Diffusion Neuroimaging of Speech Acquisition in Infants

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How white matter maturation supports speech — an emergent property of integrated human brain networks — remains unclear. Leveraging the Baby Connectome Project, the largest longitudinal infant neuroimaging and behavioral dataset available, we characterized white matter maturation across five major pathways (motor, auditory, visual, ventral language, and dorsal language) from

birth to 24 months and correlated these trajectories with emerging motor, perceptual, and cognitive skills. We found that dorsal language tracts, initially immature at birth, rapidly matured in parallel with motor tracts, reaching maturity levels comparable to primary sensory tracts by approximately 24 months. Our data suggest two potential mechanisms: (*i*) *Widespread brain–behavior interdependencies*, wherein both ventral and dorsal tracts correlated significantly not only with speech but also broadly with other behavioral domains, and advanced speech skills were associated across multiple tracts; and (*ii*) *a nonlinear developmental cascade*, in which early gross motor skills promoted subsequent social interactions thus influencing later speech development, meanwhile, early social interactions fostered subsequent fine motor refinement indirectly influencing later speech development. Our data thus portray early brain networks as a malleable, integrative scaffold, coordinating information across motor, auditory, and visual systems into a coherent whole immediately after birth. Collectively, these findings reveal speech acquisition as an emergent property reflecting a fundamental integrative principle of early brain development.

Infants are exceptional learners, rapidly adapting — both physiologically and mentally — to novel environments, as vividly illustrated by their immediate transition from aquatic to terrestrial life at birth (*1, 2*). This transition is marked by the infant's first cry, signaling the successful pulmonary adaptation to breathing air (*3, 4*). Initially, newborns may not clearly associate their cries with self-generated vocal actions (*5*), and caregivers typically find these early vocalizations ambiguous and challenging to interpret. Over time, sustained reciprocal interactions with caregivers help infants overcome perceptual opacity (*6, 7*), progressively shaping neural circuits critical for acquiring increasingly complex cognitive skills, notably speech (*8, 9, 10*).

Speech represents one of the most complex cognitive capabilities developed during infancy (*11*), highlighting infants' extraordinary *learning efficiency*, surpassing that observed in adults, other animals, and artificial intelligence systems (*12, 13, 14*). Contemporary perspectives commonly

attribute the initial rapid learning to neonatal imitation, traditionally viewed as an innate ability to directly copy observed gestures without requiring postnatal experience (*15, 5*). Classical evidence supporting this view includes neonatal imitation of tongue protrusion (*16, 17*). This imitation is perceptually opaque because newborns lack direct visual experiences of their own facial gestures (*18*). Despite its widespread acceptance (*19*), this nativist interpretation remains controversial due to inconsistent replication of neonatal imitation (*20, 21, 17*) and incomplete understanding of underlying neural mechanisms. Recent functional neuroimaging studies in adults and older infants consistently suggest involvement of the mirror neuron system (*22, 23*), responding to both sensory and motor stimuli (*24, 25, 26*). However, how sensory and motor systems integrate during early infancy to collectively support speech acquisition remains unclear.

Speech processing has recently been conceptualized as an emergent property of the human brain connectome (*27, 28*). Long-range white matter connections integrate incomplete information across functionally segregated brain networks, collectively contributing to intrinsic speech processing (*29, 30, 31*). This complexity makes it challenging to understand speech acquisition by examining individual brain systems in isolation. Moreover, infant brains undergo dramatic structural development, involving initial proliferation and subsequent pruning of neural connections, ultimately forming sparse yet efficient networks (*32, 33*), characterized by *network efficiency* (*34, 35*). Given this rapid structural maturation, precisely identifying when infants' processing capacities shift from simple to complex remains difficult (*36, 37*), especially considering substantial individual variability. Despite accumulating evidence on rapid neural and behavioral changes during early infancy (*38, 39, 9, 40*), a holistic view of the early integrative learning mechanisms remains scarce (*41, 27*).

White matter tracts enable extensive integration across brain regions, necessarily supporting network functions (*28*). Microstructural attributes of white matter critically influence neural signal transmission speed and oscillatory synchronization, exhibiting plasticity continuously shaped by daily experiences (*42, 43, 44*). Diffusion MRI (dMRI) provides a unique non-invasive longitudinal opportunity to assess experience-driven white matter changes, potentially clarifying mechanisms underlying network and learning efficiency (*29, 45*). Current research largely focuses on ventral and dorsal language pathways (*27, 46*), leaving unclear how these language pathways co-develop with motor, auditory, and visual tracts. Additionally, comprehensive tract-behavior correlations during

early development remain scarce (*47*). Both limitations primarily stem from challenges in collecting reliable neuroimaing and behavioral data in infants. These challenges are further compounded by difficulties in accurately extracting white matter tracts across multiple brain systems during the first 24 months of life, a period characterized by substantial spatiotemporal variability in neuroimaing data (*48, 49*). Therefore, the full methodological potential of dMRI for clarifying neural mechanisms underlying early speech acquisition has not been fully realized.

