06$, $\beta = .08$, $p < .001$), there

Table 4
Correlations between IBQ-R scores at 6 and 12 months.

Variable	NEG (6 months)	PAS (6 months)	ORC (6 months)	NEG (12 months)	PAS (12 months)	ORC (12 months)
NEG (6 months)	1	0.20	−0.62	**0.59** * *	**0.42** * *	0.14
PAS (6 months)	0.20	1	**0.31** *	0.18	**0.56** * *	0.19
ORC (6 months)	−0.06	**0.31** *	1	−0.11	**0.39** * *	**0.57** * *
NEG (12 months)	**0.59** * *	0.18	−0.11	1	**0.38** * *	0.05
PAS (12 months)	**0.42** * *	**0.56** * *	**0.35** *	**0.38** * *	1	**0.39** * *
ORC (12 months)	0.14	0.20	**0.57** * *	0.05	**0.39** *	1

Note: Bold text indicates statistically significant correlations; 0 ‘* ** ’ 0.001 ‘* *’ 0.01 ‘* ’ 0.05 ‘.’ 0.1 ‘ ’ 1
NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. The correlation table displays the correlation between temperament variables at 6 and 12 months of age.

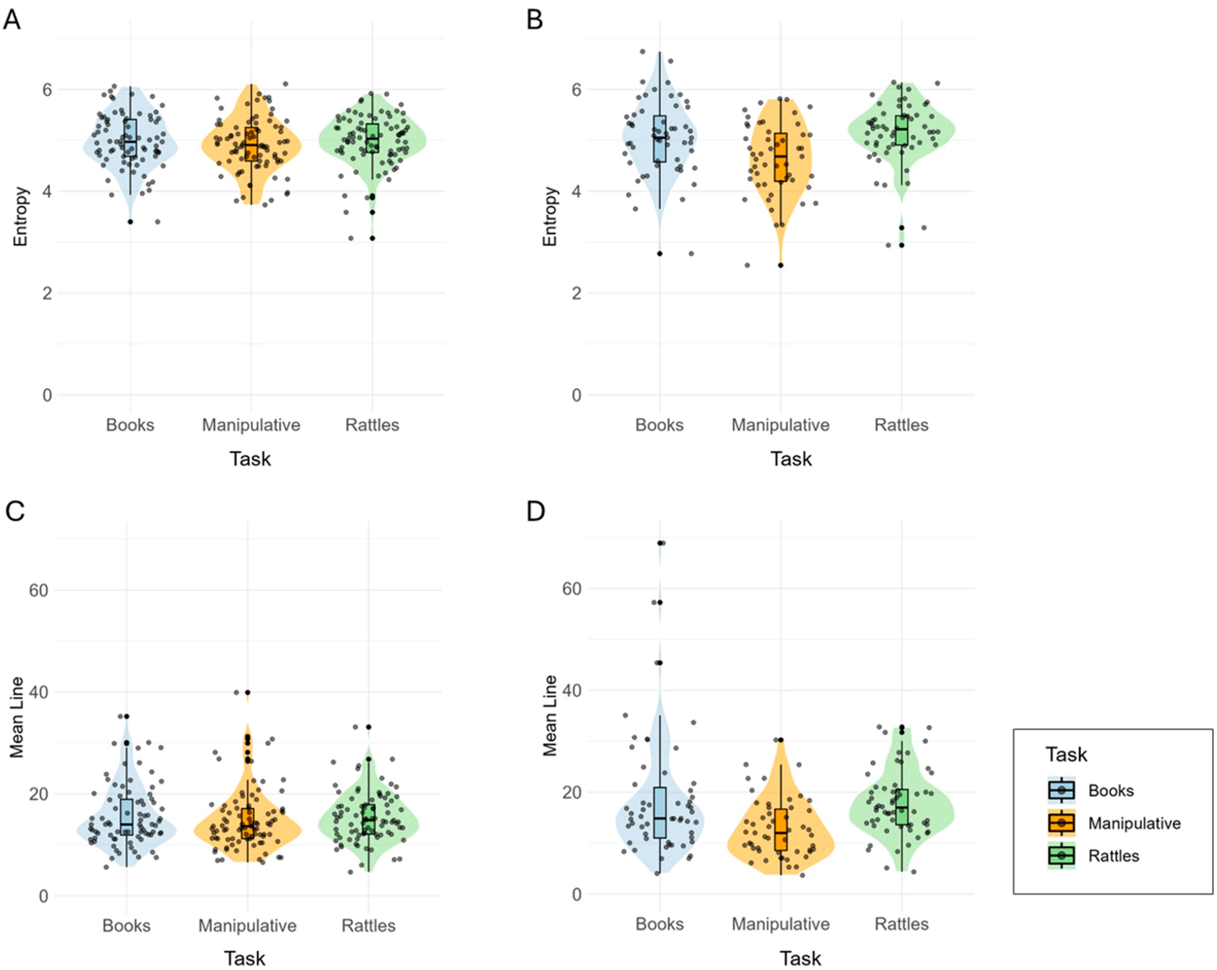

Fig. 2. *Distribution of Entropy and Mean Line at 6 and 12 months by task. Note:* Violin plots display the distribution of the MdRQA variables at 6 and 12 months across the three different tasks: Entropy 6 months (panel A) and 12 months (panel B) and Mean Line at 6 months (panel C) and 12 months (panel D). Task 1, book-sharing is represented in light blue. Task 2, manipulative toys is represented in orange. Task 3, rattles is represented in green. Books = Book-sharing, Manipulative = Manipulative Toys, Rattles = Rattle-shaking.

were no significant differences observed across tasks (see Model 1 in Table 6 and Fig. 3A). In the next step (model 2), the estimate for NEG revealed a significant positive association with Entropy ($\beta = .17, p < .05$), which indicates that as NEG at 6 months was higher, the value of Entropy was predicted to increase as well (contrary to H1) (see Fig. 4A). The marginal and conditional R^2 values suggest that the fixed and random effects explain a substantial proportion of variability in Entropy (around 28.7 %). There were no significant additive effects of task and NEG, therefore, H1a was not supported. There were no significant effects of PAS or ORC at 6 months on Entropy, therefore, H3 was not supported.

Table 5
Descriptive statistics for infants' motor system dynamic complexity (Entropy) and dynamic stability (Mean Line) per task and time-point.

	Task 1. Book-sharing			*Task 2. Manipulative toys*			*Task 3. Rattle-shaking*		
Variable	*M*	*SD*	*Range*	*M*	*SD*	*Range*	*M*	*SD*	*Range*
Entropy (6 months)	4.99	0.53	[3.40, 6.06]	4.91	0.52	[3.73, 6.11]	4.99	0.50	[3.08, 5.92]
Mean Line (6 months)	15.7	6.05	[5.60, 35.18]	14.98	6.04	[6.54, 39.89]	15.41	4.93	[4.63, 33.11]
Entropy (12 months)	5.05	0.73	[2.77, 6.74]	4.63	0.71	[2.55, 5.82]	5.15	0.60	[2.94, 6.14]
Mean Line (12 months)	18.53	12	[4.04, 68.88]	12.93	5.84	[3.68, 3.25]	17.79	6.40	[4.36, 32.80]

Note: $N_{6\ months}$ = 83 participants. $N_{12\ months}$ = 59 participants. M = mean, SD = standard deviation.

