Journal of Integrative Neuroscience

J. Integr. Neurosci. **2026**; 25(9): 54429
https://doi.org/10.31083/JIN54429

Hypothesis and Concept

Toward a Developmental Timing Framework for Autism: Linking Hemispheric Asymmetry, Motor Organization, and Motor-Social Coupling

Gerry Leisman[1,2,*], Robert Melillo[1,3]

[1]Movement and Cognition Laboratory, Department of Physical Therapy, University of Haifa, 3498838 Haifa, Israel
[2]Resonance Therapeutics Laboratory, Department of Neurology, University of the Medical Sciences of Havana, 10600 Havana, Cuba
[3]Center for Developing Minds, Rockville Centre, NY 11570, USA
*Correspondence: g.leisman@edu.haifa.ac.il; g.leisman@alumni.manchester.ac.uk (Gerry Leisman)
Academic Editor: Bettina Platt
Submitted: 20 April 2026 Revised: 21 July 2026 Accepted: 7 August 2026 Published: 15 September 2026

Abstract

Early behavioral features associated with autism spectrum disorder (ASD) are frequently examined within separate motor, sensory, and social domains rather than as interacting components of a developing neurobiological system. In this article, we present a hypothesis-driven conceptual framework proposing that variation in developmental timing and coordination across neural, motor, and interpersonal systems may contribute to differences in early social developmental trajectories. Drawing on evidence from fetal, infant, and early childhood development, we consider how hemispheric specialization, interhemispheric coordination, oscillatory synchronization, corticalization of motor control, and dyadic interaction timing may jointly influence the emergence of motor organization and social engagement. From this perspective, persistent primitive reflex expression, atypical motor asymmetry, increased motor variability, and differences in dyadic synchrony are discussed as candidate developmental indicators that may reflect broader variation in neural timing and coordination. Within this framework, we further consider how genetic, neurobiological, and environmental factors associated with ASD risk may converge on developmental timing processes expressed through neural communication, motor regulation, and social interaction. Rather than proposing a deterministic causal sequence, the present account examines how variation in motor-social interaction may influence opportunities for social learning through recurrent cycles of action, perception, prediction, and caregiver feedback. We advance a set of empirically testable developmental hypotheses linking neural timing measures, motor organization indices, reflex integration profiles, and dyadic interaction metrics within prospective longitudinal research designs. Specifically, the framework predicts that variation in early neural timing and coordination will be associated with differences in motor organization and motor-social coupling, which may in turn relate to later social developmental outcomes. By emphasizing developmental timing, coordination, and reciprocal interaction across neural, motor, and interpersonal systems, this conceptual framework is intended not as a causal account of ASD, but a hypothesis-generating developmental model that organizes existing evidence while generating explicit, empirically testable predictions regarding relationships among neural timing, motor organization, and early social interaction.

Keywords: autism spectrum disorder; brain lateralization; interhemispheric communication; motor skills; infant development; social behavior

1. Introduction

Autism spectrum disorder (ASD) is increasingly understood as a condition involving atypical neurodevelopmental trajectories rather than a static collection of behavioral symptoms [1,2,3,4,5]. Prospective longitudinal studies have identified early differences in motor coordination, gaze control, laterality, sensory responsiveness, and social engagement in infants who later meet diagnostic criteria for ASD [4,5,6,7]. However, these findings are often examined within relatively separate motor, sensory, or social domains rather than as interacting components of early neurodevelopment. An important unresolved question is whether some of these early differences may reflect differences in the developmental timing and coordination across neural, motor, and interpersonal systems and whether diverse genetic, neurobiological, and environmental influences associated with ASD risk may converge on these timing-related developmental processes.

Although substantial progress has been made in identifying early behavioral and neural features associated with ASD, less attention has been directed toward how hemispheric specialization, interhemispheric coordination, motor organization, and dyadic interaction timing may relate to one another across development. The present article advances the central hypothesis that variation in the developmental timing of hemispheric specialization and interhemispheric coordination may contribute to individual differences in early motor organization and social interaction. Rather than proposing a definitive mechanistic explanation of ASD, the framework seeks to organize existing empirical observations into a coherent developmental model that generates explicit and empirically testable hypotheses.

Neurodevelopment unfolds through partially overlapping maturation processes involving hemispheric specialization, interhemispheric connectivity, oscillatory coordination, and progressive cortical regulation of motor behavior. These processes contribute to the temporal organization of neural communication and behavior across development. From this perspective, some early behavioral features associated with ASD may reflect broader variation in developmental timing and coordination rather than isolated impairments within specific domains. Motor development may be particularly relevant within this context because posture, gaze stabilization, manual exploration, imitation, and turn-taking all contribute to the temporal structure of early interaction [8,9,10,11,12].

Repeated interactions between infants and caregivers provide opportunities for the gradual refinement of social expectations and interpersonal coordination, processes that are central to early social brain development [13]. Variability in motor timing or interaction timing may therefore influence how infants experience socially contingent feedback during early development. Within the present framework, motor-social interaction is proposed as one developmental interface through which variation in neural timing may influence emerging social developmental trajectories.

The present article considers whether early differences in hemispheric asymmetry, interhemispheric coordination, oscillatory timing, and cortical modulation of motor behavior may be associated with later differences in motor organization and social interaction. Persistent primitive reflex expression, atypical motor asymmetry, and variability in dyadic synchrony are discussed as candidate developmental indicators that may reflect broader variation in neural timing and coordination, although direct mechanistic evidence linking these processes remains limited. The article further explores how neural timing measures, motor organization indices, reflex integration profiles, and dyadic interaction measures could be examined within prospective longitudinal research designs. The framework generates specific developmental predictions regarding relationships among neural timing measures, motor organization, motor-social coupling, and later social developmental outcomes that can be evaluated within longitudinal designs.

Rather than replacing genetic, connectivity-based, predictive-processing, or developmental systems accounts of ASD, the present framework is intended to provide a complementary developmental perspective that emphasizes the temporal coordination of interacting neural, motor, and interpersonal processes. The relationships discussed are intended as heuristic and hypothesis-generating, and developmental influences are likely to be reciprocal, heterogeneous, and shaped by multiple interacting biological and environmental factors.

The remainder of this review develops the proposed developmental timing framework in a sequential manner. Section 2 examines evidence concerning the maturation of hemispheric specialization, interhemispheric coordination, oscillatory synchronization, and cortical regulation as the neurobiological substrate of the model. Section 3 considers how these processes may shape the organization of early motor behavior. Section 4 examines reciprocal motor-social interactions as a developmental interface linking neural organization with emerging social cognition. Section 5 integrates these observations into a developmental timing framework that generates explicit, empirically testable predictions while remaining complementary to existing genetic, neurodevelopmental, and environmental models of autism.

2. Developmental Timing and Hemispheric Asymmetry in Early Neurodevelopment

Neurodevelopment unfolds through coordinated timing gradients across hemispheres, circuits, and hierarchical control systems. Functional specialization does not emerge uniformly across the cortex; rather, hemispheric asymmetries appear early in gestation and continue to refine across infancy and childhood [14,15,16,17,18,19,20,21,22,23,24]. These asymmetries may contribute to the organization of neural processing and behavioral timing across development, potentially influencing how sensorimotor and social functions gradually differentiate during infancy and childhood. From this perspective, hemispheric specialization may contribute to how developmental timing emerges across distributed neural systems. By partitioning computational demands across hemispheres and progressively refining interhemispheric coordination, the developing brain can stabilize action-perception loops that support sensorimotor learning and emerging social cognition [19,25,26].

2.1 Emergence of Hemispheric Asymmetry During Prenatal Development

Evidence from fetal neuroimaging and developmental connectomics indicates that hemispheric asymmetries arise during prenatal brain development. Structural differences in cortical folding patterns, white-matter pathways, and regional growth trajectories can be detected during the second and third trimesters [13,27,28,29,30,31,32]. Studies of gene expression in the developing human cortex similarly demonstrate lateralized transcriptional patterns linked to cortical arealization and neuronal differentiation [16,24].

These early asymmetries appear to contribute to the organization of large-scale functional networks. Connectomic analyses suggest that hemispheric differentiation may facilitate efficient network architecture by reducing redundancy and enabling specialized processing streams [18,19,21,23,33].

Rather than emerging abruptly in later childhood, hemispheric lateralization develops progressively through coordinated prenatal and early postnatal maturation processes. The present framework proposes that the developmental timing of this differentiation may be as consequen-

tial as its eventual magnitude. While the degree of hemispheric specialization has been extensively investigated, comparatively less attention has been directed toward how variation in the timing and coordination of its emergence may influence subsequent neural, motor, and social development. Developmental systems theories suggest that early biases in neural organization can shape later developmental trajectories by constraining the organization of action-perception interactions [25,34]. Within this perspective, hemispheric asymmetry is conceptualized as an early organizational constraint that contributes to the progressive specialization of neural circuits supporting motor coordination, perception, and social interaction.

2.2 Hemispheric Specialization and the Structuring of Action-Perception Loops

Hemispheric specialization is most often discussed in relation to language and visuospatial processing, yet its developmental significance extends beyond these domain-specific functions. Early asymmetries in motor planning, temporal sequencing, and sensory integration suggest that lateralization contributes to structuring action-perception loops from the earliest stages of postnatal life [18,19,26,35]. Building on hemispheric specialization, the coordination between hemispheres becomes critical for the integration of lateralized functions.

"Action-perception interactions" refer to recurrent cycles in which motor behavior influences perceptual experience while perceptual feedback contributes to the ongoing refinement of behavior across development. Within these loops, hemispheric specialization may allow different neural populations to support partially differentiated functional roles, such as temporal sequencing, spatial integration, or motor coordination. Partitioning these operations across hemispheres may reduce metabolic cost while increasing processing precision.

Recent work examining functional connectome asymmetry supports this view, demonstrating that hemispheric specialization is closely linked to the organization of distributed cortical networks and their dynamic interactions [14,18,21,22,36]. These findings suggest that lateralization may serve as a fundamental architectural feature that stabilizes large-scale neural communication during development.

Within the developmental timing framework advanced here, action-perception interactions constitute the principal mechanism through which variation in neural timing is hypothesized to influence emerging motor organization and, ultimately, social developmental trajectories. The following sections examine how these interactions may be shaped by interhemispheric coordination, oscillatory synchronization, and the progressive cortical regulation of motor behavior.

2.3 Interhemispheric Coordination

Hemispheric specialization unfolds in concert with the maturation of interhemispheric connectivity. Progressive development of the corpus callosum and related commissural pathways supports increasingly selective coordination and modulation between the hemispheres, enabling both functional integration and the progressive specialization of lateralized processing [14,15,30,37].

During early infancy, relatively diffuse bilateral activation patterns are common and may reflect immature inhibitory control. Over developmental time, increasing lateralization is accompanied by more selective cross-hemispheric modulation. Structural and diffusion-based imaging studies indicate that this refinement is closely tied to the maturation of callosal white-matter pathways and the strengthening of long-range cortical connectivity [15,33,37,38,39].

The balance between hemispheric integration and segregation represents a dynamic developmental process. Excessive bilateral activation may reduce computational efficiency, whereas premature rigidity of lateralization may constrain adaptive integration. Optimal developmental trajectories likely involve progressive calibration of this balance across early childhood [19,26]. Beyond structural connectivity, effective integration of distributed neural systems also depends on precise temporal coordination of neural activity. Within the present framework, the progressive calibration of structural and temporal coordination is proposed to provide an important foundation for subsequent motor organization and action-perception interactions.

Structural connectivity alone, however, does not fully determine functional integration. Coordinated communication among distributed neural systems also depends on the temporal synchronization of neural activity, providing a complementary mechanism through which developmental timing may influence emerging patterns of neural and behavioral organization.

2.4 Oscillatory Coordination and Temporal Precision

Oscillatory neural dynamics provide an additional mechanism through which hemispheric timing and interregional coordination are regulated [12,14,17,37,38]. Neural oscillations synchronize distributed neuronal populations through phase alignment, creating temporal windows that facilitate efficient communication between brain regions [17,40,41,42,43,44].