Emergence of sensory-motor interactions in speech acquisition

Recent research emphasizes sensory-motor interactions as fundamental to early learning (*41, 50, 40*). Evidence increasingly suggests that speech perception extends beyond the auditory domain and critically involves the motor system (*51, 52, 53, 54, 55*). Diverse neuroimaging techniques — electroencephalography or event-related potentials (EEG or ERPs) (*56*), NIRS (*57*), functional magnetic resonance imaging (fMRI) (*58*), MEG (*22*), and dMRI (*59*) — have been employed to characterize the neural basis of these sensory-motor interactions.

Non-invasive neuroimaging techniques have been widely utilized to investigate speech acquisition (*9, 45*). These techniques are particularly valuable in detecting subtle neural responses to speech stimuli, characterizing speech-related neural activity as early as the prenatal period (*60, 61*). Prenatal motor and auditory development, involving synaptogenesis and myelination, is well-documented through histological analyses and structural MRI (sMRI) studies (*62, 63, 64, 65*). The prenatal brain matures sufficiently to enable basic motor responses to acoustic stimuli, such as fetal movements and heart rate changes (*66, 67, 68, 69*). Fetal MEG and fMRI studies clearly demonstrate activation of auditory cortices in response to external acoustic stimuli, providing direct neural evidence of fetal auditory processing (*70, 71*). Additionally, fetal dMRI studies have identified major speech-related white matter tracts, such as arcuate fasciculus (AF) and superior longitudinal fasciculus (SLF), connecting auditory cortices to Broca's area (*72, 73*).

Prenatal interaction patterns — marked by fetal motor responses to auditory stimuli — reveal an asymmetric communication mode, in which acoustic input elicits motor output, suggesting early functional integration between auditory and motor systems (*74*). This asymmetry persists postnatally: newborns initially respond to sensory stimuli through voluntary motor behaviors, such

as limb movements and crying, which gradually transition into to gesture- and then vocal-based communication (*75, 76, 77, 78*). These early sensorimotor asymmetries thus serve as foundational precursors to explicit speech-based interactions (*61*).

After birth, infants gradually refine their vocal responses to sensory stimuli, progressing sequentially from initial cries to cooing, babbling, and finally recognizable spoken words by approximately 12 months of age (*10*). Concurrently, infants become increasingly proficient at discriminating speech sounds and phonological patterns, with substantial improvements by approximately 12 months of age (*12, 79*). This development progression is conceptualized as a cascading series of critical periods (*80, 81, 37*). During these critical periods, infants become selectively attuned to specific linguistic regularities (*82*). By around 12 months, infants show sharpened perceptual sensitivity to native phonetic contrasts, and decreased sensitivity to non-native phonetic contrasts — a developmental shift usually described as *perceptual narrowing*, reflecting only the maintenance and loss of sensitivity (*83*). Here, however, we prefer the broader descriptive term *perceptual attunement* (*84, 85, 79*), encompassing both sharpening/improvement and maintenance/loss. More accurately, from a neurobiological perspective, this phenomenon is understood as *perceptual reorganization*, capturing the initial neural organization and experience-dependent dynamic changes in perceptual sensitivity (*Janet F. Werker, personal communication, January 2025*).

Recent studies suggest that early learning experiences establish crucial associations across motor, auditory, and visual systems, then enabling imitation to overcome perceptual opacity (*18, 15, 5*). Further evidence further indicate that speech acquisition inherently involves not just auditory processing but also motor and visual systems (*86, 87, 55, 40*). Training-based studies additionally support this view, showing that sensorimotor experiences facilitate learning more effectively than isolated sensory or motor experience alone (*88, 6*). Moreover, infants show increased activation in motor cortical regions when perceiving unfamiliar non-native speech compared to familiar native speech stimuli (*23*). Given the multimodal nature of speech (*89*), dMRI provides a powerful tool to characterize the maturation of white matter tracts linking sensory and motor systems, offering critical insights into the neural mechanisms of speech acquisition (*39, 28*).