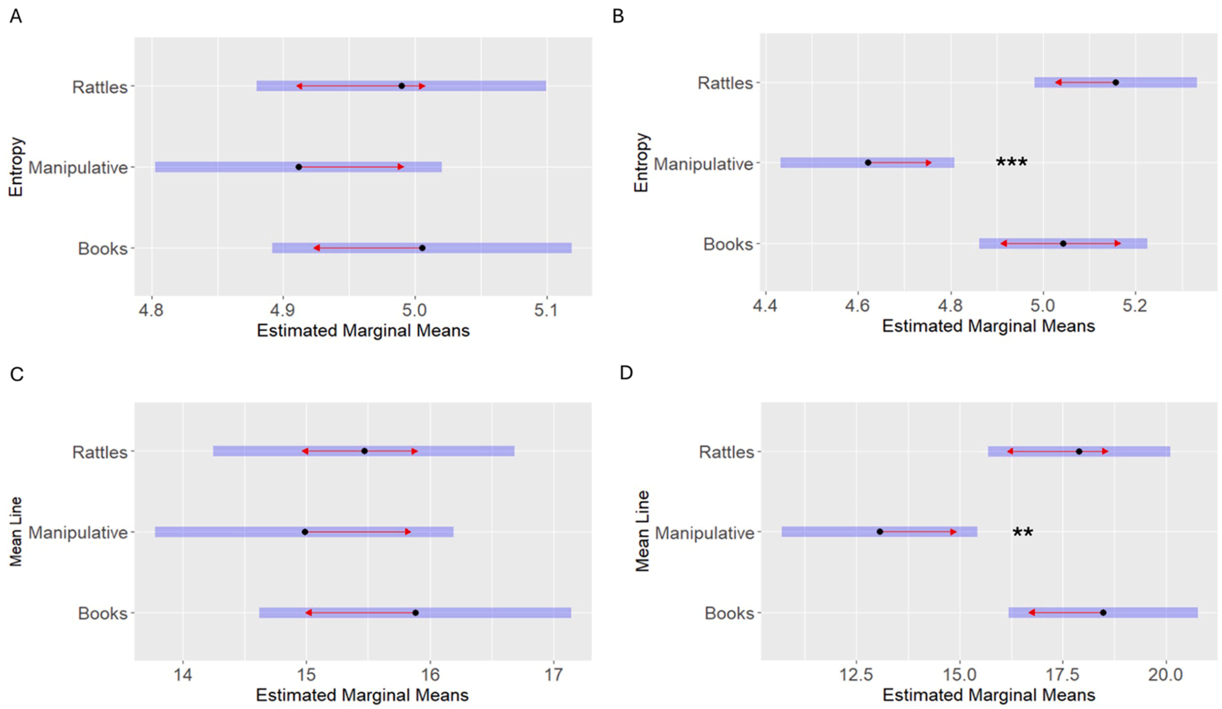

Fig. 3. *Predicted effects of task on Entropy and Mean Line at 6 and 12 months. Note:* Signif. codes: 0 '* ** '.001 '* *'.01 '* '.05 '.'.1 ' ' 1. Predicted effects of different tasks on Entropy at 6 months (panel A) and 12 months of age (panel B), with the estimated values of Entropy of task 2 (Manipulative) < task 1 (Books) ($p < .001$). Predicted effects of different tasks on Mean Line at 6 months (panel C) and 12 months of age (panel D), with the estimated values of the Mean Line of task 2 (Manipulative) < task 1 (Books) ($p < .01$). Task 1 (Books) was the baseline. Books = task 1, Manipulative = task 2, Rattles = task 3. Books = Book-sharing, Manipulative = Manipulative Toys, Rattles = Rattle-shaking.

3.4.1.2. Mean Line. Subsequently, we modeled the effects of task and each temperament variable (NEG, PAS, ORC) on Mean Line – infants' motor dynamic stability – at 6 months. The same sequential modeling approach was employed. First, only the task was included, in the subsequent models each temperament variable was included separately, and finally, a comprehensive full model was performed including all temperament variables in interaction with the task. Similarly, no significant task effects were found (*estimate* = 15.88, *SE* = 0.64, β =.07, $p < .001$) (see Model 1 in Table 7 and Fig. 3C). The estimate for NEG in models 2 and 5 (full model) revealed a significant positive effect (β =.21, $p < .01$; and β =.21, $p < .05$, respectively) (see Table 7). This suggests that as Negative Affectivity increased, the values of the motor system dynamic stability (Mean Line) were also expected to increase (contrary to H2) (See Fig. 4B). No task effects were observed at 6 months in these models, therefore, H2a was not supported. The marginal and conditional R^2 values for models 2 and 5 suggest that the fixed and random effects explain a substantial proportion of variability in Entropy (around 34 %). No significant effects were found for PAS and ORC at 6 months, therefore, H3 and H4 were not supported in our sample.

3.4.2. Predicting motor system complexity (Entropy) and stability (Mean Line) concurrently at 12 months

3.4.2.1. Entropy. We followed the same sequential procedure to model task effects and each temperament variable (NEG, PAS, ORC) on Entropy—infants' motor complexity—at 12 months. First, we included only the task as a predictor. In subsequent models, each temperament variable was added separately, and finally, a full comprehensive model incorporated all temperament variables along with the task. The mixed-effects model included task variations, with "Manipulative" as task 2, and "Rattle-shaking" as task 3, and the

Table 6
Models results for Entropy (infants' motor system complexity) at 6 months predicted by temperament and task.

	Model 1: Task (t)		*Model 2: NEG*		*Model 3: PAS*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate (SE)	β	Estimate (SE)	β	Estimate (SE)	β	Estimate (SE)	β	Estimate (SE)	β
Intercept	**5.01 (0.06)**	**0.08 * ****	**5.02 (0.06)**	**0.11 * ****	**5.01 (0.06)**	**0.11 * ****	**5.01 (0.06)**	**0.11 * ****	**5.02 (0.06)**	**0.11 * ****
Task 2: Manipulative	−0.09 (0.07)	−0.18	−0.11 (0.07)	−0.21	−0.11 (0.07)	−0.21	−0.11 (0.07)	−0.21	−0.11 (0.07)	−0.21
Task 3: Rattle-shaking	−0.02 (0.07)	−0.03	−0.05 (0.07)	−0.09	−0.04 (0.07)	−0.08	−0.04 (0.07)	−0.08	−0.04 (0.07)	−0.09
NEG			**0.09 (0.04)**	**0.17 ***					0.08(0.04)	0.16.
PAS					0.07(0.04)	0.13			0.03(0.04)	0.07
ORC							0.04(0.04)	0.07	0.04(0.04)	0.07
Random effects	*Var (SD)*		*Var (SD)*		*Var (SD)*		*Var (SD)*		*Var (SD)*	
Level 1, σ^2	0.19(0.43)		0.19(0.43)		0.19(0.43)		0.19(0.43)		0.19(0.43)	
Level 2 Intercept, τ_{00} ID	0.07(0.27)		0.07(0.26)		0.07(0.26)		0.07(0.27)		0.06(0.25)	
ICC	0.28		0.26		0.28		0.28		0.25	
Model fit										
Marginal R^2 /Conditional R^2	0.006/ 0.282		0.035/ 0.288		0.013/ 0.287		0.013/ 0.287		0.048/ 0.289	
Observations	251		238		238		238		238	
AIC	369.2		**348.4**		350.1		352.0		350.2	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1. N_i = 83. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/ Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

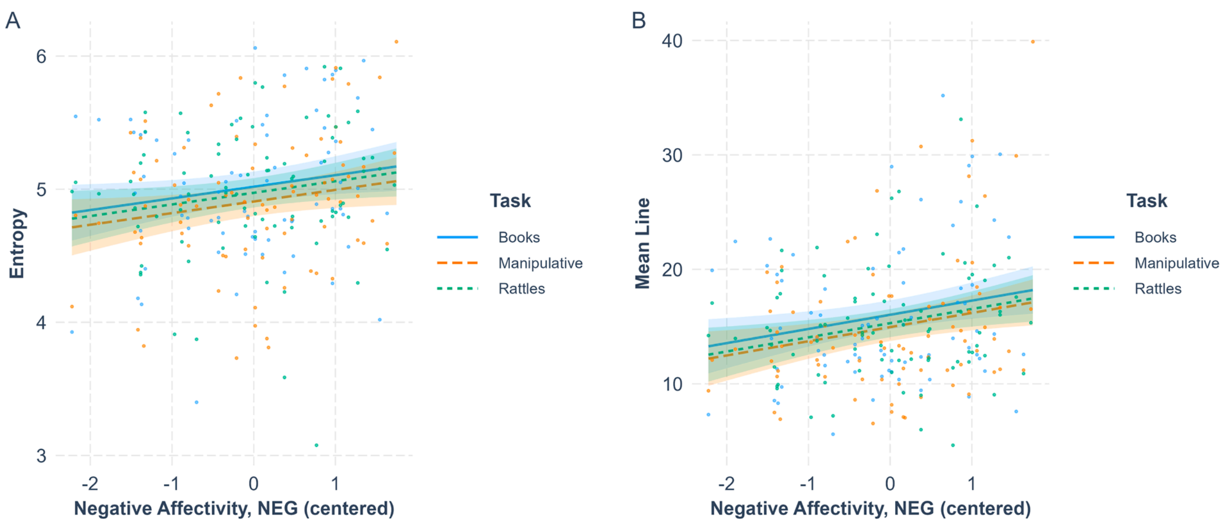

Fig. 4. *Predicted effects of Negative Affectivity (NEG) on Entropy and Mean Line at 6 months. Note:* NEG= Negative Affectivity. Panel A exhibits the effects of Negative Affectivity on Entropy and task at 6 months of age. In this case, only the effect of Negative Affectivity (NEG) was statistically significant ($p < .05$), and the effect of task was not significant ($p > .05$). Panel B exhibits the effects of Negative Affectivity on Mean Line (stability) and the task at 6 months of age. Only the effect of Negative Affectivity (NEG) was statistically significant ($p < .05$), whereas the effect of task was not significant ($p > .05$). NEG was centered and it represents the standardized scores of the original raw scores. Each unit in the x-axis corresponds to units of standard deviations from the centered mean of '0'. Books = Book-sharing, Manipulative = Manipulative Toys, Rattles = Rattle-shaking.

baseline task "Book-sharing" was denoted as task 1. The intercepts in all models were found to be statistically significant ($p < .001$, see Table 8).