Through these mechanisms, oscillatory coherence can regulate the timing of information exchange both within and across hemispheres, supporting functional integration across distributed neural systems [45]. Developmental changes in oscillatory phase precision and coherence are therefore thought to support the increasing temporal stability of neural networks involved in perception, action planning, and social interaction [44,46].

Variability in oscillatory coupling, particularly across hemispheres, may increase variability in distributed neural communication. Such noise could propagate into action-perception loops, increasing variability in motor output and perceptual integration. From this perspective, hemispheric asymmetry and oscillatory coordination should be viewed not as separate phenomena but as interacting components of a broader temporal architecture governing neural development.

2.5 Corticalization of Motor Control and Reflex Integration

A final dimension of hemispheric timing involves the progressive cortical modulation of subcortical motor programs. Early motor behavior is largely mediated by brainstem-generated reflexive patterns that support survival, orienting, and early postural organization [47,48]. As corticospinal and corticobulbar pathways mature, cortical circuits exert increasing top-down regulation over these subcortical programs [49,50,51,52].

This process of corticalization reflects coordinated maturation across hemispheric and descending motor control systems. Primitive reflexes are not simply eliminated but are progressively inhibited, integrated, or transformed into voluntary motor behaviors as cortical regulation strengthens. Persistent or asymmetrical expression of reflex patterns beyond expected developmental windows may be associated with differences in the maturation of cortical and hemispheric motor regulation [53,54].

The relationship between primitive reflex persistence and hemispheric asymmetry is not yet directly established. However, reflex integration depends on the maturation of descending cortical control, which is itself asymmetrically organized during development. Disruptions in the timing or balance of hemispheric maturation may therefore bias the inhibition of brainstem-mediated reflex circuits, leading to asymmetrical or prolonged reflex expression. In this view, persistent or asymmetric reflex expression may represent one possible developmental indicator of variation in cortical and interhemispheric motor maturation, although direct evidence linking these processes remains limited. This provides a developmental link between early reflex integration and the emergence of asymmetrical motor organization.

2.6 Biological Sources of Timing Variability

The developmental processes described above do not occur independently of broader biological influences associated with neurodevelopment. A growing body of evidence suggests that many genetic, cellular, and environmental factors implicated in ASD influence neural maturation through mechanisms that could affect developmental timing and coordination across distributed neural systems [10,49,55,56]. Although the present framework does not propose a single etiological pathway, diverse biological influences may converge on common timing-related developmental processes.

Genes associated with ASD have been linked to synaptic development, neuronal differentiation, cortical circuit formation, excitation-inhibition balance, myelination, and transcriptional regulation [10,49,55,56]. Alterations in these processes may influence the precision and stability of neural communication by affecting the maturation of large-scale networks, hemispheric specialization, and interhemispheric connectivity [20,57,58,59]. Similarly, developmental variation in callosal maturation, long-range white-matter organization, and network connectivity may influence the temporal coordination of distributed neural activity during critical periods of development [22,60,61,62,63].

Neural oscillatory dynamics are also sensitive to the organization and coordination of distributed neural systems. Oscillatory synchronization and phase coupling contribute to the temporal regulation of communication within and between cortical networks [12,14,37,38,64,65]. Variability in the developmental processes supporting neural communication and network organization may therefore influence oscillatory coherence and temporal precision, potentially affecting perception, motor control, and social interaction.

In addition to genetic and circuit-level influences, neuroimmune and environmental factors may contribute to variability in developmental timing. Prenatal and early postnatal influences, including inflammatory processes, environmental exposures, and developmental stressors, have been associated with alterations in neural maturation, connectivity, and functional organization [40,66]. Such influences may affect the timing and coordination of developmental processes that support hemispheric specialization, interhemispheric communication, and cortical regulation of behavior.

Within the present framework, these biological factors are not viewed as alternative explanations to developmental timing but rather as potential upstream contributors to timing variability. Diverse genetic, neurobiological, and environmental influences may therefore converge on common developmental pathways involving hemispheric specialization, interhemispheric coordination, oscillatory synchronization, and cortical regulation of motor behavior. This convergence provides one possible mechanism through which heterogeneous ASD risk factors may contribute to variability in early developmental trajectories while remaining consistent with the substantial heterogeneity observed across ASD populations.

2.7 Developmental Timing Relationships Across Neural and Motor Systems

Hemispheric asymmetry, interhemispheric coordination, oscillatory synchronization, and cortical regulation of subcortical motor programs can be conceptualized as interacting developmental processes unfolding across partially overlapping maturation trajectories [25,26]. Variability in the timing or coordination of these processes may be asso-

ciated with differences in motor organization and the temporal stability of action-perception interactions across development. From this perspective, subtle variation in hemispheric differentiation or oscillatory coherence could contribute to differences in motor timing, sensorimotor coordination, and early social interaction patterns.

At this stage, it is important to distinguish between empirically established findings, theoretically grounded inferences, and components of the present framework that remain to be directly tested. Converging evidence supports the early emergence of hemispheric asymmetry, the progressive maturation of interhemispheric connectivity, and the role of oscillatory coordination in structuring neural communication, as well as the transition from brainstem-mediated reflexive motor patterns to increasingly cortically regulated motor control. It is also well established that early motor development and dyadic interaction dynamics are closely linked to later social and communicative outcomes. However, the integration of these findings into a continuous developmental sequence, in which variation in hemispheric specialization and interhemispheric coordination may be associated with differences in motor organization and early social interaction across development, remains a theoretical synthesis. Consistent with developmental systems perspectives, the present framework assumes that developmental outcomes emerge through dynamic interactions among multiple biological and behavioral processes rather than through isolated deficits in individual components [67]. In particular, the proposal that persistent or asymmetric primitive reflex expression indexes alterations in hemispheric timing and that such motor signatures mediate downstream social outcomes via motor-social coupling should be regarded as testable hypotheses rather than established causal relationships. The framework advanced here is intended to organize existing evidence into a coherent developmental model while generating explicit predictions for longitudinal investigation.

Rather than conceptualizing early motor differences in ASD as isolated anomalies, a timing framework suggests that such differences may represent potentially related developmental differences involving hemispheric and interhemispheric organization [50,52]. The proposed developmental timing relationships linking hemispheric asymmetry, interhemispheric coordination, oscillatory dynamics, and corticalization are illustrated in Fig. 1.

One behavioral domain in which such timing differences may become observable is the developmental transition from brainstem-mediated reflexive motor programs to cortically modulated voluntary control. During early infancy, descending corticospinal and corticobulbar pathways progressively regulate subcortical motor circuits, integrating primitive reflex patterns into more flexible motor coordination [47,48,49,51,52,54,68]. Because these descending control systems depend on coordinated hemispheric maturation and interhemispheric communication, variability in the timing of hemispheric specialization may plausibly manifest behaviorally as delayed or asymmetric reflex integration. These large-scale coordination processes are reflected in early motor behavior, particularly in the development and integration of primitive reflexes.

The evidence reviewed in this section indicates that hemispheric specialization, interhemispheric coordination, oscillatory synchronization, and cortical maturation follow distinct yet interacting developmental trajectories. The developmental timing framework proposed in the present review builds on these observations by hypothesizing that variation in the temporal coordination among these processes, rather than alteration of any single mechanism alone, may influence the emergence and organization of early motor behavior. The following section considers how these neurodevelopmental processes may be expressed through the developing motor system and how early motor organization may provide an observable behavioral interface for underlying differences in developmental timing.

3. Primitive Reflex Development and Early Motor Organization

Section 2 examined the neurodevelopmental processes that establish the temporal architecture of the developing brain, including hemispheric specialization, interhemispheric coordination, oscillatory synchronization, and progressive corticalization. The present section considers how variation in the timing of these interacting processes may become behaviorally expressed during infancy. Within the developmental timing framework proposed here, early motor organization is conceptualized as the first observable developmental interface through which underlying variation in neural timing may become apparent. Primitive reflex integration is therefore considered not in isolation but as one component of a broader developmental transition from subcortically organized motor behavior to progressively cortically regulated action.

Primitive (primary) reflex expression provides a behavioral window into the maturation of descending cortical control systems and the progressive reorganization of early motor behavior [38,39,55,60]. These reflexes are normal components of early neurodevelopment, emerging during fetal life and early infancy before gradually diminishing as corticospinal, corticoreticular, cerebellar, and basal ganglia networks mature [38,39,55,60]. Their developmental significance lies not simply in their presence or disappearance, but in the orderly transition from predominantly subcortical motor organization to progressively integrated cortical regulation. Within the developmental timing framework proposed here, this transition is conceptualized as one observable manifestation of the broader temporal coordination among interacting neural systems reviewed in the preceding section.

The maturation of reflex regulation occurs within broader neurodevelopmental processes influenced by ge-

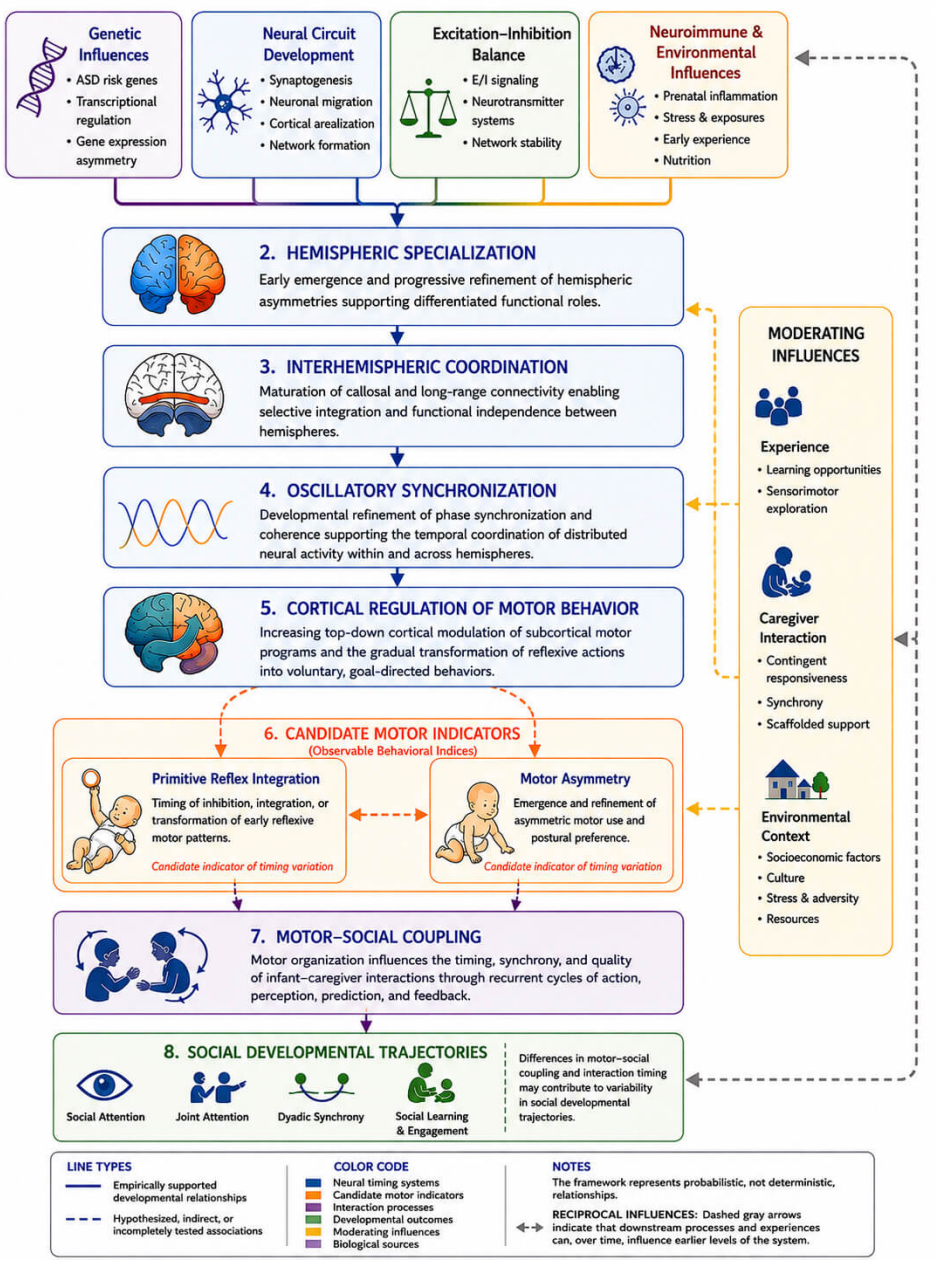

Fig. 1. Developmental timing framework linking neural, motor, and social development. The figure illustrates a conceptual developmental framework in which biological influences associated with neurodevelopment, including genetic, circuit-level, neuroimmune, and environmental factors, may contribute to variability in developmental timing across multiple interacting neural systems. Hemispheric specialization, interhemispheric coordination, oscillatory synchronization, and the progressive cortical regulation of motor behavior are depicted as partially overlapping developmental processes that contribute to the temporal organization of neural communication and action-perception interactions. Within the framework, primitive reflex integration and motor asymmetry are presented as candidate developmental indicators that may reflect variation in neural timing and coordination rather than established causal consequences of atypical hemispheric development. These motor features are hypothesized to influence motor–social coupling, including the timing and coordination of infant-caregiver interactions, which may contribute to differences in social developmental trajectories through recurrent cycles of action, perception, prediction, and feedback. Solid lines indicate developmental relationships supported by converging empirical evidence. Dashed lines indicate hypothesized, indirect, or incompletely tested developmental associations. The figure is intended as a heuristic model that organizes existing findings into a set of empirically testable developmental hypotheses and should not be interpreted as a strictly linear or deterministic account of ASD development. ASD, autism spectrum disorder.