In this study, by addressing challenges in infant neuroimaging data analysis (*90, 91*) and utilizing the Baby Connectome Project (BCP), the largest high-quality longitudinal infant neuroimaging and behavioral dataset (*92*), we extracted white matter tracts within five major neural pathways

(motor, auditory, visual, ventral language, and dorsal language) using high angular resolution diffusion imaging (HARDI) data. We then applied neurite orientation dispersion and density imaging (NODDI) model to calculate neurite density index (NDI) (*93*), a microstructural model known for greater reliability compared to diffusion tensor imaging (DTI) (*94*). Using longitudinal data spanning birth to 24 months, we employed linear mixed-effects models (LMMs) to characterize the developmental trajectories of tract-specific mean NDI values. Mean NDI values were correlated with behavioral measures across six developmental domains (motor skills, social interaction, visual awareness, emotional regulation, living skills, and speech; Tables S9, S10, S11, S12, S13, and S14). Finally, we in turn conducted cross-sectional and longitudinal mediation analyses to identify significant behavioral mediators for speech learning and investigate cascading developmental processes.

In the following sections, we first clarify the criteria for including white matter tracts of these five pathways. We then characterize their developmental trajectories. Finally, we examine neural-behavioral correlations to illustrate how interactions across multiple brain systems and dynamic developmental cascades support the emergent property of speech acquisition.

Functional categorization of white matter tracts

We extracted white matter tracts from the longitudinal BCP HARDI data spanning birth to 24 months (Table S1), using protocols derived from the Human Connectome Project (HCP) dataset (*95, 96, 91*). These tracts were categorized into five functional groups — **motor**, **auditory**, **visual**, **ventral** language, and **dorsal** language — each represented consistently by a distinct color in the text, trajectory figures, and legends.

- The **motor** group includes the **corticospinal tract** (**CST**), **thalamo-precentral tract** (**T-PREC**), and **corpus callosum anterior midbody** (**CC_4**), each connecting to the primary motor cortex (precentral gyrus).

- The **auditory** group comprises tracts spanning peripheral, subcortical, and cortical regions, delineated based on established anatomical criteria (*97*). Peripheral auditory tracts were excluded due to significant noise in their microstructural data.

- The **visual** group includes the **optic radiation** (**OR**), **middle longitudinal fasciculus** (**MLF**), and **superior longitudinal fasciculus II** (**SLF II**). Although traditionally classified within language pathways (*27*), we reclassified the **MLF** and **SLF II** into the **visual** group given their established roles in **auditory**-**visual**-**semantic** integration (**MLF**) (*98, 99*) and **visual**-**motor** integration (**SLF II**) (*100*).

- The **ventral** language group comprises the **uncinate fasciculus** (**UF**), **inferior fronto-occipital fasciculus** (**IFOF**), and **inferior longitudinal fasciculus** (**ILF**). The **IFOF**, closely associated with **visual** processing (*27*), is highlighted in **yellow** throughout figures to underscore its dual role in **visual** and semantic integration (*101*).

- The **dorsal** language pathway includes the **AF** and **SLF III**, both closely associated with speech articulation (*102*).

Fig. 1 illustrates these tracts across developmental stages from neonates to 24-month-olds, arranged visually on an octahedral representation. These tracts exhibit significant variability in maturation rates. For instance, the **ILF** and **UF** show relatively slower maturation, aligning with their prolonged developmental trajectory in semantic learning (*103, 10, 104*). In contrast, the **AF** exhibits one of the most rapid maturation patterns among the examined tracts. Notably, our data showed structural connectivity of the neonatal **AF**, predominantly terminating in the precentral gyrus, along with sparse yet detectable connections extending to inferior frontal cortex (IFC; Brodmann's area 44, BA44; Fig. S2). This finding is generally consistent with prior reports highlighting predominant precentral connectivity of the neonatal **AF** (*105, 106, 107*). However, our use of HARDI and anatomically constrained tractography (*108*) with constrained spherical deconvolution model (*109*) may explain our ability to detect these subtle IFC connections. Collectively, these findings provide anatomical evidence of early-established neural connectivity between superior temporal cortex (STC) and IFC regions from birth, facilitating the integration of sensory and motor areas critical for primordial speech networks.

Previous studies have primarily examined white matter tracts within the classical dual-stream language model (**ventral** and **dorsal** language pathways) in infant speech acquisition research (*110, 47*). However, speech processing inherently involves integration across diverse brain systems (*89, 27, 28, 40*). Beyond these dual pathways, we additionally extracted white matter tracts

across motor, auditory, and visual systems (*e.g.*, **CST**, **T-PREC**, **AR**, and **OR**), using advanced AI-based processing and analysis tools recently developed by our group (*111, 112, 90, 113, 91*). These methodological advancements enabled us to comprehensively extract tracts covering **motor**, sensory (**auditory** and **visual**), and sensorimotor integration (**auditory**-**motor**, **visual**-**motor**, and **auditory**-**visual**-**motor**). Our aims were to: (*i*) characterize developmental trajectories of these tracts across a broader *age range* and a more *comprehensive set of pathways* compared to previous studies (*46*); (*ii*) correlate tract-specific mean NDI values with behavioral assessments across six developmental domains (motor skills, social interaction, visual awareness, emotional regulation, living skills, and speech; Tables S9, S10, S11, S12, S13, and S14); and (*iii*) examine potential cascading nonlinear relationships among these behavioral measures.