In the model including only task effects on Entropy, the intercept, estimated at 5.04, signifies the baseline Entropy level when infants are engaged in the reference task (task 1: book-sharing), this baseline level of Entropy was found to be statistically significant ($SE = 0.09$, β =.12, $p < .001$) (see Model 1, Table 8, and Fig. 3B). The effect of the manipulative toys task (task 2) revealed a negative association with Entropy (*estimate* = −0.42, SE = 0.11, β = −.59, p < .001), indicating that when infants were engaged in the manipulative toys task, Entropy decreased compared to the baseline task (book-sharing). The effect of task 3 (rattle-shaking) was not

Table 7
Models results for Mean Line (infants' motor dynamic stability) at 6 months predicted by temperament and task.

	Model 1: Task (t)		*Model 2: NEG*		*Model 3: PAS*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*
Intercept	**15.88 (0.64)**	**0.07 * ****	**16.03 (0.64)**	**0.12 * ****	**15.98 (0.65)**	**0.12 * ****	**15.99 (0.66)**	**0.12 * ****	**16.02 (0.64)**	**0.12 * ****
Task 2: Manipulative	−0.90 (0.73)	−0.16	−1.08 (0.75)	−0.19	−1.04 (0.76)	−0.18	−1.02 (0.76)	−0.18	−1.07 (0.75)	−0.19
Task 3: Rattle-shaking	−0.41 (0.71)	−0.07	−0.73 (0.75)	−0.13	−0.71 (0.76)	−0.12	−0.71 (0.76)	−0.12	−0.73 (0.75)	−0.13
NEG			**1.24 (0.46)**	**0.21 * ***					**1.24 (0.49)**	**0.21 ***
PAS					0.70(0.46)	0.12			0.24(0.49)	0.04
ORC							0.40(0.47)	0.07	0.49(0.48)	0.09
Random effects	*Var (SD)*		*Var (SD)*		*Var (SD)*		*Var (SD)*		*Var (SD)*	
Level 1, σ^2	21.96 (4.69)		21.97		22.13 (4.70)		22.05 (4.70)		21.96 (4.69)	
Level 2 Intercept, τ_{00} ID	10.40 (3.23)		9.49		10.19 (3.19)		10.68 (3.27)		9.14(3.02)	
ICC	0.32		0.30		0.32		0.33		0.29	
Model fit										
Marginal R^2 /Conditional R^2	0.004/ 0.324		0.050/ 0.336		0.021/0.329		0.010/ 0.333		0.061/ 0.337	
Observations	251		238		238		238		238	
AIC	1572.6		1489.3		1494.0		1495.5		**1488**	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1. N_i = 83. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

statistically significant (β =.16, p > .05), indicating no significant difference in Entropy compared to the baseline task (book-sharing). The marginal R^2 (0.102) and conditional R^2 (0.345) values indicate that the fixed effects explain approximately 10.2 % of the variability in Entropy, while both fixed and random effects combined explain about 34.5 %.

When examining the impact of temperament variables (NEG, PAS, ORC) on Entropy, models were constructed with individual temperament variables, and a full model encompassing all temperament variables and their interactions with specific tasks (see Table 8). In the models including each temperament variable individually (Models 2, 3, and 4, Table 8), only the fixed effect of the "Manipulative task" (task 2) was a significant predictor of Entropy in all models (all $p < .01$). The full model (Model 5) demonstrated that the fixed effect of the task was the only significant predictor of Entropy in infants at 12 months ($\beta = -.55$, $p < .01$). This suggests that the task differentiation effect on Entropy was predominantly relevant at 12 months. Temperament variables were not statistically significant in these models.

3.4.2.2. Mean line. Subsequently, when examining the impact of task and temperament (NEG, PAS, ORC) on Mean Line (infants' motor dynamic stability), we followed the same sequential procedure mentioned before. First, the task was included as a predictor, and in the next steps, each temperament variable was included, to conclude with a comprehensive full model including all temperament variables and the task.

When modeling the effects of the task on the Mean Line at 12 months, the intercept of 18.48 ($SE = 0.15$, β =.22, $p < .001$) signifies the baseline Mean Line when infants are engaged in the reference task (task 1: book-sharing) (see Model 1, Table 9, and Fig. 3D). The significant negative effect of task 2 (*estimate* = −5.41, SE = 1.52, $\beta = -.61$, $p < .01$) suggests that when infants are engaged in the manipulative toys task, their motor dynamic stability is lower compared to the baseline task 1. The effect of task 3 (Rattle-shaking) was not statistically significant ($\beta = -.07$, $p > .05$), indicating no significant difference in the Mean Line compared to the baseline task 1. The marginal R^2 (.073) and conditional R^2 (.226) values suggest that the fixed effects explain approximately 7.3 % of variability in the Mean Line, while both fixed and random effects combined explain about 22.6 %.

The task differentiation results at 12 months are congruent with the results previously presented by Laudańska et al. (2022). However, both tasks, book-sharing and rattles, exhibited higher Entropy and Mean Line than the manipulative toys task, where the latter involved exploratory play with toys.

In the models including each temperament variable individually (Models 2, 3, and 4, Table 9), only the fixed effect of the "Manipulative task" (task 2) was a significant predictor of the Mean Line in all models (all $p < .01$). The full model (Model 5, Table 9) demonstrated that the fixed effect of the task was the only significant predictor of Mean Line in infants at 12 months ($\beta = -.56$, $p < .01$). This suggests that the task differentiation effect on infants' motor dynamic stability was predominantly relevant at 12 months, in the same way as observed for infants' motor dynamic complexity (Entropy). No significant effects of temperamental variables were observed (H4 was not supported in our sample).

Table 8
Models results for Entropy (infants' motor system complexity) at 12 months predicted by temperament and task.

	Model 1: Task (t)		*Model 2: NEG*		*Model 3: SUR*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*
Intercept	**5.04(0.09)**	**0.12** * **	**5.06(0.10)**	**0.12** * **	**5.06(0.10)**	**0.11** * **	**5.06(0.10)**	**0.12** * **	**5.05(0.10)**	**0.12** * **
Task 2: Manipulative	**−0.42(0.11)**	**−0.59** * **	**−0.39(0.12)**	**−0.55** * *	**−0.39(0.12)**	**−0.55** * *	**−0.39(0.12)**	**−0.55** * *	**−0.39(0.12)**	**−0.55** * *
Task 3: Rattle-shaking	0.11(0.11)	0.16	0.09(0.12)	0.12	0.08(0.12)	0.12	0.08(0.12)	0.12	0.09(0.12)	0.12
NEG			−0.04(0.07)	−0.07					−0.08(0.08)	−0.12
PAS					0.04(0.07)	0.06			0.09(0.09)	0.14
ORC							0.00(0.07)	0.00	−0.04(0.08)	−0.05
Random effects										
Level 1, σ^2	0.34(0.58)		0.33(0.57)		0.32(0.57)		0.33(0.57)		0.32(0.57)	
Level 2 Intercept, τ_{00} ID	0.12(0.35)		0.14(0.37)		0.14(0.38)		0.14(0.38)		0.14(0.37)	
ICC	0.27		0.30		0.31		0.31		0.30	
Model fit										
Marginal R^2 /Conditional R^2	0.102/0.345		0.084/0.361		0.084/0.364		0.080/0.361		0.095/0.367	
Observations	135		135		135		135		135	
AIC	340		**281.8**		281.9		282.2		284.8	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1. $N_i = 83$. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

Table 9
Models results for Mean Line (infants' motor system dynamic stability) at 12 months predicted by temperament and task.