netic, cellular, and environmental factors. Biological mechanisms associated with synaptic development, cortical circuit formation, neural connectivity, myelination, and network maturation may contribute to variability in the timing of cortical regulation and motor integration [10,49,55,56,58]. The developmental significance of primitive reflexes depends not only on their presence or persistence but also on their timing, sequence of integration, and relationship to the maturation of broader motor and neural systems. Within the present framework, primitive reflexes are therefore interpreted as one component of an evolving developmental process rather than as isolated markers of atypical neurodevelopment.

Although primitive reflex persistence has long been used clinically as an indicator of delayed corticalization, systematic empirical evidence linking reflex integration to neural timing mechanisms remains limited. Accordingly, associations between reflex persistence and hemispheric or interhemispheric timing processes should be interpreted as theoretically motivated and empirically testable rather than as established mechanistic relationships. Within the present framework, reflex persistence is treated not as a diagnostic marker but as a candidate developmental indicator of broader developmental timing processes that require rigorous longitudinal investigation.

The developmental timing framework advanced here does not propose that persistent primitive reflexes constitute specific biomarkers of autism or other neurodevelopmental conditions. Rather, it hypothesizes that variation in the timing of reflex integration may provide one observable indicator of broader differences in the temporal organization of early neural maturation, particularly when interpreted alongside other developmental findings and complementary measures of motor organization and neural timing.

Reflex integration follows a broadly predictable developmental trajectory, with age-normed windows for attenuation of patterns such as tonic neck, grasp, Moro, and related reflexes [50,52,53,57]. Although variability exists, persistent or asymmetrical expression beyond expected developmental periods may indicate incomplete cortical modulation or delayed integration within sensorimotor networks. Within the present developmental timing framework, such persistence is conceptualized not as an isolated motor anomaly but as one observable manifestation of broader variation in hemispheric coordination, cortical motor maturation, and the temporal organization of early neural development. Accordingly, reflex persistence should be interpreted within the context of an individual's overall developmental profile rather than as an independent clinical finding.

Importantly, many primitive reflexes are themselves lateralized or asymmetrically expressed. For example, tonic neck patterns influence midline crossing, postural alignment, and limb coordination. Asymmetric persistence may be associated with differences in unilateral motor stabilization. Such motor differences may contribute to variation in early exploratory behavior, shaping how infants reach for, orient to, stabilize gaze on, and interact with objects and social partners [69,70,71,72]. Over repeated interactions, such subtle motor biases may influence the temporal organization of action-perception loops through which infants explore their environment and engage with caregivers. Within the developmental timing framework proposed here, these repeated motor experiences are hypothesized to contribute to the calibration of subsequent motor-social coupling rather than directly determining later social outcomes.

From a developmental systems perspective, persistent reflex activity may be associated with increased variability or asymmetry in motor output [8,34,51,52]. Such variability could influence gaze stabilization, postural alignment, orienting behavior, and other aspects of early sensorimotor interaction. Differences in motor timing and coordination may therefore contribute to variation in how infants engage with socially contingent sensory input across development. Within this perspective, the emphasis is not on global impairment but on possible differences in the temporal organization of early motor-social interaction.

Emerging evidence suggests that early motor differences are among the earliest observable prospective indicators of later ASD diagnosis [73,74,75,76]. These differences include atypical postural control, reduced midline crossing, altered laterality patterns, and increased motor variability in high-risk infants. Within the developmental timing framework proposed here, these observations are interpreted as potentially related manifestations of a common developmental process rather than as independent motor findings. Primitive reflex persistence, motor asymmetry, altered postural organization, and increased motor variability are conceptualized as complementary behavioral readouts through which underlying variation in neural timing may become observable during infancy. This interpretation does not imply that reflex persistence causes ASD or constitutes a specific marker of autism. Rather, it suggests that variation in early motor organization may reflect broader differences in the temporal coordination of neural maturation that could influence subsequent motor-social coupling and developmental trajectories [50,51,73,77].

Critically, this perspective generates falsifiable predictions. If primitive reflex persistence is a candidate behavioral proxy of corticalization timing, it could plausibly be examined in relation to hemispheric asymmetry and interhemispheric coherence. It should predict subsequent motor asymmetry patterns and variability in dyadic synchrony. Longitudinal studies could examine whether associations between reflex persistence and later social outcomes are related to intermediate differences in motor-social interaction. Such questions illustrate how reflex persistence might be incorporated into prospective developmental investigation within broader longitudinal models of early neurodevelopment. These processes provide a developmental bridge be-

tween early motor integration and the emergence of asymmetrical functional organization.

In the next section, we examine how motor asymmetry and reflex-related motor biases may influence motor-social coupling dynamics, positioning action-perception timing as a potential contributor to variation in early social developmental trajectories.

4. Motor-Social Coupling as a Scaffold for Predictive Social Brain Development

Motor behavior does not merely accompany social development; it structures the temporal conditions under which social learning occurs [8,10,78]. From the earliest postnatal months, posture, orienting, gaze stabilization, reaching, and vocal timing form the sensorimotor substrate through which infants engage with caregivers and the surrounding environment [10,11,71]. These behaviors are embedded within recurrent action-perception loops in which motor output generates socially contingent feedback, and that feedback in turn updates internal predictive models of the environment [56,79,80,81,82]. The stability and precision of these loops depend on coordinated timing across neural and motor systems [29,83]. Within this framework, motor timing is proposed to influence the temporal alignment between action and feedback, thereby constraining the precision with which prediction errors can be detected and corrected during social interaction. Within the developmental timing framework advanced here, motor-social coupling is proposed to provide the principal developmental interface through which variation in neural timing and motor organization may influence opportunities for predictive social learning. Rather than acting as a direct cause of later social differences, motor behavior is hypothesized to shape the temporal structure of infant-caregiver interaction through which social expectations are progressively calibrated.

4.1 Motor Development as a Foundation for Social Learning

Motor development provides the embodied infrastructure through which infants engage with the social world. Stabilization of the head and trunk reduces sensory noise and enables consistent alignment of gaze with social partners, thereby supporting early joint attention and shared reference frames [8,10,70,78]. Improvements in postural control can influence the quality of perceptual input available for social learning.

Manual exploration extends these interaction loops by linking object manipulation with caregiver responses. Reaching and grasping behaviors frequently elicit contingent reactions from caregivers, such as verbal labeling, imitation, or assistance. These interactions allow infants to experience systematic relationships between their actions and socially mediated outcomes [69,71]. Repeated interaction cycles may contribute to the gradual organization of expectations regarding social contingency and interaction timing [25,82].

Evidence from developmental research indicates that motor milestones are associated with changes in social engagement and communicative behavior during infancy [10,70,71]. These observations support the view that motor development does not simply accompany cognitive maturation but may actively organize the temporal conditions under which infants experience socially contingent interaction. Within the present framework, motor development is therefore conceptualized as a developmental scaffold linking neural maturation with emerging social cognition.

4.2 Dyadic Synchrony and Temporal Coordination

Early social interaction unfolds through temporally coordinated exchanges between infants and caregivers. These exchanges involve dynamic alignment of gaze shifts, vocalizations, gestures, and postural adjustments. Such alignment produces dyadic synchrony, a pattern of mutual temporal coordination that emerges through continuous adjustment between interacting partners [64,84,85,86]. In developmental research, dyadic synchrony is commonly quantified through measures such as gaze coordination, turn-taking timing, imitation latency, vocal contingency, and cross-recurrence analyses of infant-caregiver interaction.

Dyadic synchrony has been proposed as one important process through which early social interaction may influence neural and behavioral development [43]. Coordinated interaction rhythms may support increasing sensitivity to the timing and consistency of caregiver responses and refine expectations about social contingencies [11,25,86,87]. These coordinated exchanges are thought to support the development of social prediction by providing a reliable temporal structure within interaction. Within the developmental timing framework, dyadic synchrony represents the behavioral context through which differences in neural timing and motor organization may become amplified, compensated, or progressively recalibrated across development.

From a dynamical systems perspective, infant-caregiver interaction can be understood as a coupled system in which both partners continuously adjust their behavior in response to the timing of the other [88,89]. Within such systems, coordinated interaction depends on ongoing temporal adjustment between interacting partners and relative stability in interaction timing.

4.3 Action-Perception Interaction and Social Learning

Motor-social interaction can be conceptualized as involving recurrent cycles linking infant motor behavior with socially contingent environmental feedback. Within these interactions, motor actions influence perceptual experience while caregiver responses contribute to the ongoing refinement of social engagement across development [41,79,80,82,90,91]. These recurrent action-perception cycles provide the developmental mechanism through which the timing-related processes described in Sections 2 and 3 are hypothesized to influence social learning.

Over repeated interactions, prediction errors arising from temporally structured mismatches between expected and observed responses drive updating of internal predictive models, consistent with predictive accounts of autism emphasizing altered prediction and model updating [92]. These calibration processes contribute to the emergence of anticipatory gaze behavior, coordinated turn-taking, and increasingly stable interaction rhythms [25,93,94,95].

Because these calibration processes depend on temporally structured interaction, variability in motor timing is hypothesized to alter the efficiency with which prediction errors are minimized. Increased variability in motor output may introduce temporal noise into the interaction loop, potentially affecting the precision with which infants detect, interpret, and update socially contingent information across repeated interactions.

4.4 Motor Variability and Early ASD Development

Evidence from prospective infant studies indicates that early motor differences are among the earliest observable indicators of later ASD diagnosis [4,6,72,73,74,76]. These differences include atypical postural control, altered motor variability, reduced anticipatory gaze shifts, and differences in the temporal coordination of social interaction.

Rather than interpreting these findings as independent abnormalities across multiple domains, a motor-social coupling framework views them as interacting components of a temporally structured developmental system. Variability in motor output is hypothesized to influence the timing of dyadic exchanges, which in turn shapes the calibration of predictive social models.

Within this perspective, motor variability does not necessarily imply impairment in social motivation. Rather, the framework proposes that variability in motor timing may influence the temporal reliability of socially contingent experience, thereby altering opportunities for predictive calibration without assuming diminished social interest or motivation.

4.5 Motor-Social Coupling as a Developmental Interface

Importantly, this account does not reduce social cognition to motor control. Rather, it proposes that early motor-social coupling provides the temporal scaffold upon which higher-order social inference is constructed. The developing social brain, encompassing networks involved in gaze processing, action understanding, and affective engagement, is refined through repeated calibration within embodied interaction loops [25,83,84,93,94,95].

When neural timing systems governing motor organization are altered, the temporal precision of these interaction loops may be affected. Increased variability in motor output or interaction phase alignment may introduce noise into predictive learning processes [80,82,91]. Over time, such differences may influence how social expectations are calibrated during development.