After applying quality control (QC) procedures to exclude scans with acquisition issues or severe artifacts — detailed in (*91*) — 246 samples were retained (Table S1). We further excluded longitudinal NDI data points inconsistent with established developmental trajectories of individual subjects, and explicitly listed the final validated data in the supplementary (`.TikZ`) files of Fig. S3. Notably, matching neural and behavioral data within a ±1-month age window substantially reduced data points that can be used in the analysis, in particular affecting the longitudinal mediation analysis. Therefore, this study can only explore potential cascading nonlinear relationships among behavioral measures, though constrained by a relatively modest sample size (~ 40 matched pairs) in the longitudinal mediation analysis.

Asynchronous and synchronous maturation of white matter

Mean NDI values, derived from the NODDI model, were calculated for each tract and modeled using linear mixed-effects models (LMMs) to characterize population-level developmental trajectories (*114*). The developmental trajectories of NDI for each tract are shown in Fig. 2, with detailed population-level trajectories and individual data points provided in Fig. S3. Trajectories were color-coded according to their functional group (**motor**, **auditory**, **visual**, **ventral** language, and **dorsal** language), revealing maturation patterns consistent with previously reported dramatic volumetric increase and microstructural changes in white matter (*115, 38, 44, 116*).These maturation patterns coincide with rapid neural reorganization crucial for speech attunement (*10, 85*).

These trajectories also reveal coexisting asynchronous and synchronous maturation patterns across different white matter tracts. As shown in Fig. 2, tracts from different functional groups exhibit distinct NDI values, reflecting variability in their maturation across the first two postnatal years. Tracts such as the **CST**, **AR**, **OR**, **UF**, and **AF** exhibit significant maturation variability at birth, suggesting developmental asynchrony established prenatally. Moreover, subsequent maturation rates differ markedly, with the **AF** maturing more rapidly than the **ventral** language tracts (**UF** and **ILF**), consistent with prior reports (*115, 59, 46*). Interestingly, due to these developmental differences, tracts such as the **AR**, **OR**, **SLF II**, **AF**, and **SLF III** converge to comparable levels of maturity by approximately 24 months. This convergence represents a critical developmental milestone, indicating that sensorimotor association tracts attain transmission efficiency comparable to primary sensory tracts, crucial for efficient integration across motor, auditory, and visual systems underlying speech acquisition (*89, 117*).

In parallel to these asynchronous patterns, several tracts exhibit synchronous developmental trajectories, potentially involving functional synchronization (*118*). Specifically, the **SLF II** (**visual–motor** association tract) and **dorsal** language tracts (**AF** and **SLF III**) exhibit closely overlapping NDI trajectories throughout the first 24 months. More than that, the developmental trajectories of these association tracts consistently parallel **motor** tracts (**CST** and **T-PREC**), though at a lower maturity level. This synchronous developmental pattern suggests coordinated maturation processes, likely driven by integral motor and sensorimotor experiences (*119, 120, 60*).

To elucidate potential mechanisms underlying these synchronous maturation patterns, we examined neural-behavioral correlations to clarify the influence of early-life experiences on neural development. We correlated mean NDI values of 33 tracts with behavioral measures across ten assessments, mainly covering 6 developmental domains, *i.e.*, motor skills, social interaction, visual awareness, emotional regulation, living skills, and speech (see Supplementary Materials, Section Data acquisition and participants). This analysis revealed a total of 367 significant neural-behavioral correlations (detailed in supplementary files `1_significant_relationships_t_b_ordered_by_behavior.csv` and `1_significant_relationships_t_b_ordered_by_tract.csv`). Notably, the **motor** and association tracts of parallel development consistently correlated with comprehension of gesture phrases, as detailed in Table 1. Infants' gesture phrase comprehension, assessed by the MacArthur-Bates Communicative Development Inventories (CDI) - Words and Gestures (W & G) (*121*),

significantly correlated with NDI values of **CST_L**, **$T\text{-}PREC_L$**, **$SLF\ II_R$**, and **AF_L**. This suggests that early gesture-based experiences may enable the parallel developmental trajectories of **motor** and association tracts. However, the precise mechanisms by which early gesture experiences shape the maturation of **motor** and association tracts remain incompletely understood.