	Model 1: Task (t)		*Model 2: NEG*		*Model 3: SUR*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*
Intercept	**18.48 (0.15)**	**0.22** * **	**18.73 (1.31)**	**0.21** * **	**18.74 (1.30)**	**0.21** * **	**18.70 (1.30)**	**0.21** * **	**18.65 (1.30)**	**0.21** * **
Task 2: Manipulative	**−5.41 (1.52)**	**−0.61** * *	**−5.18 (1.78)**	**−0.57** * *	**−5.15 (1.77)**	**0.19** * *	**−5.19**	**−0.57** * *	**−5.16 (1.76)**	**−0.56** * *
Task 3: Rattle-shaking	−0.59 (1.46)	−0.07	−0.89 (1.70)	−0.10	−0.90 (1.69)	0.18	−0.86	−0.09	−0.85 (1.69)	−0.09
NEG			0.05 (0.82)	0.01					−0.43 (0.92)	−0.05
PAS					0.65 (0.84)	0.07			1.39 (1.06)	0.16
ORC							−0.53 (0.86)	−0.06	−1.17 (0.98)	−0.13
Random effects										
Level 1, σ^2	60.44 (7.77)		67.32 (8.21)		66.79 (8.17)		67.24 (8.20)		66.13 (8.13)	
Level 2 Intercept, τ_{00} ID	12.03 (3.47)		11.36 (3.37)		11.61 (3.41)		11.19 (3.35)		11.37 (3.37)	
ICC	0.17		0.14		0.15		0.14		0.15	
Model fit										
Marginal R^2 /Conditional R^2	0.073/ 0.226		0.059/ 0.195		0.064/ 0.203		0.062/ 0.196		0.077/ 0.212	
Observations	135		135		135		135		135	
AIC	1181.1		982.1		**981.5**		981.7		983.9	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1. N_i = 83. Number of observations: 243. *β* = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/ Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

Table 10
Longitudinal Model results for Entropy (infants' motor system complexity) at 12 months predicted by temperament and task at 6 months.

	Model 1: NEG		*Model 2: PAS*		*Model 3: ORC*		*Model 4: Full model*	
Fixed effects	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*
Intercept	**5.05(0.09)**	**0.13** * **	**5.05(0.09)**	**0.12** * **	**5.05(0.09)**	**0.12** * **	**5.05(0.09)**	**0.12** * **
Task 2: Manipulative	**−0.43(0.11)**	**0.16** * **	**−0.43(0.11)**	**−0.59** * **	**−0.42(0.11)**	**−0.59** * **	**−0.43(0.11)**	**−0.59** * *
Task 3: Rattle-shaking	0.11(0.11)	0.15	0.12(0.11)	0.16	0.12(0.11)	0.16	0.12(0.11)	0.17
NEG	**0.19(0.09)**	**0.13** *					0.22(0.10)	0.29
NEG*task 2	−0.12(0.12)	0.16					−0.12(0.12)	−0.16
NEG*task 3	−0.13(0.11)	0.16					−0.20(0.12)	−0.27
PAS			0.03(0.09)	0.04			−0.06(0.10)	−0.08
PAS*task 2			−0.07(0.11)	−0.10			−0.03(0.12)	−0.05
PAS*task 3			0.02(0.11)	0.03			0.15(0.12)	0.22
ORC					0.04(0.08)	0.06	0.09(0.09)	0.13
ORC*task 2					−0.03(0.10)	−0.04	−0.03(0.11)	−0.04
ORC*task 3					−0.13(0.10)	−0.20	−0.21(0.11)	−0.32
Random effects								
Level 1, σ^2	0.33(0.58)		0.33(0.58)		0.33(0.57)		0.31(0.56)	
Level 2 Intercept, τ_{00} ID	0.12(0.34)		0.13(0.36)		0.13(0.36)		0.13(0.36)	
ICC	0.26		0.28		0.28		0.29	
Model fit								
Marginal R^2 /Conditional R^2	0.128/0.355		0.106/0.354		0.110/0.360		0.148/0.393	
Observations	164		164		164		164	
AIC	**340.8**		344		342.9		347.8	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects: 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1. N_i = 83. Number of observations: 243. *β* = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/ Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

3.5. Longitudinal effects

3.5.1. Predicting motor system complexity (Entropy) at 12 months from temperament at 6 months

Longitudinal models were performed to predict Entropy at 12 months using the temperament variables at 6 months in interaction with task as predictors. Table 10 presents the results of longitudinal mixed-effects models predicting Entropy at 12 months. The models were performed including each temperament variable in a separate model – Negative Affectivity (NEG), Positive Affectivity/Surgency (PAS), and Orienting and Regulatory Capacity (ORC) measured at 6 months, and tasks (task 2, manipulative toys, task 3, rattle-shaking). Also, a full model was performed, including all temperament variables (model 4). The intercept of each model represents the baseline of Entropy when engaging in the reference task (task 1, book-sharing). Task 2 (manipulative toys) at 6 months significantly predicted Entropy at 12 months ($\beta = -.59, p < .01$ in full model, Table 10). In the short model, Negative Affectivity (NEG) at 6 months had a significant positive effect on Entropy ($\beta =.13, p < .05$), indicating that higher levels of Negative Affectivity at 6 months were associated with increased Entropy at 12 months (effect in opposite direction to H1b). Positive Affectivity/Surgency (PAS) and Orienting/Regulatory Capacity (ORC) did not show a significant direct effect on Entropy (H3b and H4b not supported).

3.5.2. Predicting motor system stability (Mean Line) at 12 months from temperament at 6 months

Similarly, longitudinal models were performed to predict, in this case, Mean Line at 12 months using the temperament variables at 6 months in interaction with the task as predictors. Table 11 presents the results of longitudinal mixed-effects models examining the predictors of Mean Line, representing infants' motor system stability at 12 months. Again, the models were performed including each temperament variable in a separate model – Negative Affectivity (NEG), Positive Affectivity/Surgency (PAS), and Orienting and Regulatory Capacity (ORC) measured at 6 months, and tasks (task 2, manipulative toys, task 3, rattle-shaking). Next, a full model was tested, including all temperament variables. The intercept of each model represents the baseline of Mean Line when engaging in the reference task (task 1, book-sharing). Estimates for task 2 (manipulative toys) and task 3 (rattle-shaking) indicate their effects on Mean Line at 12 months. Task 2 exhibited a significant negative effect on the Mean Line ($p < .001$) in the individual NEG, ORC, and PAS models, suggesting decreased motor stability (Mean Line) compared to the baseline. Task 3 did not show a significant effect relative to task 1. After correcting for multiple hypothesis testing, there were no significant effects from temperamental variables at 6 months predicting infants' motor system dynamic stability (Mean Line) at 12 months (H2b, H3b, and H4b not supported).

3.6. Maternal anxiety

As part of an exploratory set of analyses, the effect of maternal trait anxiety (STAI) was included in the prediction of Entropy (complexity) and Mean Line (stability), in addition to temperament and task. Maternal anxiety (STAI) was measured at 4 months of age. We generally expected to find differences in the prediction of Entropy (complexity) and Mean Line (stability) by maternal anxiety. In this study, the internal consistency of the STAI scale was assessed using Cronbach's alpha, yielding a value of 0.86, indicating good reliability.

Table 11
Longitudinal Model results for Mean Line (infants' motor system stability) at 12 months predicted by temperament and task at 6 months.