4.6 Motor-Social Coupling Within a Developmental Timing Framework

Within the developmental timing framework proposed in this article, motor-social coupling represents one context through which neural timing, motor organization, and social interaction may relate across development. Hemispheric specialization, interhemispheric coordination, and oscillatory timing may contribute to the temporal organization of motor behavior, while motor behavior helps structure the timing of infant-caregiver interaction [11,64,96]. Variation in neural timing may therefore be associated with differences in motor organization and dyadic interaction dynamics across development. Increased variability in motor output or interaction phase alignment may introduce temporal noise into predictive learning processes, potentially contributing to heterogeneous developmental trajectories rather than a single developmental pathway [11,80,83,88]. The developmental action-perception loop linking neural timing, motor organization, and dyadic synchrony through recurrent interaction, prediction, and feedback processes is illustrated in Fig. 2.

The evidence reviewed in this section suggests that motor-social coupling provides the principal developmental interface linking neural timing with emerging social cognition. Within the present framework, action-perception loops are conceptualized as recurrent developmental processes through which variation in neural timing and motor organization may influence the temporal structure of infant-caregiver interaction and predictive social learning. This perspective emphasizes dynamic reciprocal interactions rather than linear causal pathways and provides the developmental bridge to the multilevel longitudinal framework developed in the following section.

If motor-social interaction reflects one behavioral context through which neural timing and motor organization influence early development, then systematic variation in these interaction patterns may provide useful longitudinal measures for examining developmental diversity in ASD trajectories [97,98]. From this perspective, motor timing, reflex development, and dyadic coordination may be investigated as interacting developmental variables within prospective studies of early neurodevelopment.

5. Motor-Social Interaction and Early Social Development

The preceding sections proposed that variation in neural timing may become behaviorally expressed through early motor organization and subsequently through motor-social coupling. The present section considers how repeated differences in the temporal organization of infant-caregiver interaction may influence broader social developmental trajectories. Within the developmental timing framework advanced here, social development is viewed not as an independent process but as emerging through recurrent cycles of action, perception, prediction, and care-

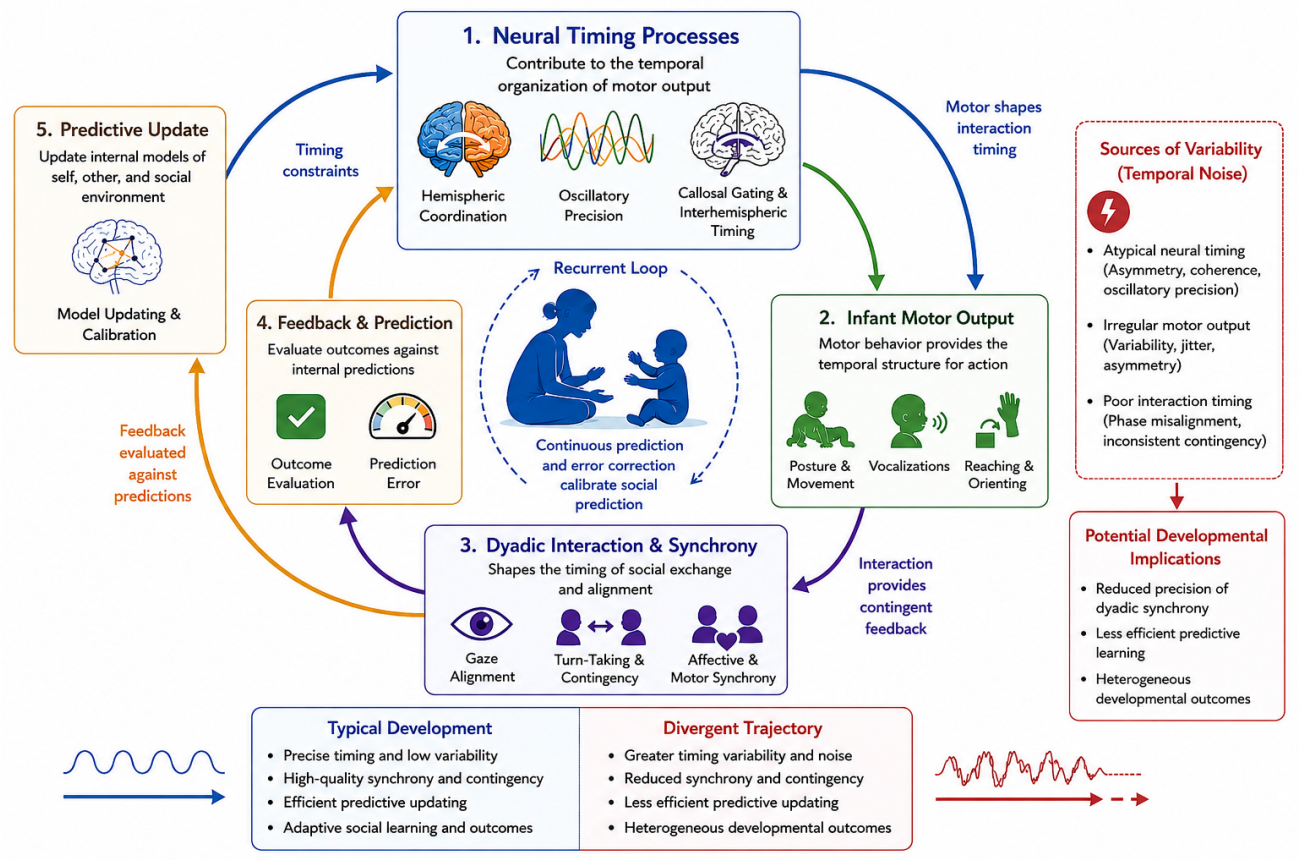

Fig. 2. Developmental action-perception loop linking neural timing, motor organization, dyadic synchrony, and predictive social learning. Neural timing processes, including hemispheric coordination, oscillatory precision, and interhemispheric communication, contribute to the temporal organization of motor output. Motor behavior, including posture, orienting, vocalization, and exploratory action, helps structure the timing of infant-caregiver interaction. These interactions generate temporally contingent feedback that is evaluated against internal predictions and incorporated into ongoing model updating. Through repeated cycles of action, perception, prediction, and feedback, infants progressively calibrate expectations regarding social contingency and interaction timing. The figure illustrates a recurrent developmental loop in which neural timing, motor organization, and dyadic synchrony are proposed to interact dynamically rather than through a strictly linear causal sequence. Sources of variability, including differences in neural timing, motor coordination, and interaction timing, may introduce temporal noise into the system, potentially influencing the precision of dyadic synchrony and the efficiency of predictive learning. The resulting developmental trajectories are expected to be heterogeneous and shaped by multiple interacting biological and environmental influences. Individual components of the model are supported by existing developmental, motor, and social interaction research, whereas their integration into a unified developmental timing framework represents the central hypothesis advanced in this article. Solid arrows indicate developmental relationships that are supported by existing empirical evidence, whereas dashed arrows indicate hypothesized, indirect, or incompletely tested developmental relationships.

giver feedback. Small differences in the temporal organization of these interactions may accumulate over development, contributing to increasingly divergent developmental trajectories without implying a deterministic or linear causal sequence.

Motor behavior does not merely accompany social development; it contributes to the temporal organization of early social interaction [8,10,78]. From the earliest postnatal months, posture, orienting, gaze stabilization, reaching, and vocal timing shape how infants engage with caregivers and the surrounding environment [10,11,71]. These interactions unfold through recurrent cycles in which infant behavior influences socially contingent feedback while caregiver responses contribute to the ongoing refinement of interaction patterns across development [56,79,80,81,82]. The temporal stability of these interactions depends on coordination across neural, motor, and interpersonal systems [29,83]. Within this perspective, differences in motor timing or coordination may influence how infants experience socially contingent interaction during early development.

Early in life, hemispheric specialization and oscillatory coherence contribute to stabilizing action-perception loops. When these processes mature within expected temporal windows, motor output becomes progressively re-

fined, reflexive patterns are integrated, and dyadic synchrony becomes more stable. In contrast, if hemispheric timing is delayed, exaggerated, or inconsistently regulated, motor output may remain more variable or asymmetrically biased. Such differences may not necessarily reflect global impairment but may be associated with variability in the timing and consistency of early social interaction. Over repeated developmental exchanges, such variability is hypothesized to influence the calibration of predictive social learning through cumulative differences in interaction experience rather than through isolated developmental events [6,19,50,66,74,76,99].

Over repeated interactions, increased temporal variability can alter the efficiency of predictive updating. If anticipatory gaze shifts are delayed, if turn-taking latency is inconsistent, or if postural instability reduces sustained engagement, the infant receives less reliable contingent feedback. This may amplify prediction error signals and shift learning dynamics [62,79,80,100,101,102,103]. Rather than progressively refining increasingly precise predictive models of social interaction, developmental resources may become preferentially allocated toward maintaining behavioral stability under conditions of increased temporal uncertainty. This proposal remains hypothetical but provides one possible mechanism linking early motor-social timing differences with later variability in social developmental trajectories [1,91,100,101,104].

Importantly, this model accommodates heterogeneity within ASD. The magnitude, direction, and developmental window of timing divergence may vary across individuals. In some trajectories, delayed hemispheric specialization may predominate; in others, premature rigidity of lateralization or altered interhemispheric inhibition may be more prominent. Likewise, reflex persistence may be transient in some infants and more pronounced in others. The present framework does not posit a single developmental pathway. Still, it explores the possibility that variation in developmental timing may represent one organizing perspective through which heterogeneity in ASD can be investigated. Developmental timing should be viewed as a multidimensional property of interacting developmental systems rather than as a simple measure of developmental delay or acceleration. In the present article, developmental timing refers to the relative temporal coordination among interacting developmental processes, including their onset, rate of maturation, synchronization, and integration across neural, motor, and interpersonal systems, rather than to chronological age or developmental delay alone.

This perspective also integrates with broader biological and environmental contributions to ASD. Genetic and neurodevelopmental influences may affect the maturation schedule of hemispheric differentiation, callosal development, oscillatory coordination, and cortical regulation of motor behavior [10,49,55,56,58,105,106,107], while environmental influences, particularly caregiver responsiveness and interaction timing, may buffer or amplify emerging variability within motor-social interaction loops [11,25,64,73,84,86].

The present developmental timing perspective generates longitudinally testable hypotheses. Primitive reflex persistence may be associated with later motor asymmetry patterns. Motor asymmetry and variability may mediate associations between early neural timing markers and subsequent social communication outcomes. Neural timing indices may moderate the strength of motor-social coupling effects. Longitudinal studies may also identify developmental periods during which coupling precision is more strongly associated with later social developmental trajectories. These predictions allow the framework to be evaluated empirically rather than treated as a purely conceptual synthesis. Equally important, failure to observe these predicted developmental relationships, or demonstration that alternative developmental models better account for longitudinal observations, would require revision or rejection of the present framework. The scientific value of the developmental timing perspective rests on the specificity and testability of its developmental predictions rather than on its capacity to accommodate existing observations retrospectively [63,108,109].

By conceptualizing ASD as potentially involving divergence in coordinated developmental timing rather than solely isolated differences within motor or social domains, this model seeks to bridge early neural maturation with emerging social brain organization. The next section formalizes these relationships within a hybrid biomarker architecture, outlining how multilevel measurement and longitudinal modeling can test the proposed cascade. Importantly, the value of the timing-cascade framework lies not only in conceptual synthesis but also in its capacity to generate empirically testable predictions linking neural timing indices, motor organization, and dyadic interaction dynamics across early development.

6. A Conceptual Framework for Prospective and Longitudinal Investigation

The timing-cascade framework advanced here implies that no single behavioral or neural measure is sufficient to characterize early divergence in ASD [1,2,3,7,15,97,98]. Instead, coordinated indices across levels are required to capture the maturation schedule of hemispheric specialization, interhemispheric coordination, motor organization, and motor-social coupling. We therefore propose a multilevel developmental research framework integrating neural timing markers, behavioral motor indices, and dyadic coupling measures within a longitudinal modeling approach. The proposed multilevel biomarker architecture linking neural timing indices, reflex integration, motor organization, and motor-social coupling within a longitudinal framework is illustrated in Fig. 3. Each component of this framework corresponds to measurable variables that can be ex-

amined using existing developmental methodologies, making it possible to investigate the relationships proposed here within prospective longitudinal studies. The framework is not intended to identify a single biomarker of autism but to provide a developmental architecture within which multiple neural, motor, and interpersonal measures can be interpreted longitudinally as interacting components of the same developmental process.