To further clarify the role of gesture-based experiences in the maturation of **motor** and association tracts, we examined broader neural-behavioral correlations beyond gesture comprehension. We identified extensive neural-behavioral associations, with tract maturation significantly correlated with diverse early behavioral domains. Individual tracts within **ventral** and **dorsal** language pathways correlated significantly across multiple behavioral domains beyond speech alone. Conversely, receptive and expressive language skills correlated widely across nearly all examined tracts. Intriguingly, among the 367 significant correlations identified, tract maturation predominantly showed positive associations with basic motor based behaviors, such as gestures, gross-motor, fine-motor, and fine skills. Conversely, more complex speech skills, including receptive language, expressive language, and communication domains, typically showed negative correlations, aligning with the previously reported negative or nonlinear findings (*122, 123, 124*). Collectively, these findings demonstrate complex, nonlinear integrative relationships between white matter tracts and developmental behaviors, reflecting *one-to-many* and *many-to-one* mappings (*125*).

Our data support that maturation of an individual tract does not exclusively or directly drive speech development but instead involves widespread neural network (*27, 28*) as well as critical precursor capacities, particularly motor skills, which scaffold more complex speech functions (*126,127,78*). Thus, the observed parallel developmental trajectories of **motor** and association tracts may reflect coordinated developmental precusors. However, the relative immaturity of association tracts at birth warrants attention (Section Immaturity of association tracts at birth). Additionally, temporal dynamics underpinning speech acquisition remain incompletely understood (*124*). Clarifying developmental timing could illuminate preciser mechanisms driving the rapid, parallel maturation of **motor** and association tracts (Section Rapid maturation of **motor** and association tracts).

Immaturity of association tracts at birth

Neonates have limited motor and sensory experiences, though basic motor, auditory, and visual capabilities sequentially emerge prenatally (*45, 39, 128, 61*). Our data empirically confirm this developmental sequence: as illustrated in Fig. 2, the primary **visual** tract (**OR**) exhibits notably lower maturity than the primary **auditory** tract (**AR**), with both demonstrating significantly lower maturity than **motor** tracts (**CST** and **T-PREC**). Consistent with this observed asynchronous maturation, association tracts, *i.e.*, **SLF II**, **AF**, **SLF III**, and **MLF**, *collectively* exhibit the lowest initial maturity among all examined tracts. Despite the relatively low maturity of association tracts, prenatal neural development remains sufficient to enable basic fetal sensorimotor behaviors, such as limb movements in response to acoustic stimuli (*66, 67, 68, 69*).

These early neural and behavioral developments offer critical insights into subsequent maturation across motor, auditory, and visual systems. At birth, the observed asynchrony across these systems explains the immaturity of association tracts, suggesting that integration pathways — such as **auditory**-**motor**, **visual**-**motor**, and **auditory**-**visual**-**motor** — have not yet essentially formed, resulting in inefficient inter-system signal transmission. Immediately after birth, pre-wired neural substrates support fundamental neonatal behaviors, such as initial crying, ensuring survival and facilitating the physiological and behavioral transition from intrauterine to terrestrial environments (*129, 4*). Such postnatal experiences progressively shape neural development from these initial connections, facilitating efficient learning without extensive neural reorganization (*60, 120, 43*). However, precisely how early-life experiences drive rapid and parallel maturation of **motor** and association tracts remains unresolved.

To address this question, we conducted a cross-sectional mediation analysis on imputed behavioral and neural data to examine three-way relationships among white matter tract maturation, developmental behaviors, and speech outcomes. We utilized 11 behavioral assessments from the BCP, with detailed inclusion criteria provided in Supplementary Materials (Section Mediation pathway analysis). We applied Predictive Mean Matching (PMM) for 100 imputations to address missing data (*130*), subsequently fitting piecewise structural equation models (SEMs) across the imputed datasets (*131*). Each SEM comprised two LMM models accounting for random subject intercepts and controlling for age and sex (*114*). We first modeled behavioral performance as a quadratic

function of tract maturation. Next, language outcomes were modeled as a function of tract maturation, behavioral performance, age, and sex. Quadratic terms ($tract^2$) were explicitly included to model nonlinear developmental effects. Estimates from SEM analyses across imputed datasets were pooled to yield robust mediation estimates (*132*), characterizing developmental correlations linking neural maturation to speech performance.