	Model 1: NEG		*Model 2: PAS*		*Model 3: ORC*		*Model 4: Full model*	
Fixed effects	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β
Intercept	**18.56(1.14)**	**0.22** * **	**18.50(1.15)**	**0.13** * **	**18.49(1.15)**	**0.22** * **	**16.04(0.64)**	**0.12** * **
Task 2: Manipulative	**−5.47(1.52)**	**−0.61** * **	**−5.45(1.53)**	**−0.61** * **	**−5.40(1.52)**	**−0.61** * **	−1.12(0.74)	−0.19
Task 3: Rattle-shaking	−0.58(1.46)	−0.06	−0.50(1.47)	−0.06	−0.52(1.46)	−0.06	−0.76(0.74)	−0.13
NEG	1.92(1.19)	0.21					1.45(0.70)	0.25
NEG*task 2	−1.59(1.55)	−0.17					0.13(0.81)	0.02
NEG*task 3	−1.66(1.53)	−0.18					−0.76(0.82)	−0.13
PAS			0.20(1.13)	0.02			−0.26(0.69)	−0.05
PAS*task 2			−0.43(1.46)	−0.05			1.18(0.81)	0.21
PAS*task 3			0.17(1.45)	0.02			0.34(0.80)	0.06
ORC					0.45(1.05)	0.06	0.74(0.68)	0.12
ORC*task 2					−0.28(1.38)	−0.03	−0.05(0.79)	−0.01
ORC*task 3					−1.07(1.34)	−0.13	−0.69(0.80)	−0.12
Random effects								
Level 1, σ^2	59.91(7.74)		60.38(7.77)		59.96(7.74)		21.21(4.61)	
Level 2 Intercept, τ_{00} ID	11.68(3.42)		12.40(3.52)		12.70(3.56)		9.34(3.06)	
ICC	0.16		0.17		0.17		0.31	
Model fit								
Marginal R^2 /Conditional R^2	0.089/0.237		0.074/0.232		0.076/0.238		0.077/0.359	
Observations	164		164		164		164	
AIC	**1178.1**		1180.5		1180.0		1497.9	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1. N_i = 83. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

The mixed-effects models for Entropy and Mean Line at 6 months predicted by maternal anxiety (STAI), temperament, and task are presented in Tables 12 and 13. In both cases, there are no specific effects of maternal anxiety on Entropy or Mean Line in any of the models. These results suggest that there are no effects of maternal anxiety on motor system complexity (Entropy) or stability (Mean Line) at 6 months of age in our sample.

Table 14 presents the longitudinal results of mixed-effects models for Entropy at 12 months predicted by maternal anxiety (STAI), temperament, and task. The first model only incorporates maternal anxiety (STAI) and task (task 2: Manipulative toys, task 3: Rattle-shaking with task 1: book-sharing as the baseline). Maternal anxiety exhibited a significant negative effect on Entropy ($\beta = -.33$, $p < .05$), suggesting that higher maternal anxiety levels (measured at 4 months) were associated with *decreased Entropy* (motor system complexity) in infants at 12 months (see Fig. 5A). The additive effect of task 2 (Manipulative toys) was significant ($\beta = -.64, p < .001$) compared to the baseline task 1 (Book-sharing). The influence of maternal anxiety varied depending on the task (manipulative toys) compared to the baseline, emphasizing task-specific associations (STAI*task 2, where task 1 is the baseline, $\beta = .35$, $p < .05$). In this case, higher maternal anxiety at 4 months and the manipulative toys task were predictive of decreases in Entropy at 12 months. In this case, H5 was supported, but only longitudinally.

Subsequent models incorporate maternal anxiety (STAI, measured at 4 months), temperament variables Negative Affectivity (NEG), Positive Affectivity/Surgency (PAS), and Orienting and Regulatory Capacity (ORC) measured at 6 months, and task on motor Entropy at 12 months of age. Similar effects were observed in the models, including NEG, PAS, and ORC, where the negative effects of STAI ($p < .05$ in all models) and task 2 (manipulative toys) ($p < .01$ in all models) were additively significant (see Table 14) (in support of H5).

Finally, the same procedure was conducted to explore the effects of maternal anxiety (STAI, measured at 4 months), task, and temperament on Mean Line (infant's motor system stability) at 12 months. The first model, including maternal anxiety and task, exhibited significant negative effects of maternal anxiety (STAI) in predicting Mean Line ($\beta = -.28$, $p < .05$), suggesting that higher maternal anxiety levels at 6 months were associated with *decreased motor system stability* (Mean Line) at 12 months (see Fig. 5B) (in support of H5). This effect was observed in all the models, including temperamental variables. The additive effect of task 2 (manipulative toys) was significant in all models without interacting with STAI ($p < .01$), suggesting that maternal anxiety and the manipulative toys task predicted decreased stability at 12 months. No further significant effects were observed (see Table 15).

4. Discussion

Temperament dimensions are thought to reflect stable individual differences in emotional and behavioral reactivity observed during infancy (Tang et al., 2020). Therefore, the differences in temperament should reflect differences in how infants respond to stimulation, which is manifested in changes in the dynamic organization of limb movements. Despite the recognized importance of movement as a key modality through which temperament is expressed in infants (Planalp et al., 2017; Lev-Enacab et al., 2022), the understanding of the dynamic organization of limb movements related to temperament dimensions in infancy remains limited. In this study, we aimed to address this gap in knowledge by investigating the relationship between temperament dimensions and limb movements in infancy.

We began by examining how temperament dimensions of Negative Affectivity (NEG), Positive Affectivity/Surgency (PAS), and Orienting/Regulatory Capacity (ORC) relate to infant limb movements at 6 and 12 months of age. Infants' spontaneous limb movements were measured with wearable motion trackers during three types of infant-parent interactions: book-sharing, playing with manipulative toys, and rattle-shaking, which differ in task-related demands. We used Multidimensional Recurrence Quantification Analysis (MdRQA) to capture higher-level patterns of infant limb movements, focusing on two MdRQA variables: Entropy, reflecting motor system complexity, and Mean Line, reflecting dynamic stability. Concurrent and longitudinal relationships between temperament dimensions, maternal anxiety, and motor system complexity and stability at both time points were investigated.

Our primary findings regarding the concurrent analyses at 6 and 12 months suggest a relationship between Negative affectivity (NEG) and motor system complexity and stability at an early stage of development (6 months of age). In contrast, at 12 months of age, temperamental variables did not significantly affect the motor system, but task-related differences played a major role. Manipulative toys task, which was the least constrained type of play, influenced both Entropy and Mean Line at 12 months. This suggests a robust task-specific effect on infants' motor behavior, showing task-related differences in the limb movement organization at the end of the first year of life (see Laudańska et al., 2022a for a similar pattern of task-specific movement patterns emerging toward the end of the first year of life).

The observed links between Negative Affectivity and motor system complexity and stability at 6 months (but not at 12 months) suggest that, at this earlier stage, infants tend to organize their motor behaviors in response to incoming stimulation in a less context-dependent manner. Temperamental differences, particularly in Negative Affectivity, may play a key role in shaping motor behavior, possibly because infants at this stage are still in the early phases of integrating sensory information with action (Gibson, 1979; Thelen & Smith, 1994). By 12 months, however, task-related demands appear to exert a stronger influence on motor complexity and dynamic stability, suggesting that infants' motor coordination becomes more attuned to environmental affordances (Adolph & Hoch, 2019). It is important to note that infants at 6 months are able to adapt their actions to external constraints (Clearfield, 2004; Claxton et al., 2009). Thus, rather than reflecting a lack of adaptability, our findings may indicate a developmental shift: While motor responses at 6 months may be more tightly coupled to individual temperamental tendencies, by 12 months, increased experience and improved sensorimotor integration support more flexible, task-dependent adjustments (Corbetta, 2021).

Although we found significant associations between body movement and temperament at 6 months, the direction of these effects differed from our initial predictions. Contrary to expectations, Negative Affectivity was positively associated with both Entropy and

Table 12
Models results for Entropy (infants' motor system complexity) at 6 months predicted by maternal anxiety (STAI), temperament and task.