Fig. 3 summarizes the central proposition of the present framework. Rather than depicting a linear causal pathway, it illustrates a multilevel developmental architecture in which biological influences, neural timing, motor organization, motor-social coupling, and developmental outcomes interact across time. The figure therefore serves primarily as a heuristic model for organizing prospective longitudinal investigation rather than as a representation of established mechanistic pathways.

Within this perspective, motor-social interaction may represent one developmental context through which neural timing and motor organization relate to later social developmental trajectories [97,98]. Genetic liability, perinatal influences, caregiver interaction timing, and broader environmental factors may contribute to variability across developmental pathways [10,52]. Longitudinal approaches may therefore be useful for examining how neural timing, motor development, reflex integration, and dyadic interaction patterns relate to one another across development. Importantly, the present framework does not assume a strictly linear or unidirectional developmental sequence, and reciprocal influences across neural, motor, and social systems are expected [89,93].

6.1 Neural Timing and Asymmetry Indices

At the neural level, candidate developmental measures include hemispheric power asymmetry, interhemispheric coherence, oscillatory phase precision, and latency variability in event-related potentials [14,32,42,64]. These measures are not assumed to constitute biomarkers of ASD in isolation but are considered candidate indicators of developmental timing and coordination that may be examined longitudinally. These indices capture temporal coordination within and across hemispheres and reflect the maturation of interhemispheric coordination and phase alignment mechanisms. Rather than treating asymmetry magnitude as inherently adaptive or maladaptive, the framework emphasizes developmental timing: delayed, exaggerated, or inconsistent trajectories of asymmetry may carry distinct implications for downstream motor organization.

Interhemispheric coherence and phase-locking measures are particularly relevant, as they index the balance between integration and segregation across hemispheres [20,32,42,83,84,110]. Increased variability in interhemispheric communication or reduced selective gating may introduce temporal variability into distributed networks supporting action planning and perception. Longitudinal assessment of these indices examines whether early variation is associated with observable motor asymmetry or reflex persistence.

6.2 Reflex Integration and Motor Organization Profiles

Behavioral indices include standardized assessments of primitive reflex persistence, operationalized as the magnitude, symmetry, and age-deviation of reflex expression relative to established developmental norms. Within this framework, reflex persistence is conceptualized as a candidate developmental indicator of corticalization timing and hemispheric coordination rather than a standalone diagnostic indicator. These measures should be interpreted longitudinally, as deviations in the timing and trajectory of reflex attenuation, rather than as isolated cross-sectional findings. The developmental relevance of reflex persistence should depend not on its isolated presence but on its relationship to concurrent measures of neural timing, motor organization, and motor-social interaction obtained within the same developmental period. Different developmental trajectories may exhibit distinct patterns of reflex persistence, asymmetry, or attenuation, further emphasizing the heterogeneous nature of developmental timing variation. Candidate measures may also include standardized parent-report instruments designed to quantify early motor development and variability across infancy [111]. Prospective developmental screening approaches that integrate motor assessment with broader neurodevelopmental surveillance may provide useful platforms for evaluating these hypotheses longitudinally [112].

Motor asymmetry metrics, including reach preference distribution, midline crossing frequency, bimanual coordination variability, and kinematic precision, provide behavioral indices of hemispheric specialization and interhemispheric coordination expressed at the level of motor output [4,62,80,81]. Increased variability or rigid asymmetry may indicate altered partitioning of motor control across hemispheres. Importantly, these indices should be analyzed dimensionally rather than categorically, reflecting developmental gradients rather than binary abnormalities [3,50,51,52,94]. When assessed within the same individuals, these motor indices can be directly related to neural timing measures, allowing evaluation of whether variability in hemispheric coordination relates to differences in motor organization across development.

6.3 Motor-Social Coupling Metrics

Motor-social coupling can be quantified as the temporal coordination between infant motor output and caregiver responses, indexed through measures of dyadic synchrony and interaction timing. Candidate metrics include gaze-reach synchrony, imitation latency, turn-taking timing differences, and cross-recurrence quantification analysis of infant-caregiver interaction dynamics [21,28,31,59,78,79,102]. These measures capture the tim-

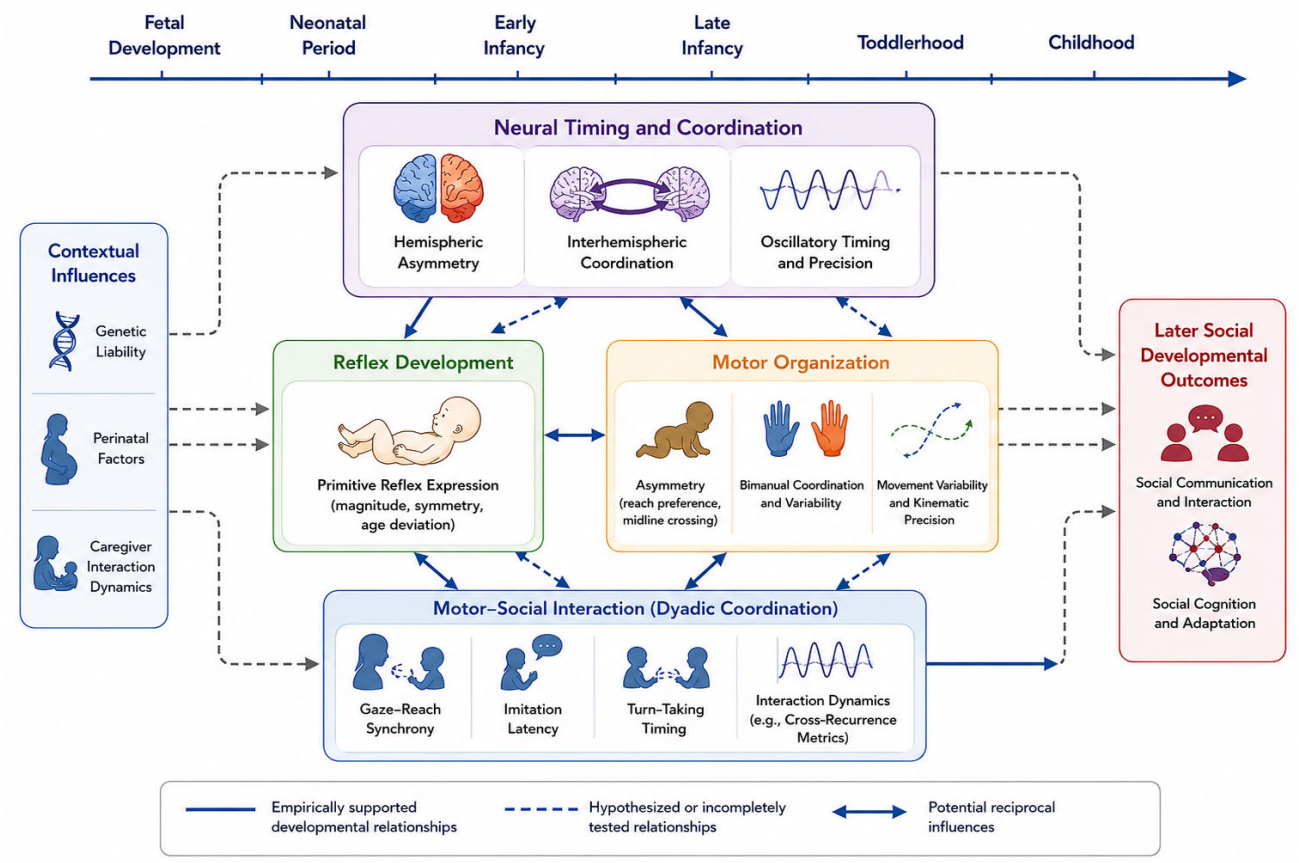

Fig. 3. Conceptual longitudinal framework linking neural timing, motor organization, reflex development, motor-social interaction, and later social developmental outcomes. The figure illustrates a multilevel developmental framework in which neural timing and coordination processes, including hemispheric asymmetry, interhemispheric coordination, and oscillatory timing, may relate to motor organization, reflex development, and motor-social interaction across early development. Genetic, perinatal, caregiver, and broader environmental influences are illustrated as interacting biological and contextual factors that may contribute to developmental variability across levels. The proposed relationships are intended as hypothesis-generating rather than as established mechanistic pathways. Reflex development, motor organization, and dyadic coordination are conceptualized as candidate developmental indicators that may reflect variation in developmental timing and coordination. Longitudinal investigation of these relationships may help determine whether specific developmental timing profiles are associated with distinct developmental trajectories and heterogeneous social outcomes. Solid lines indicate developmental relationships supported by existing empirical evidence, dashed lines indicate hypothesized or incompletely tested developmental associations, and bidirectional arrows indicate potential reciprocal influences across developmental levels. The framework is intended to guide prospective longitudinal investigation rather than to serve as a validated biomarker or diagnostic model.

ing, and variability of interaction cycles at sub-second to second timescales, providing quantitative measures of interaction timing and coordination during social exchange.

Within longitudinal designs, motor-social coupling metrics may be examined as potential mediators of associations between early neural timing indices and later social communication outcomes [28,48,69,75,98]. Within the developmental timing framework, these measures provide the principal behavioral interface through which hypothesized relationships between early neural timing and later social developmental trajectories can be examined empirically.

6.4 Longitudinal Modeling and Sensitive Windows

Longitudinal developmental research may help clarify how neural timing, motor organization, reflex development, and dyadic interaction patterns relate across infancy and childhood. Approaches such as growth-curve analysis, longitudinal trajectory analysis, and developmental subgroup characterization could be used to examine whether variability in neural timing and motor coordination is associated with later developmental differences [58,75,76,98,113].

Such modeling also allows for examination of heterogeneity within ASD trajectories. Rather than assuming a single pathway, clustering and group-based trajectory approaches may identify distinct developmental pro-

files characterized by different patterns of hemispheric specialization, motor organization, reflex development, and dyadic interaction [85]. Identifying these profiles may support characterization of developmental variability within prospective cohorts. Such analyses may also help determine whether multiple developmental pathways converge on similar behavioral outcomes or whether distinct timing profiles are associated with different developmental trajectories.

6.5 Moderating and Contextual Influences

Genetic liability, perinatal factors, caregiver responsiveness, interaction timing, and broader environmental influences are expected to moderate the strength and direction of developmental relationships [2,10,30,38,52,97]. Caregiver responsiveness and interaction timing, for example, may buffer the effects of motor variability on dyadic synchrony. Conversely, reduced environmental contingency may amplify variability in social interaction timing. Incorporating such moderators ensures that the model remains probabilistic and interactive rather than deterministic. The developmental timing framework should be regarded as probabilistic, multilevel, and context-dependent rather than deterministic, emphasizing developmental interactions over single causal pathways.

The present developmental timing perspective is intended to organize diverse neural, motor, and interpersonal developmental findings into a conceptually integrated framework that may support future longitudinal investigation [1,3,15,48,75,98]. Neural timing and coordination may be examined using electroencephalography (EEG)-based measures of oscillatory activity, hemispheric asymmetry, and interhemispheric synchronization, while motor organization and dyadic interaction patterns may be assessed using established behavioral and kinematic methodologies. The framework advanced here is not intended as a validated biomarker model or diagnostic platform, but rather as a hypothesis-generating developmental perspective through which relationships among neural timing, motor development, and social interaction may be explored across early development. Ultimately, the contribution of the present framework lies less in proposing a novel biological mechanism than in organizing diverse developmental findings into a coherent, multilevel hypothesis that can be evaluated prospectively. Its value will therefore depend on whether future longitudinal research supports the predicted relationships among neural timing, motor organization, motor-social coupling, and later social developmental outcomes. In the final section, we consider broader conceptual implications, limitations, and future directions for this timing-based synthesis.