From 74,409 potential mediation pathways examined, we identified 849 significant pathways after applying Benjamini-Hochberg false discovery rate (FDR) correction (*133*). These 849 significant mediation pathways were identified following rigorous FDR correction, which was stringently applied across all 74,276 evaluated cases (excluded null pathways) (*134*). Detailed results for these significant pathways are provided in Table S6 and supplementary file (`2_combined_results_with_fdr_and_mediation.csv`). Two key insights emerged from these mediation analyses. First, significant positive correlations were identified between tract maturation and both motor skills and visual awareness, which in turn positively correlated with speech outcomes. These findings imply that tract maturation indirectly facilitates speech acquisition via motor and visual skills. Second, motor skills — including gross-motor, fine-motor, and fine subdomains — were dominant mediators, accounting for 111 of 118 pathways identified with tract maturation as the predictor. This finding underscores the pivotal role of motor skills in early speech acquisition.

Considering recent evidence highlighting social interaction's facilitating roles in speech acquisition (*135, 136, 137*), we further explored mediation pathways using social interaction or motor skills as predictor (X) and speech performance as the outcome (Y). Our mediation analysis identified 731 statistically significant pathways involving various mediators (M) such as visual awareness, living skills, emotional regulation, motor skills, and social interaction. These findings underscore two aspects of *complexity* in speech acquisition. First, speech development likely relies on integrated experiences across diverse functional domains rather than solely on isolated motor, sensory, or social experiences alone. Second, we potentially identified dynamic reciprocal relationships exemplified by *motor* $\rightarrow$ *social* $\rightarrow$ *speech* and *social* $\rightarrow$ *motor* $\rightarrow$ *speech* pathways, where motor skills and social interaction seem to be mutually reinforcing. Our data support previously reported evidence indicating that motor, sensorimotor, and social experiences play crucial roles in speech acquisition (*138, 55, 139, 15, 135, 7, 5, 137*). However, it remains unclear how these experiences are coordinated. Examining fine-grained temporal interactions between motor and social experi-

ences could further clarify mechanisms underlying the rapid and parallel maturation of motor and association tracts.

Rapid maturation of motor and association tracts

Longitudinal behavioral data from the BCP cohort indicate informative temporal patterns of early development. To clarify how early motor and social experiences contribute to later speech outcomes, we conducted longitudinal mediation analyses using matched behavioral data, without employing data imputation. Specifically, we employed linear regression models within a piecewise SEM framework (*131*). The first linear model examined whether early social skills predicted later motor outcomes and, conversely, whether early motor skills predicted later social outcomes. The second model examined the joint influence of early motor skills and social interactions on later speech outcomes. Piecewise SEM identified significant mediation pathways, illustrating cascading developmental interactions linking early motor and social experiences to subsequent speech acquisition.

We focused on two key mediation pathways, guided by theoretical predictions regarding early speech acquisition (*135, 138, 15*). (*i*) The *motor* → *social* → *speech* pathway examined whether motor skills at 4-6 months predicted social interaction at 12-14 months, which in turn predicted speech outcomes at 24-26 months. (*ii*) The *social* → *motor* → *speech* pathway examined whether social interaction at 4-6 months predicted motor skills at 12-14 months, which subsequently predicted speech outcomes at 24-26 months. Results from these mediation analyses are summarized in Tables 2 and 3, with detailed results provided in supplementary files (`3_mediation_results_m_s_l.xlsx` and `3_mediation_results_s_m_l.xlsx`).

In the *motor* → *social* → *speech* pathway, *gross-motor* skill served as the primary predictor. Gross-motor skills at 4–6 months predicted social interaction at 12-14 months, which subsequently predicted speech performance at 24-26 months. This aligns with previous evidence highlighting a role of early gross-motor skills in facilitating social and communication development during infancy (*140, 77, 126, 78*). It also supports studies indicating that social interaction promotes subsequent speech acquisition (*135, 141, 137*). In contrast, the *social* → *motor* → *speech* pathway indicated that early social interaction primarily predicted later *fine-motor* skills rather than gross-motor skills.

This pattern confirms previous findings that social engagement facilitates the refinement of infants' fine-motor skills through cross-modal sensorimotor integration (*142, 143, 5*). Notably, early social interaction did not directly predict subsequent speech performance in this pathway. Taken together, these findings underline that enriched social interaction and fine-motor experiences at 12-14 months contribute positively to speech outcomes at 24-26 months.