	Model 1: STAI		*Model 2: NEG*		*Model 3: PAS*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*	Estimate(SE)	*β*
Intercept	5.01(0.06)	**0.08** * **	**5.03(0.06)**	**0.11** * **	**5.02(0.06)**	**0.11** * **	**5.02(0.06)**	**0.11** * **	**5.03(0.06)**	**0.11** * **
STAI	−0.01(0.06)	−0.01	−0.04(0.06)	−0.08	−0.03(0.06)	−0.07	−0.03(0.06)	−0.05	−0.04(0.06)	−0.09
Task 2: Manipulative	−0.10(0.07)	−0.20	−0.12(0.07)	−0.23	−0.12(0.07)	−0.23	−0.12(0.07)	−0.22	−0.12(0.07)	−0.23
Task 3: Rattle-shaking	−0.00(0.07)	−0.00	−0.04(0.07)	−0.06	−0.03(0.07)	−0.06	−0.03(0.07)	−0.06	−0.04(0.07)	−0.06
STAI*task 2	−0.01(0.07)	−0.01	0.02(0.07)	0.03	0.02(0.07)	0.03	0.01(0.07)	0.03	0.01(0.07)	0.03
STAI*task 3	0.04(0.07)	0.08	0.07(0.07)	0.14	0.07(0.07)	0.13	0.06(0.07)	0.13	0.07(0.07)	0.14
NEG			**0.10(0.04)**	**0.19** *					**0.11(0.04)**	**0.20** *
PAS					0.07(0.04)	0.15			0.03(0.04)	0.06
ORC							0.05(0.04)	0.10	0.06(0.04)	0.12
Random effects										
Level 1, σ^2	0.19(0.44)		0.19(0.43)		0.19(0.44)		0.19(0.43)		0.19(0.43)	
Level 2 Intercept, τ_{00} ID	0.07(0.26)		0.06(0.25)		0.06(0.25)		0.07(0.26)		0.06(0.24)	
ICC	0.27		0.25		0.25		0.27		0.23	
Model fit										
Marginal R^2/Conditional R^2	0.011/0.276		0.048/0.283		0.033/0.279		0.022/0.283		0.072/0.285	
Observations	242		229		229		229		229	
AIC	361.2		**338.8**		341.4		343.1		338.9	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1 $N_i = 83$. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. Predictors (NEG, PAS, ORC, STAI) are centered.

Table 13
Models results for Mean Line (infants' motor system stability) at 6 months predicted by maternal anxiety (STAI), temperament and task.

	Model 1: STAI		*Model 2: NEG*		*Model 3: PAS*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β
Intercept	**15.92(0.65)**	**0.09** * **	**10.57(1.95)**	**0.12** * **	**16.06(0.67)**	**0.12** * **	**16.04(0.67)**	**0.12** * **	**16.10(0.65)**	**0.12** * **
STAI	−0.06(0.62)	−0.01	−0.43(0.63)	−0.08	−0.31(0.64)	−0.06	−0.24(0.64)	−0.04	−0.44(0.62)	−0.08
Task 2: Manipulative	−0.94(0.75)	−0.17	−1.15(0.77)	−0.20	−1.10(0.78)	−0.19	−1.08(0.78)	−0.19	−1.14(0.77)	−0.20
Task 3: Rattle-shaking	−0.34(0.75)	−0.06	−0.70(0.77)	−0.11	−0.67(0.78)	−0.11	−0.67(0.78)	−0.11	−0.69(0.77)	−0.11
STAI*task 2	−0.18(0.73)	−0.03	0.04(0.74)	0.01	0.02(0.75)	0.00	−0.00(0.75)	−0.00	0.02(0.74)	0.00
STAI*task 3	0.57(0.72)	0.10	0.80(0.74)	0.14	0.78(0.74)	0.14	0.74(0.74)	0.13	0.79(0.74)	0.14
NEG			**1.52(0.51)**	**0.24** * *					**1.51(0.50)**	**0.26** * *
PAS					0.79(0.47)	0.14			0.23(0.49)	0.04
ORC							0.55(0.48)	0.10	0.77(0.49)	0.13
Random effects										
Level 1, σ^2	22.17(4.71)		22.21(4.74)		22.37(4.73)		22.26(4.72)		22.17(4.71)	
Level 2 Intercept, τ_{00} ID	10.39(3.22)		9.05(3.01)		10.03(3.17)		10.55(3.25)		8.37(2.89)	
ICC	0.32		0.29		0.31		0.32		0.27	
Model fit										
Marginal R^2 /Conditional R^2	0.008/0.325		0.065/0.336		0.028/0.239		0.019/0.335		0.087/0.337	
Observations	242		229		229		229		229	
AIC	1524.3		**1439.4**		1445.2		1446.7		1439.9	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1
N_i = 83. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. Predictors (NEG, PAS, ORC, STAI) are centered.

Table 14
Models results for Entropy (infants' motor system complexity) at 12 months predicted by maternal anxiety (STAI), temperament and task.

	Model 1: STAI		*Model 2: NEG*		*Model 3: PAS*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β	Estimate(SE)	β
Intercept	**5.08(0.09)**	**0.16** * **	**5.10(0.10)**	**0.16** * **	**5.10(0.10)**	**0.16** * **	**5.10(0.10)**	**0.16** * **	**5.09(0.10)**	**0.16** * **
STAI	**−0.22(0.09)**	**−0.33** *	**−0.20(0.10)**	**−0.30** *	**−0.22(0.10)**	**−0.33** *	**−0.22(0.09)**	**−0.32** *	**−0.20(0.10)**	**−0.30** *
Task 2: Manipulative	**−0.45(0.12)**	**−0.64** * **	**−0.41(0.13)**	**−0.60** * *	**−0.41(0.13)**	**−0.60** * *	**−0.41(0.13)**	**−0.60** * *	**−0.41(0.13)**	**−0.60** * *
Task 3: Rattle-shaking	0.08(0.11)	0.11	0.05(0.12)	0.32	0.05(0.12)	0.32	0.05(0.12)	0.06	0.05(0.12)	0.06
STAI*task 2	0.23(0.11)	0.35 *	0.21(0.12)	0.32	0.21(0.12)	0.32	0.21(0.12)	0.32	0.21(0.12)	0.32
STAI*task 3	0.11(0.10)	0.17	0.09(0.11)	0.14	0.09(0.11)	0.14	0.09(0.11)	0.14	0.09(0.11)	0.14
NEG			−0.04(0.08)	−0.06					−0.07(0.08)	−0.10
PAS					0.03(0.07)	0.05			0.08(0.09)	0.11
ORC							−0.01(0.07)	−0.01	−0.04(0.08)	−0.05
Random effects										
Level 1, σ^2	0.33(0.57)		0.31(0.56)		0.31(0.56)		0.31(0.56)		0.31(0.56)	
Level 2 Intercept, τ_{00} ID	0.12(0.34)		0.12(0.35)		0.13(0.36)		0.13(0.36)		0.12(0.35)	
ICC	0.26		0.28		0.29		0.29		0.28	
Model fit										
Marginal R^2 /Conditional R^2	0.150/0.373		0.132/0.378		0.132/0.382		0.130/0.380		0.140/0.384	
Observations	156		129		129		129		129	
AIC	322.3		**268.9**		**268.9**		269.1		272.1	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface).
Signif. codes: 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1
N_i = 83. Number of observations: 243. β = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/Regulatory Capacity. Predictors (NEG, PAS, ORC, STAI) are centered.

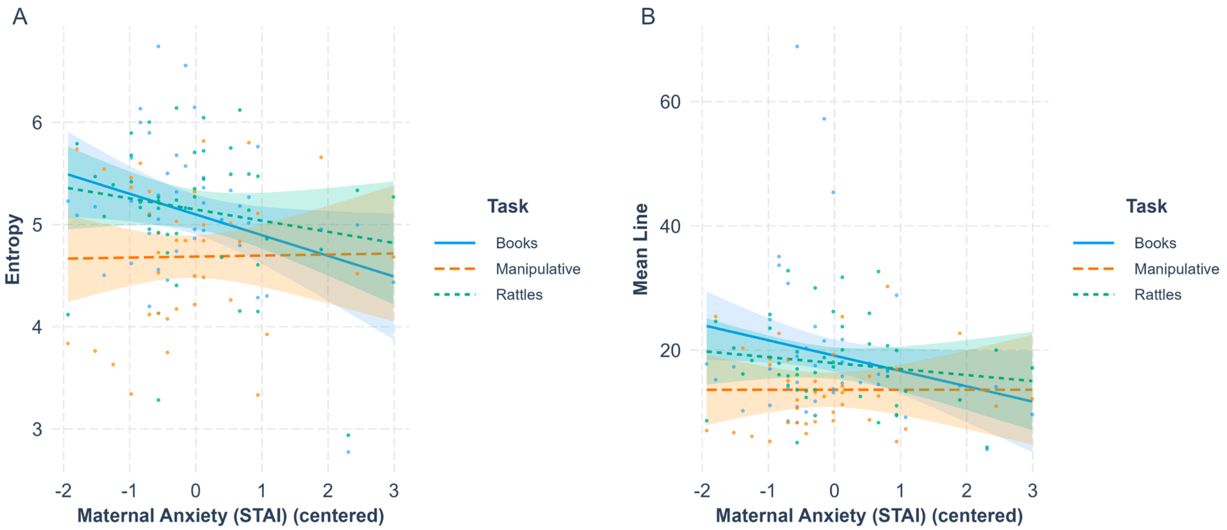

Fig. 5. *Predicted effects of STAI on Entropy and Mean Line at 12 months. Note:* The plots display the longitudinal effects of maternal anxiety (STAI) measured at 4 months on infants' motor system Entropy (Panel A) and Mean Line (Panel B) at 12 months of age across the three different tasks (Books, Manipulative Toys, Rattles). The effect of maternal anxiety (STAI) is statistically significant in predicting Entropy and Mean Line at 12 months (both $p < .05$). The additive effect of the Manipulative Toys task is significant compared to the baseline (Books) ($p < .001$ for Entropy and $p < .01$ for Mean Line). STAI was centered, and it represents the standardized scores of the original raw scores. Each unit in the x-axis corresponds to units of standard deviations from the centered mean of '0'. Books = Book-sharing, Manipulative = Manipulative Toys, Rattles = Rattle-shaking.