7. Conceptual Implications and Future Directions

By considering early motor development, hemispheric maturation, and dyadic interaction within a shared developmental perspective, the present framework contributes to broader efforts in developmental neuroscience to understand neurodevelopmental conditions as emerging through interacting neural, motor, and interpersonal processes across time [15,48,70,91]. The account advanced here is intended as a conceptual synthesis and hypothesis-generating perspective rather than as an established causal model of ASD development. While each of these domains has been independently investigated within the developmental literature, the present article's central contribution is the proposal that variation in their temporal coordination may provide an organizing developmental principle through which heterogeneous neural, motor, and social findings can be interpreted within a common longitudinal perspective.

The developmental timing perspective advanced in this review considers whether early motor differences associated with ASD may relate to broader variation in hemispheric coordination, oscillatory timing, motor organization, and dyadic interaction across development. Rather than emphasizing isolated impairments within separate domains, the framework highlights the possibility that developmental timing and coordination may contribute to interactions among neural, motor, and social developmental processes. In this sense, the synthesis shifts attention toward temporally organized developmental variability rather than toward static domain-specific deficits. In doing so, the framework encourages investigation of developmental interactions and trajectories rather than isolated behavioral characteristics measured at single developmental time points.

7.1 Integrating Motor and Social Theories of ASD

Historically, motor theories and social-cognitive theories of ASD have developed largely in parallel [1,56,65,71,82,97,104]. Motor accounts emphasize postural control, coordination variability, and sensorimotor integration, while social theories focus on joint attention, predictive inference, and social motivation. The present framework does not privilege one domain over the other but situates both within a temporally structured developmental architecture. Motor-social coupling is conceptualized as the bridge between these domains: motor timing may influence perceptual experience, while social contingency refines motor calibration through feedback [28,31,48,69,79,102]. Within this perspective, motor behavior is not viewed as replacing social cognition but as helping to organize the developmental conditions under which social cognition emerges. This bidirectional coupling provides a developmental pathway through which early neural timing differences may shape social development without reducing ASD to motor dysfunction.

Although the present framework shares conceptual ground with predictive processing and developmental systems accounts of autism, it differs in its specific emphasis on the timing of hemispheric specialization and interhemispheric coordination as organizing constraints on early action-perception loops. Rather than focusing primarily on domain-specific deficits, the present perspective explores whether variation in hemispheric timing and coordination may contribute to differences in motor and social development across infancy and childhood.

7.2 Timing as an Organizing Principle

A central implication of this synthesis is that developmental timing, rather than simply the magnitude of asymmetry or the presence of specific behaviors, may represent an important contributor to developmental trajectory divergence [15,50,52,55,62,94]. Both delayed and prematurely rigid hemispheric specialization may be associated with differences in the stability of action-perception [9,80,83,84,110]. Likewise, transient reflex persistence may be developmentally normative, whereas prolonged or asymmetrical persistence may be associated with differences in cortical motor maturation. Emphasizing timing accommodates heterogeneity within ASD and aligns with contemporary views of neurodevelopment as dynamic and probabilistic, emerging through interactions among multiple biological and behavioral systems [114,115]. Developmental timing should be regarded as a systems property that emerges from interactions among multiple developmental processes rather than as an independent biological variable.

7.3 Methodological Considerations and Limitations

Several limitations warrant consideration. First, empirical evidence directly linking primitive reflex persistence to hemispheric asymmetry and oscillatory coherence remains limited [15,22,49,51,94]. While the present developmental timing perspective generates empirically investigable questions, systematic longitudinal studies integrating neural timing measures, reflex profiles, and motor-social coupling metrics are needed. Second, measurement precision presents challenges: reflex scoring requires standardized protocols, dyadic synchrony metrics demand high-resolution temporal data, and neural timing indices must be developmentally calibrated [22,28,42,79,102]. Third, causal inference will require carefully designed longitudinal and interventional studies to distinguish primary timing effects from secondary adaptations [75,76,98].

Additionally, ASD is etiologically heterogeneous [1,2,10,38,52,97]. Genetic, epigenetic, and environmental factors may influence neural maturation through diverse mechanisms. The developmental timing perspective does not claim to supersede genetic or connectivity-based accounts but rather to provide a systems-level framework within which such influences may operate. Future work must examine how specific biological pathways interact with hemispheric timing and motor-social coupling dynamics. It is also possible that some developmental relationships proposed here will prove to be weaker, indirect, or developmentally specific than currently hypothesized. Such findings would refine rather than invalidate the broader objective of understanding how developmental timing contributes to heterogeneous developmental trajectories.

7.4 Directions for Future Research

Prospective longitudinal studies beginning in early infancy may help clarify how neural timing, motor organization, reflex development, and dyadic interaction patterns relate across development [27,72,80,98,102]. Multi-method approaches integrating neural, behavioral, and interaction-based measures could help characterize developmental variability across infancy and childhood. Longitudinal designs may also support examination of developmental periods during which neural timing and motor coordination are more strongly associated with later developmental trajectories [1,48,82,97]. An important objective of such studies will be to evaluate the specific developmental predictions generated by the present framework, including proposed relationships among neural timing, motor organization, reflex development, and dyadic interaction across development. Equally important, such studies will be to determine whether the developmental relationships proposed here are consistently observed across independent cohorts and diverse developmental contexts. Particularly informative will be studies that simultaneously measure neural timing, motor organization, dyadic synchrony, and developmental outcomes within the same cohorts, allowing the temporal ordering of proposed developmental relationships to be evaluated directly.

Advanced modeling approaches, including growth mixture modeling and dynamic systems analysis, may reveal distinct timing profiles within ASD populations. Such stratification could improve understanding of heterogeneity and inform further conceptual investigation. Importantly, future research should remain cautious in translating timing markers into clinical screening tools until predictive validity is established across diverse populations [2,27,98]. These approaches are also consistent with broader efforts aimed at improving the early identification of ASD through prospective developmental surveillance and longitudinal monitoring [116].

A potentially valuable direction for future work involves the development of integrated longitudinal datasets combining neural timing measures, motor kinematics, reflex development, and dyadic interaction measures within the same infant cohorts. Such multimodal approaches may help clarify how neural timing, motor organization, and social interaction relate across development while improving understanding of developmental variability within ASD trajectories.

7.5 Broader Conceptual Contributions

Beyond ASD, the present developmental timing perspective highlights the importance of considering motor development, neural coordination, and interpersonal interaction together within broader developmental models [15,31,47,48,49,62,69,80]. The framework emphasizes how neural timing, motor organization, and dyadic interaction may contribute to embodied aspects of social development across infancy and childhood. Beyond ASD specifically, it illustrates the potential value of integrating neural, motor, and interpersonal developmental processes within longitudinal developmental neuroscience research. More broadly, the present framework illustrates how developmental neuroscience may benefit from organizing complex neurodevelopmental phenomena around interactions among timing, coordination, and reciprocal developmental processes rather than around isolated functional domains.

8. Conclusion

ASD involves developmental variability across neural, motor, and social domains [1,2,27,97,98]. The present article explores the possibility that variation in hemispheric specialization, interhemispheric coordination, motor organization, and dyadic interaction timing may be associated with differences in early developmental trajectories across infancy and childhood. Rather than proposing a deterministic causal sequence, the framework advanced here is intended as a conceptual developmental perspective that organizes existing findings into a set of empirically investigable and longitudinally testable developmental relationships.

Ultimately, the contribution of the present article lies not in proposing a single explanation for autism but in offering a coherent developmental architecture through which diverse findings concerning neural maturation, motor organization, and social interaction can be interpreted within a common longitudinal perspective. Whether this developmental timing framework proves to be broadly explanatory or requires substantial revision will depend on prospective empirical investigation. Its principal value therefore lies in generating explicit, falsifiable hypotheses capable of advancing understanding of the heterogeneous developmental pathways associated with ASD.

Author Contributions

GL: Conceptualization, Formal analysis, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing—Original Draft Preparation, Writing—Review & Editing. RM: Conceptualization, Formal analysis, Writing—Original Draft Preparation, Writing—Review & Editing. Both authors read and approved the final manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflicts of interest. Gerry Leisman is serving as one of the Editorial Board members of this journal. We declare that Gerry Leisman had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to Bettina Platt.

Declaration of AI and AI-Assisted Technologies in the Writing Process

Generative AI was not used in the writing, interpretation, or scientific content of this manuscript. It was used solely to assist in preparing graphical material and identifying editorial revisions.

References

[1] Adolphs R. The social brain: neural basis of social knowledge. Annual Review of Psychology. 2009; 60: 693–716. https://doi.org/10.1146/annurev.psych.60.110707.163514

[2] Adolph KE, Franchak JM. The development of motor behavior. Wiley Interdisciplinary Reviews. Cognitive Science. 2017; 8: e1430. https://doi.org/10.1002/wcs.1430

[3] Leisman G, Alfasi R, Meiron O, D'Angiulli A. The Inverted U: Exploring the Interconnectedness of Movement and Cognitive Function Across the Lifespan. Wiley Interdisciplinary Reviews. Cognitive Science. 2026; 17: e70020. https://doi.org/10.1002/wcs.70020

[4] Adolph KE, Robinson SR. In Lerner RM (ed.) Handbook of Child Psychology and Developmental Science (pp. 1–45). 7th edn. Wiley: New York. 2015. https://doi.org/10.1002/9781118963418.childpsy204

[5] American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders. 5th edn. American Psychiatric Association: Washington DC. 2013.

[6] Begum Ali J, Charman T, Johnson MH, Jones EJH, BASIS/STAARS Team. Early Motor Differences in Infants at Elevated Likelihood of Autism Spectrum Disorder and/or Attention Deficit Hyperactivity Disorder. Journal of Autism and Developmental Disorders. 2020; 50: 4367–4384. https://doi.org/10.1007/s10803-020-04489-1

[7] Bethlehem RAI, Seidlitz J, White SR, Vogel JW, Anderson KM, Adamson C, et al. Brain charts for the human lifespan. Nature. 2022; 604: 525–533. https://doi.org/10.1038/s41586-022-04554-y

[8] Berger A, Posner MI. Beyond Infant's Looking: The Neural Basis for Infant Prediction Errors. Perspectives on Psychological Science: a Journal of the Association for Psychological Science. 2023; 18: 664–674. https://doi.org/10.1177/17456916221112918