Both mediation pathways consistently involved the *interpersonal* and *socialization* components of the social interaction domain (Table 2 and 3). These components may serve as integrating factors, connecting both pathways into a broader developmental loop. Early gross-motor activities elicited by external stimuli may initially facilitate social exchanges between infants and caregivers, especially before infants can clearly express their needs through speech (*76, 126*). Simultaneously, these social interactions provide infants with rich learning opportunities and sensorimotor experiences (*15, 5*). These experiences are essential for refining fine-motor skills, which critically depend on sensory–motor integration (*18, 144, 7*). In addition, social interaction may facilitate or gate the acquisition of more complex skills by transforming perceptually opaque actions into transparent, imitable behaviors, substantially enriching the quality of infants' developmental experiences (*135, 145, 5*).

It is important to note that we do not propose a strictly linear sequence of skill acquisition (such as *gross-motor* → *social interaction* → *fine-motor* → *speech*). Instead, our data indicate a nonlinear and interactive process wherein developing skills continuously influence and co-evolve. For example, social interaction at 12–14 months exhibited a significant positive correlation with subsequent speech performance, but not at earlier stages (4–6 months), highlighting important temporal dynamics in early development. This perspective aligns with established developmental timing effects and critical periods in early speech acquisition (*37, 124*), suggesting that neural plasticity is particularly pronounced during specific early-life stages, pointing to the importance of temporally-sensitive experiences in shaping speech development.

This extended developmental loop of early motor-social interactions provides an explanation for why **motor** and association tracts (*i.e.*, **CST**, **T-PREC**, **SLF II** , **AF**, and **SLF III**) mature rapidly and in parallel during the first postnatal year (Fig. 2). During the fetal stage and early infancy, responses to external stimuli rely heavily on motor activities. These responses — such as spontaneous limb movements or reflexes — often appear ambiguous to caregivers, reflecting considerable

randomness in neonatal behaviors and necessitating repeated trials (*21*). Early motor behaviors serve as primitive communicative signals (*74, 76*), initiating caregiver-infant interactions that provide rich, high-quality, multimodal experiences in concert; and these interactions, particularly through imitation and repetition, actively reduce perceptual ambiguity, facilitating precise cross-modal mappings (*77, 6*). Such repeated motor and sensorimotor experiences reinforce neural connections, enabling rapid maturation and efficient cross-modal integration across motor, auditory, and visual domains (*120, 146, 75*). Thus, this extended loop model explains the parallel co-development of **motor** and association tracts. This interpretation aligns with recent evidence linking motor–sensory transmission efficiency to sensorimotor skill performance (*147, 148*). Conversely, deficits in motor skills or insufficient social interactions may disrupt this integrative loop, leading to developmental delays or disorders (*149, 138, 150, 140, 151*), thereby underscoring the critical roles of early motor-social interactions in typical cognitive development.

Lastly, it should be acknowledged that our proposed developmental loop currently offers indirect evidence regarding how early-life experiences shape the maturation of **motor** and association tracts. Further longitudinal neuroimaging and intervention studies are necessary to formally test the hypothesis that both **motor** and association tracts actively reorganize in response to early motor and sensorimotor experiences gained during regular social interactions. These future studies could elucidate the precise mechanisms through which rapid and parallel maturation of **motor** and association tracts facilitates speech acquisition in early infancy.

Discussion

Speech, a uniquely complex human capability (*152, 11*), is increasingly viewed as an emergent property of dynamically integrated neural networks (*27, 28*). How infants rapidly develop such sophisticated cognitive capacities remains unresolved. Our data indicate a rapid postnatal emergence of functional integration across motor and sensory systems, characterized by initially immature but rapidly strengthening association tracts (**SLF II**, **AF**, and **SLF III**). Crucially, these tracts mature in parallel with **motor** tracts (**CST** and **T-PREC**), achieving maturity levels comparable to primary sensory tracts (**AR** and **OR**) by 24 months. This rapid structural integration increasingly supports efficient early integration of sensory information, crucial for speech emergence.

Our HARDI data revealed previously undetected neonatal connectivity between STC and IFC (BA44) via the left $\mathbf{AF_L}$. This observation refines earlier conclusions from lower-resolution DTI studies, which generally reported an absence of clear neonatal **AF** connectivity to IFC (*105*). Nonetheless, consistent with previous findings (*106*), our data confirmed predominant **AF** connections terminating in the precentral gyrus, highlighting the critical role of motor development in early speech development. According to previous studies (*105, 106*) and further clarified in a personal communication, the dorsal language pathway comprises two distinct sub-pathways: one targeting the premotor cortex (BA6), which is myelinated and functional at birth, crucial for supporting early auditory-to-motor mapping during speech perception and early vocalizations; and another targeting BA44, which is implicated in syntactic processing and matures fully in early childhood (*Angela D. Friederici, May 2025*). This functional differentiation is directly relevant to our findings: while the BA6 pathway aligns with well-established early sensory–motor mapping, the sparse BA44 connectivity we observed at birth may represent the earliest detectable substrate for later-developing syntactic functions. Collectively, our data strengthen motor-based and sensorimotor theories of speech perception and learning by underscoring early sensorimotor integration as foundational for speech acquisition (*153, 154, 155, 117, 15, 40*).