Mean Line at 6 months, indicating that higher Negative Affectivity corresponded to greater motor complexity (Entropy) and stability (Mean Line). Interestingly, Entropy can reflect either complexity and flexibility (e.g., De Jonge-Hoekstra et al., 2020) or irregular and unpredictable dynamics (Shannon, 1948). Therefore, our hypothesis that higher Negative Affectivity would be linked to reduced motor complexity and stability was not supported. Instead, we observed the opposite pattern—higher Negative Affectivity predicted greater complexity and stability of limb movements.

There are several possibilities for interpreting the observed patterns. Negative Affectivity (NEG) captures individual differences in the tendency to express reactive behavior (Rothbart & Ahadi, 1994; Wittig & Rodriguez, 2019) and reflects infants' distress in response to physical limitations and sudden changes (Gartstein & Rothbart, 2003). Reactive behaviors related to this temperamental dimension are discomfort, fear, anger, sadness, negative facial expressions, and explicit demonstrations of frustration and distress, such as crying (Rothbart & Bates, 2006; Putnam et al., 2008; Olino et al., 2011; Wittig & Rodriguez, 2019). Negative Affectivity can also be interpreted as difficulties in dealing with novelty and high stimulation above the usual threshold. In early infancy, this is frequently manifested through extensive upper and lower limb movements, with greater speed compared to movements accompanying positive infant affect (Egmose et al., 2019).

The association between limb movements and higher Negative Affectivity may reflect motor responses driven by heightened levels of stimulation, suggesting difficulties in processing sensory information (DeSantis et al., 2011; Nakagawa et al., 2016). This interpretation aligns with the observed positive relationship between Negative Affectivity and Entropy. Coordinated movement depends on integrated sensory information and the dynamic coupling of perception and action (Gibson, 1979; De Jonge-Hoekstra et al., 2016). Thus, greater movement irregularity in infants with higher Negative Affectivity may indicate differences in perception-action integration, consistent with previous research linking Negative Affectivity to reduced behavioral control (Gerardi-Caulton, 2000) and sensory processing difficulties (Dunn, 2001; Nakagawa et al., 2016). The developmental timing of these effects is particularly relevant. The presence of a temperament-motor association at 6 months but not at 12 months may reflect a transition in how motor responses are regulated in relation to environmental stimuli (Clearfield, 2004; Claxton et al., 2009; Corbetta, 2021). By 12 months, infants undergo a reorganization of motor control processes, potentially driven by increasing experience with goal-directed actions and the refinement of sensorimotor coordination. This shift may conceal earlier temperament-driven patterns as motor responses become increasingly shaped by task demands rather than temperament alone. Future research should investigate how these developmental changes influence the interplay between temperament and motor complexity across infancy.

In psychological research, the concept of Entropy is often described as uncertainty or irregularity in the dynamics of complex systems, emerging as a function of competing perceptual and behavioral affordances, and is thought to be experienced as anxiety (Hirsh et al., 2012). The positive association between Entropy and Negative Affectivity may reflect increased irregularity in the activity of the infant's developing motor system. This is reflected by the motor system's activation and reactivity that characterizes Negative Affectivity, and that has been reliably documented in infants before the age of 9 months of age (Rothbart & Bates, 2006). Moreover, Negative Affectivity is thought to increase during infancy and toddlerhood and to decrease over school years, which can explain why increased Entropy, understood as lower regularity of movement, was observed at 6 months (Sallquist et al., 2009; Cioffi et al., 2021).

The connection between Negative Affectivity and infants' motor system organization may be linked to global changes in the

Table 15
Models results for Mean Line (infants' motor system stability) at 12 months predicted by maternal anxiety (STAI), temperament and task.

	Model 1: STAI		*Model 2: NEG*		*Model 3: PAS*		*Model 4: ORC*		*Model 5: Full model*	
Fixed effects	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*	Estimate (SE)	*β*
Intercept	**18.96 (1.17)**	**0.25 * ****	**19.14 (1.32)**	**0.25 * ****	**19.13 (1.32)**	**0.24 * ****	**19.12 (1.32)**	**0.24 * ****	**19.07 (1.32)**	**0.24 * ****
STAI	**−2.39 (1.10)**	**−0.28 ***	**−2.47 (1.30)**	**−0.28.**	**−2.51 (1.26)**	**−0.29 ***	−2.42 (1.26)	−0.28	−2.47 (1.29)	−0.28.
Task 2: Manipulative	**−5.82 (1.58)**	**−0.66 * ***	**−5.51 (1.84)**	**−0.61 * ***	**−5.48 (1.83)**	**−0.61 * ***	**−5.53 (1.83)**	**−0.61 * ***	**−5.50 (1.82)**	**−0.61 * ***
Task 3: Rattle-shaking	−0.95 (1.52)	−0.11	−1.24 (1.75)	−0.14	−1.25 (1.74)	−0.14	−1.22 (1.75)	−0.14	−1.20 (1.73)	−0.14
STAI*task 2	2.38 (1.48)	0.28	2.53 (1.75)	0.29	2.53 (1.74)	0.29	2.49 (1.75)	0.28	2.47 (1.73)	0.28
STAI*task 3	1.42 (1.42)	0.17	1.51 (1.65)	0.17	1.53 (1.65)	0.17	1.48 (1.65)	0.17	1.51 (1.64)	0.17
NEG			0.11 (0.91)	0.01					−0.33 (1.00)	−0.04
PAS					0.59 (0.84)	0.06			1.28 (1.04)	0.14
ORC							−0.61 (0.84)	−0.07	−1.19 (0.96)	−0.13
Random effects										
Level 1, σ^2	61.38 (7.84)		68.07 (8.25)		67.55 (8.22)		68.04 (8.25)		66.86 (8.18)	
Level 2 Intercept, τ_{00} ID	10.46 (3.23)		9.14 (3.02)		9.44 (3.07)		8.80 (2.97)		9.16 (3.03)	
ICC	0.15		0.12		0.12		0.11		0.12	
Model fit										
Marginal R^2 /Conditional R^2	0.109/ 0.239		0.095/ 0.202		0.098/ 0.209		0.099/ 0.202		0.111/ 0.219	
Observations	156		129		129		129		129	
AIC	1122.7		943.2		942.8		**942.7**		945.2	

Note: task 1 (book-sharing) was considered the baseline; task 2 (Manipulative toys); task 3 (Rattle-shaking). AIC = Akaike's Information Criterion (lower values indicate better fit, best fit in boldface). Bold text indicates statistically significant effects; 0 '* ** ' 0.001 '* *' 0.01 '* ' 0.05 '.' 0.1 ' ' 1 N_i = 83. Number of observations: 243. *β* = Standardized beta. NEG= Negative Affectivity, PAS= Positive Affectivity/Surgency, ORC= Orienting/ Regulatory Capacity. Predictors (NEG, PAS, ORC) are centered.

developmental system, such as the formation of new large-scale synergies, given the constant exchanges between the developing system and the environment (Adolph & Hoch, 2019). This can occur in the context of developmental cascades, as the dynamics in a specific domain can have wide-ranging effects in other developmental domains over longer time scales (Iverson, 2010; 2021). In this sense, perception and action at the early stages of development promote the emergence of more complex forms of behavioral synergies over time, as infants experience a wide range of sensorimotor experiences (Corbetta, 2021). Infants' Negative Affectivity has also been related to maladaptive caregiver-infant relational dynamics, which are linked to maternal negative emotions and intrusiveness, as well as infants' lower socio-emotional skills (An & Kochanska, 2022). These maladaptive caregiver-infant dynamics can interfere with the optimal achievement of developmental milestones by constraining the exploratory behaviors in the environment (Corbetta, 2021; An & Kochanska, 2022). However, it is important to keep in mind the different and sometimes divergent interpretations that the concept of Entropy may have in different contexts and studies, as it has also been linked to children's flexibility and adaptability in previous studies (De Jonge-Hoekstra et al., 2020). Moreover, it has been emphasized that studies investigating movement complexity in infancy need to account for age and motor development to accurately capture the effect of developmental risk factors (Chua et al., 2025).