[9] Bhat AN, Landa RJ, Galloway JC. Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. Physical Therapy. 2011; 91: 1116–1129. https://doi.org/10.2522/ptj.20100294
[10] Bourgeron T. From the genetic architecture to synaptic plasticity in autism spectrum disorder. Nature Reviews. Neuroscience. 2015; 16: 551–563. https://doi.org/10.1038/nrn3992
[11] Brian JA, Bryson SE, Zwaigenbaum L. Autism spectrum disorder in infancy: developmental considerations in treatment targets. Current Opinion in Neurology. 2015; 28: 117–123. https://doi.org/10.1097/WCO.0000000000000182
[12] Buzsáki G. Rhythms of the Brain. Oxford University Press: Oxford. 2006.
[13] Elsabbagh M, Johnson MH. Autism and the Social Brain: The First-Year Puzzle. Biological Psychiatry. 2016; 80: 94–99. https://doi.org/10.1016/j.biopsych.2016.02.019
[14] Buzsáki G, Draguhn A. Neuronal oscillations in cortical networks. Science (New York, N.Y.). 2004; 304: 1926–1929. https://doi.org/10.1126/science.1099745
[15] Cao Z, Zhao Z, Zhu Q, Shen Y, Shen Y, Li M, et al. Developmental changes in connectivity-based parcellation in typical cortical areas during early life. Cerebral Cortex (New York, N.Y.: 1991). 2025; 35: bhae468. https://doi.org/10.1093/cercor/bhae468
[16] Cannon J, O'Brien AM, Bungert L, Sinha P. Prediction in Autism Spectrum Disorder: A Systematic Review of Empirical Evidence. Autism Research: Official Journal of the International Society for Autism Research. 2021; 14: 604–630. https://doi.org/10.1002/aur.2482
[17] Cariani P, Baker JM. Time Is of the Essence: Neural Codes, Synchronies, Oscillations, Architectures. Frontiers in Computational Neuroscience. 2022; 16: 898829. https://doi.org/10.3389/fncom.2022.898829
[18] Clark A. Whatever next? Predictive brains, situated agents, and the future of cognitive science. The Behavioral and Brain Sciences. 2013; 36: 181–204. https://doi.org/10.1017/S0140525X12000477
[19] Constantino JN, Charman T. Diagnosis of autism spectrum disorder: reconciling the syndrome, its diverse origins, and variation in expression. The Lancet. Neurology. 2016; 15: 279–291. https://doi.org/10.1016/S1474-4422(15)00151-9
[20] de Kovel CGF, Lisgo SN, Fisher SE, Francks C. Subtle left-right asymmetry of gene expression profiles in embryonic and foetal human brains. Scientific Reports. 2018; 8: 12606. https://doi.org/10.1038/s41598-018-29496-2
[21] Delafield-Butt JT, Trevarthen C. The ontogenesis of narrative: from moving to meaning. Frontiers in Psychology. 2015; 6: 1157. https://doi.org/10.3389/fpsyg.2015.01157
[22] Dubois J, Poupon C, Thirion B, Simonnet H, Kulikova S, Leroy F, et al. Exploring the Early Organization and Maturation of Linguistic Pathways in the Human Infant Brain. Cerebral Cortex (New York, N.Y.: 1991). 2016; 26: 2283–2298. https://doi.org/10.1093/cercor/bhv082
[23] Dubois J, Lefèvre J, Angleys H, Leroy F, Fischer C, Lebenberg J, et al. The dynamics of cortical folding waves and prematurity-related deviations revealed by spatial and spectral analysis of gyrification. NeuroImage. 2019; 185: 934–946. https://doi.org/10.1016/j.neuroimage.2018.03.005
[24] Dumas G, Nadel J, Soussignan R, Martinerie J, Garnero L. Inter-brain synchronization during social interaction. PloS One. 2010; 5: e12166. https://doi.org/10.1371/journal.pone.0012166
[25] Einspieler C, Prechtl HFR. Prechtl's assessment of general movements: a diagnostic tool for the functional assessment of the young nervous system. Mental Retardation and Developmental Disabilities Research Reviews. 2005; 11: 61–67. https://doi.org/10.1002/mrdd.20051
[26] Einspieler C, Bos AF, Libertus ME, Marschik PB. The General Movement Assessment Helps Us to Identify Preterm Infants at Risk for Cognitive Dysfunction. Frontiers in Psychology. 2016; 7: 406. https://doi.org/10.3389/fpsyg.2016.00406
[27] Einspieler C, Prayer D, Marschik PB. Fetal movements: the origin of human behaviour. Developmental Medicine and Child Neurology. 2021; 63: 1142–1148. https://doi.org/10.1111/dmcn.14918
[28] Endevelt-Shapira Y, Feldman R. Mother-Infant Brain-to-Brain Synchrony Patterns Reflect Caregiving Profiles. Biology. 2023; 12: 284. https://doi.org/10.3390/biology12020284
[29] Engel AK, Fries P, Singer W. Dynamic predictions: oscillations and synchrony in top-down processing. Nature Reviews. Neuroscience. 2001; 2: 704–716. https://doi.org/10.1038/35094565
[30] Estes A, Zwaigenbaum L, Gu H, St John T, Paterson S, Elison JT, et al. Behavioral, cognitive, and adaptive development in infants with autism spectrum disorder in the first 2 years of life. Journal of Neurodevelopmental Disorders. 2015; 7: 24. https://doi.org/10.1186/s11689-015-9117-6
[31] Feldman R. Parent-infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2007; 48: 329–354. https://doi.org/10.1111/j.1469-7610.2006.01701.x
[32] Feldman R. The Neurobiology of Human Attachments. Trends in Cognitive Sciences. 2017; 21: 80–99. https://doi.org/10.1016/j.tics.2016.11.007
[33] Feldman R. The adaptive human parental brain: implications for children's social development. Trends in Neurosciences. 2015; 38: 387–399. https://doi.org/10.1016/j.tins.2015.04.004
[34] Foulkes L, Blakemore SJ. Studying individual differences in human adolescent brain development. Nature Neuroscience. 2018; 21: 315–323. https://doi.org/10.1038/s41593-018-0078-4
[35] Franchak JM, Adolph KE. An update of the development of motor behavior. Wiley Interdisciplinary Reviews. Cognitive Science. 2024; 15: e1682. https://doi.org/10.1002/wcs.1682
[36] Frankenhuis WE, Walasek N. Modeling the evolution of sensitive periods. Developmental Cognitive Neuroscience. 2020; 41: 100715. https://doi.org/10.1016/j.dcn.2019.100715
[37] Fries P. A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. Trends in Cognitive Sciences. 2005; 9: 474–480. https://doi.org/10.1016/j.tics.2005.08.011
[38] Fries P. Rhythms for Cognition: Communication through Coherence. Neuron. 2015; 88: 220–235. https://doi.org/10.1016/j.neuron.2015.09.034
[39] Friston K. The free-energy principle: a unified brain theory? Nature Reviews. Neuroscience. 2010; 11: 127–138. https://doi.org/10.1038/nrn2787
[40] Giraud A, Stephens CM, Boylan GB, Walsh BH. The impact of perinatal inflammation on the electroencephalogram in preterm infants: a systematic review. Pediatric Research. 2022; 92: 32–39. https://doi.org/10.1038/s41390-022-02038-3
[41] Grossmann T. The development of social brain functions in infancy. Psychological Bulletin. 2015; 141: 1266–1287. https://doi.org/10.1037/bul0000002
[42] Grossmann T, Wood A. Variability in the expression and perception of positive affect in human infancy. Social Cognitive and Affective Neuroscience. 2023; 18: nsad049. https://doi.org/10.1093/scan/nsad049
[43] Grossmann T. Social Perception in the Infant Brain and Its Link to Social Behavior. Journal of Cognitive Neuroscience. 2024; 36: 1341–1349. https://doi.org/10.1162/jocn_a_02165
[44] Hadders-Algra M. Early diagnosis and early intervention in cerebral palsy. Frontiers in Neurology. 2014; 5: 185. https://doi.org/10.3389/fneur.2014.00185

[45] Singer W. Neuronal synchrony: a versatile code for the definition of relations? Neuron. 1999; 24: 49–65. https://doi.org/10.1016/s0896-6273(00)80821-1
[46] Hadders-Algra M. Early human motor development: From variation to the ability to vary and adapt. Neuroscience and Biobehavioral Reviews. 2018; 90: 411–427. https://doi.org/10.1016/j.neubiorev.2018.05.009
[47] Hadders-Algra M. Early Diagnostics and Early Intervention in Neurodevelopmental Disorders-Age-Dependent Challenges and Opportunities. Journal of Clinical Medicine. 2021; 10: 861. https://doi.org/10.3390/jcm10040861
[48] Hadders-Algra M. Emerging signs of autism spectrum disorder in infancy: Putative neural substrate. Developmental Medicine and Child Neurology. 2022; 64: 1344–1350. https://doi.org/10.1111/dmcn.15333
[49] Havdahl A, Niarchou M, Starnawska A, Uddin M, van der Merwe C, Warrier V. Genetic contributions to autism spectrum disorder. Psychological Medicine. 2021; 51: 2260–2273. https://doi.org/10.1017/S0033291721000192
[50] Happé F, Frith U. Annual Research Review: Looking back to look forward - changes in the concept of autism and implications for future research. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2020; 61: 218–232. https://doi.org/10.1111/jcpp.13176
[51] Hazlett HC, Gu H, Munsell BC, Kim SH, Styner M, Wolff JJ, et al. Early brain development in infants at high risk for autism spectrum disorder. Nature. 2017; 542: 348–351. https://doi.org/10.1038/nature21369
[52] Hohwy J. The Predictive Mind. Oxford University Press: Oxford. 2013.
[53] Iverson JM. Developing language in a developing body: the relationship between motor development and language development. Journal of Child Language. 2010; 37: 229–261. https://doi.org/10.1017/S0305000909990432
[54] Johnson MH, Grossmann T, Cohen Kadosh K. Mapping functional brain development: Building a social brain through interactive specialization. Developmental Psychology. 2009; 45: 151–159. https://doi.org/10.1037/a0014548
[55] Geschwind DH. Genetics of autism spectrum disorders. Trends in Cognitive Sciences. 2011; 15: 409–416. https://doi.org/10.1016/j.tics.2011.07.003
[56] Lord C, Brugha TS, Charman T, Cusack J, Dumas G, Frazier T, et al. Autism spectrum disorder. Nature Reviews. Disease Primers. 2020; 6: 5. https://doi.org/10.1038/s41572-019-0138-4
[57] Karlebach G, Francks C. Lateralization of gene expression in human language cortex. Cortex; a Journal Devoted to the Study of the Nervous System and Behavior. 2015; 67: 30–36. https://doi.org/10.1016/j.cortex.2015.03.003
[58] Sha Z, Schijven D, Carrion-Castillo A, Joliot M, Mazoyer B, Fisher SE, et al. The genetic architecture of structural left-right asymmetry of the human brain. Nature Human Behaviour. 2021; 5: 1226–1239. https://doi.org/10.1038/s41562-021-01069-w
[59] Sha Z, van Rooij D, Anagnostou E, Arango C, Auzias G, Behrmann M, et al. Subtly altered topological asymmetry of brain structural covariance networks in autism spectrum disorder across 43 datasets from the ENIGMA consortium. Molecular Psychiatry. 2022; 27: 2114–2125. https://doi.org/10.1038/s41380-022-01452-7
[60] Gao W, Lin W, Grewen K, Gilmore JH. Functional Connectivity of the Infant Human Brain: Plastic and Modifiable. The Neuroscientist: a Review Journal Bringing Neurobiology, Neurology and Psychiatry. 2017; 23: 169–184. https://doi.org/10.1177/1073858416635986
[61] Gilmore JH, Knickmeyer RC, Gao W. Imaging structural and functional brain development in early childhood. Nature Reviews. Neuroscience. 2018; 19: 123–137. https://doi.org/10.1038/nrn.2018.1
[62] van den Heuvel MP, Kersbergen KJ, de Reus MA, Keunen K, Kahn RS, Groenendaal F, et al. The Neonatal Connectome During Preterm Brain Development. Cerebral Cortex (New York, N.Y.: 1991). 2015; 25: 3000–3013. https://doi.org/10.1093/cercor/bhu095
[63] Zhao T, Ouyang M, Shou XJ, Zhang S, Ju J, Liao X, et al. Hierarchical maturation of structural brain connectomes from birth to childhood. Nature Communications. 2026; 17: 1945. https://doi.org/10.1038/s41467-026-68704-w
[64] Nguyen T, Abney DH, Salamander D, Bertenthal BI, Hoehl S. Proximity and touch are associated with neural but not physiological synchrony in naturalistic mother-infant interactions. NeuroImage. 2021; 244: 118599. https://doi.org/10.1016/j.neuroimage.2021.118599
[65] Seymour RA, Rippon G, Kessler K. The Detection of Phase Amplitude Coupling during Sensory Processing. Frontiers in Neuroscience. 2017; 11: 487. https://doi.org/10.3389/fnins.2017.00487
[66] Thomason ME, Hendrix CL. Prenatal Stress and Maternal Role in Neurodevelopment. Annual Review of Developmental Psychology. 2024; 6: 87–107. https://doi.org/10.1146/annurev-devpsych-120321-011905
[67] Karmiloff-Smith A. Development itself is the key to understanding developmental disorders. Trends in Cognitive Sciences. 1998; 2: 389–398. https://doi.org/10.1016/s1364-6613(98)01230-3
[68] Johnson MH, Charman T, Pickles A, Jones EJH. Annual Research Review: Anterior Modifiers in the Emergence of Neurodevelopmental Disorders (AMEND)-a systems neuroscience approach to common developmental disorders. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2021; 62: 610–630. https://doi.org/10.1111/jcpp.13372
[69] Kievit RA, Brandmaier AM, Ziegler G, van Harmelen AL, de Mooij SMM, Moutoussis M, et al. Developmental cognitive neuroscience using latent change score models: A tutorial and applications. Developmental Cognitive Neuroscience. 2018; 33: 99–117. https://doi.org/10.1016/j.dcn.2017.11.007
[70] King KM, Littlefield AK, McCabe CJ, Mills KL, Flournoy J, Chassin L. Longitudinal modeling in developmental neuroimaging research: Common challenges, and solutions from developmental psychology. Developmental Cognitive Neuroscience. 2018; 33: 54–72. https://doi.org/10.1016/j.dcn.2017.11.009
[71] Konvalinka I, Roepstorff A. The two-brain approach: how can mutually interacting brains teach us something about social interaction? Frontiers in Human Neuroscience. 2012; 6: 215. https://doi.org/10.3389/fnhum.2012.00215
[72] Koster-Hale J, Bedny M, Saxe R. Thinking about seeing: perceptual sources of knowledge are encoded in the theory of mind brain regions of sighted and blind adults. Cognition. 2014; 133: 65–78. https://doi.org/10.1016/j.cognition.2014.04.006
[73] Landa RJ, Gross AL, Stuart EA, Bauman M. Latent class analysis of early developmental trajectory in baby siblings of children with autism. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2012; 53: 986–996. https://doi.org/10.1111/j.1469-7610.2012.02558.x
[74] Leisman G, Melillo R, Melillo T. Prefrontal functional connectivities in autism spectrum disorders: A connectopathic disorder affecting movement, interoception, and cognition. Brain Research Bulletin. 2023; 198: 65–76. https://doi.org/10.1016/j.brainresbull.2023.04.004
[75] Leonard HC, Hill EL. Review: The impact of motor development on typical and atypical social cognition and language: a systematic review. Child and Adolescent Mental Health. 2014; 19: 163–170. https://doi.org/10.1111/camh.12055
[76] Libertus K, Sheperd KA, Ross SW, Landa RJ. Limited fine