Furthermore, in complex adaptive systems, Entropy is often accompanied by relatively patterned dynamics and stability. This could be one explanation for the higher Mean Line values or stability predicted by Negative Affectivity. However, the link between Negative Affectivity and motor system organization suggests that more research is needed to explore the mechanisms of this association. Temperament is related to an individual's emotional and motor reactivity; it may also affect subsequent social functioning (Calkins and Swingler, 2012), so it is plausible that higher Entropy might be linked to greater motor activation. In this sense, previous research showed the relationship between Negative Affectivity and maladaptive behavior, internalizing and externalizing problems (e.g., Oldehinkel et al., 2004; Brandes et al., 2018).

Contrary to our expectations, no relationships between Entropy and Mean Line with other temperament dimensions (PAS and ORC) were found. Previous reports suggested that motor coordination may be influenced by effortful control in 3-year-old children (Nakagawa et al., 2016), so the effects of temperament can vary across different developmental periods. The absence of significant effects for Positive Affectivity/Surgency and Orienting and Regulatory Capacity opens further questions regarding the developmental pathways and specificity of the relation between temperament and early motor development. In this sense, it would be important to explore the effects of different facets of each temperamental dimension, as they can provide more nuanced information about infants' behavior and underlying mechanisms (e.g., Nakagawa et al., 2016). We should also mention that it is important to further explore these relationships with larger samples.

The observed task-specific effects, particularly the influence of playing with manipulative toys on Entropy and Mean Line, indicate task-specificity of movement organization in early motor development. This finding aligns with our expectations of varied motor experiences contributing to motor system outcomes, reflecting a task differentiation that emerges with age. We expected higher stability of motor actions during the manipulative toys task compared to other tasks, more rhythmic and stable patterns during rattle-shaking, and less defined motor coordination patterns during book-sharing (i.e., higher Entropy), which involves more vocal than motor actions. In this sense, it is plausible that a less constrained task involves more different possibilities for actions, which results in more variability and lower stability – in contrast to rattle-shaking that promotes highly repetitive, recurrent, and rhythmic movement patterns and book-sharing that elicits more fine-grained manipulation through holding, pointing, and turning pages. The manipulative toys task exhibited the lowest stability and complexity of the three tasks. The observed task effects at 12 months show that the motor system becomes more context-sensitive. More specifically, in complex adaptive systems, system reorganization in response to specific task demands is only possible when the coupling between system components becomes less strict so that the system exhibits flexibility towards those demands (De Jonge-Hoekstra et al., 2020). This seems to be present to a larger degree at 12 months than at 6 months of age. Therefore, our results seem to be aligned with previous findings that showed relations between task-specific effects and the system's specialization in modalities such as speech and gesture (De Jonge-Hoekstra et al., 2016; 2020).

The longitudinal analysis revealed that Negative Affectivity (NEG) at 6 months continued to exert a significant positive effect on Entropy at 12 months, suggesting a persistent effect on the developing motor system. Task demands, related to different sets of toys available to infant-parent dyads, significantly modified infants' motor system's dynamic complexity and dynamic stability at 12 (but not at 6) months of age. This may reflect a better capacity to flexibly adapt actions to environmental demands and to coordinate body parts onto the appropriate task-specific configurations (functional synergies). This finding emphasizes the importance of considering temperament as a dynamic factor influencing the developmental trajectory of motor skills and studying the mechanisms by which motor system organization is related to temperamental dimensions.

Incorporating maternal trait anxiety provided additional insights. Maternal anxiety (measured when infants were 4 months old) exhibited a significant negative effect on both Entropy and Mean Line at 12 months (but not at 6 months), indicating a time-dependent association between maternal anxiety and the dynamic organization of infant limb movement across the first year of life. The relation between maternal anxiety and infant motor development can potentially be linked to how mothers structure their child's proximal environment and constrain (or not constrain) their spontaneous movements. They could encourage or discourage infant movement through space (e.g., by using equipment such as baby bouncers) as well as provide more or less opportunity for their exploration of the surrounding environment (e.g., Piallini et al., 2016). Future research should explore different factors that can mediate the relationship between parental anxiety and child development. Overall, parenting is acknowledged as a crucial factor influencing children's development, as parents are the primary source of socialization, shaping socio-emotional development (Bornstein, 2002; Wittig & Rodriguez, 2019). In previous studies, high maternal anxiety during pregnancy and early child development have been linked to an increased likelihood of displaying difficulties in achieving developmental milestones assessed by standardized motor and language scales (Kikkert et al., 2010; Nasreen et al., 2013; Piallini et al., 2016; Irwin et al., 2020; Jeličić et al., 2021). Furthermore, children may express difficulties or adverse trait development when encountering adverse parenting, promoting the development of externalizing and internalizing behaviors ((Belsky et al., 2007; Slagt et al., 2016; Wittig & Rodriguez, 2019).

Overall, our results suggest that temperament, maternal trait anxiety, and task-related demands jointly shape infants' motor system's complexity and dynamic stability. However, each of these factors seems to play a role at different periods of development, with earlier (6 months) and longer-lasting effects of temperamental Negative Affectivity and later (12 months) effects of the task-related context. Finally, the infant's motor system's complexity and dynamic stability at 12 months seem to be further modulated by maternal trait anxiety.

As limitations of our study, we recognize the limited sample size, especially at 12 months of age. On the other hand, given our research questions, we focused on the motor system organization of the infant uniquely, but we understand that the mother (or caregiver) plays a fundamental role in infants' behavior, especially at early developmental stages. Thus, future research should investigate the relationship between dyadic motor synchrony and temperament dimensions. We also acknowledge the relatively low internal consistency of the Positive Affectivity/Surgency (PAS) and Orienting/Regulatory Capacity (ORC) subscales at 6 months in our sample, which calls for caution in interpreting the negative effects for these temperamental traits. Furthermore, maternal trait anxiety was measured only once, at the first time point of the longitudinal study (when infants were 4 months of age), so earlier than infant temperament and limb movements. As strengths, we emphasize the longitudinal and experimental design, the use of wearable motion trackers to measure spontaneous limb movements, and innovative time series analysis, which open possibilities for future studies. Finally, future research should focus on further understanding the mechanisms by which the dynamic organization of the motor system and temperament dimensions are connected from a developmental perspective on a longer timescale into early childhood.

5. Conclusion

Our findings highlight the interplay between temperament dimensions and motor organization across infancy. Particularly, motor systems' organization –complexity and stability– depend on Negative Affectivity, the type of infant-parent play, and maternal anxiety. Furthermore, our study suggests an effect of temperament on sensorimotor integration and the emergence of motor synergies. Specifically, we observed associations between Negative Affectivity and the complexity and stability of infant limb movements. In this regard, the infant's temperament, maternal anxiety, and situational factors such as different types of play become crucial for understanding how motor coordination patterns develop over-sensitive periods of motor development in the first year of life. Further research is needed to understand the underlying mechanisms of these associations and explore their implications for long-term motor, cognitive, and emotional development.

Ethics statement

This study was approved by the Ethics Committee for research with human participants of the Institute of Psychology, Polish Academy of Sciences.

CRediT authorship contribution statement

Laudańska Zuzanna: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Arellano-Véliz Nicol Alejandra:** Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Cox Ralf F.A.:** Writing – review & editing, Supervision, Conceptualization. **Duda-Goławska Joanna:** Software, Formal analysis. **Tomalski Przemysław:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare no conflict of interest related to this research, authorship, or publication.

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Further materials such as data and scripts can be accessed at https://osf.io/jbkdw/?view_only= 98c437aeb3f9436dbb45ecac0df470ec. Matlab code for movement data preprocessing and MdRQA can be accessed here: https://osf.io/xzt3m/?view_only= 5daf73673db7469fb4dac74bc8b931cf

Data availability

I have attached the link to my data and code at the Attach File step
Temperament and MdRQA dataset (OSF)

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