motor and grasping skills in 6-month-old infants at high risk for autism. Child Development. 2014; 85: 2218–2231. https://doi.org/10.1111/cdev.12262

[77] Karolis VR, Corbetta M, Thiebaut de Schotten M. The architecture of functional lateralisation and its relationship to callosal connectivity in the human brain. Nature Communications. 2019; 10: 1417. https://doi.org/10.1038/s41467-019-09344-1

[78] Libertus K, Violi DA. Sit to Talk: Relation between Motor Skills and Language Development in Infancy. Frontiers in Psychology. 2016; 7: 475. https://doi.org/10.3389/fpsyg.2016.00475

[79] Libertus K, Hauf P. Editorial: Motor Skills and Their Foundational Role for Perceptual, Social, and Cognitive Development. Frontiers in Psychology. 2017; 8: 301. https://doi.org/10.3389/fpsyg.2017.00301

[80] Liu G, Huo E, Liu H, Jia G, Zhi Y, Dong Q, et al. Development and emergence of functional network asymmetry in 3- to 9-month-old infants. Cortex; a Journal Devoted to the Study of the Nervous System and Behavior. 2022; 154: 390–404. https://doi.org/10.1016/j.cortex.2022.06.009

[81] McArdle JJ. Latent variable modeling of differences and changes with longitudinal data. Annual Review of Psychology. 2009; 60: 577–605. https://doi.org/10.1146/annurev.psych.60.110707.163612

[82] Muthén B. Latent variable analysis: Growth mixture modeling and related techniques for longitudinal data. The SAGE Handbook of Quantitative Methodology for the Social Sciences (pp. 345–368). SAGE Publications: California. 2004.

[83] Morgan C, Fetters L, Adde L, Badawi N, Bancale A, Boyd RN, et al. Early Intervention for Children Aged 0 to 2 Years With or at High Risk of Cerebral Palsy: International Clinical Practice Guideline Based on Systematic Reviews. JAMA Pediatrics. 2021; 175: 846–858. https://doi.org/10.1001/jamapediatrics.2021.0878

[84] Mundy P. Autism and Joint Attention: Development, Neuroscience, and Clinical Fundamentals. Guilford Press: New York. 2018.

[85] Nagin DS. Group-Based Modeling of Development. Harvard University Press: Cambridge. 2005.

[86] Ocklenburg S, Güntürkün O. The Lateralized Brain: The Neuroscience and Evolution of Hemispheric Asymmetries. Academic Press: London. 2018. https://doi.org/10.1016/C2014-0-03755-0

[87] Örtqvist M, Einspieler C, Ådén U. Early prediction of neurodevelopmental outcomes at 12 years in children born extremely preterm. Pediatric Research. 2022; 91: 1522–1529. https://doi.org/10.1038/s41390-021-01564-w

[88] Ozonoff S, Young GS, Landa RJ, Brian J, Bryson S, Charman T, et al. Diagnostic stability in young children at risk for autism spectrum disorder: a baby siblings research consortium study. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2015; 56: 988–998. https://doi.org/10.1111/jcpp.12421

[89] Palmer CJ, Lawson RP, Hohwy J. Bayesian approaches to autism: Towards volatility, action, and behavior. Psychological Bulletin. 2017; 143: 521–542. https://doi.org/10.1037/bul0000097

[90] Papadatou-Pastou M, Ntolka E, Schmitz J, Martin M, Munafò MR, Ocklenburg S, et al. Human handedness: A meta-analysis. Psychological Bulletin. 2020; 146: 481–524. https://doi.org/10.1037/bul0000229

[91] Patterson JW, Armstrong V, Duku E, Richard A, Franchini M, Brian J, et al. Early trajectories of motor skills in infant siblings of children with autism spectrum disorder. Autism Research: Official Journal of the International Society for Autism Research. 2022; 15: 481–492. https://doi.org/10.1002/aur.2641

[92] Sinha P, Kjelgaard MM, Gandhi TK, Tsourides K, Cardinaux AL, Pantazis D, et al. Autism as a disorder of prediction. Proceedings of the National Academy of Sciences of the United States of America. 2014; 111: 15220–15225. https://doi.org/10.1073/pnas.1416797111

[93] Pellicano E, Burr D. When the world becomes 'too real': a Bayesian explanation of autistic perception. Trends in Cognitive Sciences. 2012; 16: 504–510. https://doi.org/10.1016/j.tics.2012.08.009

[94] Pelphrey KA, Shultz S, Hudac CM, Vander Wyk BC. Research review: Constraining heterogeneity: the social brain and its development in autism spectrum disorder. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2011; 52: 631–644. https://doi.org/10.1111/j.1469-7610.2010.02349.x

[95] Postema MC, Hoogman M, Ambrosino S, Asherson P, Banaschewski T, Bandeira CE, et al. Analysis of structural brain asymmetries in attention-deficit/hyperactivity disorder in 39 datasets. Journal of Child Psychology and Psychiatry, and Allied Disciplines. 2021; 62: 1202–1219. https://doi.org/10.1111/jcpp.13396

[96] Prechtl HF (ed.) Continuity of Neural Functions from Prenatal to Postnatal Life. Cambridge University Press: Cambridge. 1984.

[97] Reynolds JE, Long X, Grohs MN, Dewey D, Lebel C. Structural and functional asymmetry of the language network emerge in early childhood. Developmental Cognitive Neuroscience. 2019; 39: 100682. https://doi.org/10.1016/j.dcn.2019.100682

[98] Richardson MJ, Marsh KL, Schmidt RC. Effects of visual and verbal interaction on unintentional interpersonal coordination. Journal of Experimental Psychology. Human Perception and Performance. 2005; 31: 62–79. https://doi.org/10.1037/0096-1523.31.1.62

[99] Trevarthen C, Delafield-Butt JT. Autism as a developmental disorder in intentional movement and affective engagement. Frontiers in Integrative Neuroscience. 2013; 7: 49. https://doi.org/10.3389/fnint.2013.00049

[100] Van de Cruys S, Evers K, Van der Hallen R, Van Eylen L, Boets B, de-Wit L, et al. Precise minds in uncertain worlds: predictive coding in autism. Psychological Review. 2014; 121: 649–675. https://doi.org/10.1037/a0037665

[101] van den Heuvel MP, Scholtens LH, van der Burgh HK, Agosta F, Alloza C, Arango C, et al. 10Kin1day: A Bottom-Up Neuroimaging Initiative. Frontiers in Neurology. 2019; 10: 425. https://doi.org/10.3389/fneur.2019.00425

[102] Vingerhoets G, Gerrits R, Verhelst H. Atypical brain asymmetry in human situs inversus: gut feeling or real evidence? Symmetry. 2021; 13: 695. https://doi.org/10.3390/sym13040695

[103] Voytek B, Knight RT. Dynamic network communication as a unifying neural basis for cognition, development, aging, and disease. Biological Psychiatry. 2015; 77: 1089–1097. https://doi.org/10.1016/j.biopsych.2015.04.016

[104] Wass SV, Whitehorn M, Marriott Haresign I, Phillips E, Leong V. Interpersonal Neural Entrainment during Early Social Interaction. Trends in Cognitive Sciences. 2020; 24: 329–342. https://doi.org/10.1016/j.tics.2020.01.006

[105] Wass SV, Phillips EAM, Haresign IM, Amadó MP, Goupil L. Contingency and synchrony: Interactional pathways toward attentional control and intentional communication. Annual Review of Developmental Psychology. 2024; 6: 63–85. https://doi.org/10.1146/annurev-devpsych-010923-110459

[106] West KL, Leezenbaum NB, Northrup JB, Iverson JM. The Relation Between Walking and Language in Infant Siblings of Children With Autism Spectrum Disorder. Child Development. 2019; 90: e356–e372. https://doi.org/10.1111/cdev.12980

[107] Zhang F, Moerman F, Niu H, Warreyn P, Roeyers H. Atypical brain network development of infants at elevated likelihood for autism spectrum disorder during the first year of life. Autism Research: Official Journal of the International Society for Autism Research. 2022; 15: 2223–2237. https://doi.org/10.

1002/aur.2827
[108] Thapar A, Cooper M, Rutter M. Neurodevelopmental disorders. The Lancet. Psychiatry. 2017; 4: 339–346. https://doi.org/10.1016/S2215-0366(16)30376-5
[109] Thelen E, Smith LB. A Dynamic Systems Approach to the Development of Cognition and Action. The MIT Press: Cambridge. 1994. https://doi.org/10.7551/mitpress/2524.001.0001
[110] Sun T, Walsh CA. Molecular approaches to brain asymmetry and handedness. Nature Reviews. Neuroscience. 2006; 7: 655–662. https://doi.org/10.1038/nrn1930
[111] Smith DK, Libertus K. The Early Motor Questionnaire revisited: Starting points, standardized scores, and stability. Journal of Experimental Child Psychology. 2022; 223: 105492. https://doi.org/10.1016/j.jecp.2022.105492
[112] Spittle AJ, Marschik PB, Adde L, Badawi N, Byrne R, Bos AF, et al. Towards universal early screening for cerebral palsy: a roadmap for automated General Movements Assessment. EClinicalMedicine. 2025; 86: 103379. https://doi.org/10.1016/j.eclinm.2025.103379
[113] Sacrey LAR, Bryson S, Zwaigenbaum L, Brian J, Smith IM, Roberts W, et al. The Autism Parent Screen for Infants: Predicting risk of autism spectrum disorder based on parent-reported behavior observed at 6-24 months of age. Autism: the International Journal of Research and Practice. 2018; 22: 322–334. https://doi.org/10.1177/1362361316675120
[114] Smith LB, Thelen E. Development as a dynamic system. Trends in Cognitive Sciences. 2003; 7: 343–348. https://doi.org/10.1016/s1364-6613(03)00156-6
[115] Spencer JP, Perone S, Buss AT. Twenty years and going strong: A dynamic systems revolution in motor and cognitive development. Child Development Perspectives. 2011; 5: 260–266. https://doi.org/10.1111/j.1750-8606.2011.00194.x
[116] Zwaigenbaum L, Bauman ML, Choueiri R, Fein D, Kasari C, Pierce K, et al. Early Identification and Interventions for Autism Spectrum Disorder: Executive Summary. Pediatrics. 2015; 136: S1–S9. https://doi.org/10.1542/peds.2014-3667B