We further identified extensive and complex neural-behavioral correlations. White matter tract maturation correlated broadly and nonlinearly with diverse developmental skills, reflecting both one-to-many (single tract correlated with multiple skills) and many-to-one (multiple tracts correlated with single skill) mappings (*125*). Such widespread and complex correlations extend prior focused structure-function observations (*156, 157, 49, 47*), offering a more integrated understanding of early cognitive development. Additionally, developmental timing mattered significantly: social interactions at 12–14 months influenced later speech skills more prominently than at earlier stages (4–6 months), consistent with known critical periods in early speech learning (*37, 124*). Together, the above findings clearly illustrate the emergent nature of speech acquisition, as a complex cognitive skill arising not merely from isolated neural systems but from integrative, interactive, and dynamic developmental processes

Central to these dynamic cascades may be early social interactions (*135, 5*). Motor activities, even prenatally and immediately after birth, serve as crucial communication signals eliciting caregiver responses (*though not always*) (*74, 76, 74, 3, 126*). Our mediation analyses identified two

complementary interactive loops: infants' motor signals trigger caregiver responses, and caregivers' imitation and feedback facilitate infants' sensorimotor learning. These reciprocal loops provide repeated, multimodal sensorimotor experiences, significantly enhancing neural substrates and cross-modal integration (*120, 146, 18, 60, 31*). Conversely, limited caregiver responsiveness or disrupted motor-social interactions may impair these developmental processes, potentially leading to delays or disorders (*140, 138*), underscoring the critical roles of motor-social interactions in normative cognitive development (*2, 78*).

Our data also contribute new insights to longstanding debates about neonatal imitation capabilities. Despite extensive controversy and mixed evidence (*16, 21, 158, 19, 17*), our structural data suggest a clear explanation: while basic **auditory**-**motor** tracts exist at birth (*66, 67*), higher-order association tracts required for precise imitation remain immature but rapidly mature postnatally. Recent behavioral studies support this interpretation, showing early social experiences — particularly caregiver imitation — significantly enhance infants' own imitative skills (*7, 5*). These structural and behavioral findings thus support an experience-dependent emergence of imitation, rather than purely innate mechanisms.

Our study advocates a holistic, experience-dependent model of early speech acquisition, in which speech emerges dynamically through coordinated maturation across multiple neural systems, closely shaped by rich postnatal experiences. This integrative developmental framework helps explain how humans effectively handle incomplete and ambiguous sensory information (*159, 23*), *from birth*, particularly addressing challenges related to perceptual opacity (*18, 15*). Practically, our findings suggest that targeted enrichment — such as promoting responsive caregiver-infant interactions and environments rich in sensorimotor experiences — could significantly enhance early language outcomes. Thus, fostering high-quality motor and social experiences during early infancy may profoundly reinforce the neural foundations necessary for robust speech and broader cognitive development.

Five limitations should be acknowledged. First, although our HARDI data significantly improve anatomical specificity compared to traditional DTI approaches, certain tract terminations, particularly sparse connections observed between STC and IFC, might reflect methodological biases (*e.g.*, thresholding parameters or atlas-based segmentation). Second, our longitudinal mediation analyses involved a relatively modest number of matched pairs (~ 40), constraining statistical ro-

bustness. Third, our analyses relied primarily on diffusion neuroimaging; incorporating functional neuroimaging methods such as EEG, MEG, or fMRI could offer deeper insights into how structural maturation relates to functional brain dynamics during speech acquisition. Fourth, the behavioral assessments, though comprehensive, primarily capture broad developmental domains rather than fine-grained behavioral variability. More precise, targeted behavioral tasks could improve our understanding of how subtle behavioral changes correlate with neural development. Fifth, our data are primarily correlational, limiting causal inference. Longitudinal intervention studies explicitly manipulating early motor, sensorimotor, and social interactions are crucial for confirming causality. Future studies should employ larger-scale longitudinal datasets, refined neuroimaging methods, and targeted experiment settings or interventions to further clarify precise causal pathways among neural substrate maturation, early-life gross-motor skills, social interactions, sensorimotor experiences, and speech outcomes.

Concluding remarks

Leveraging the BCP neuroimaging and behavioral dataset, we comprehensively characterized developmental trajectories of white matter tracts across **motor**, **auditory**, **visual**, **ventral** language, and **dorsal** language pathways, establishing extensive correlations between tract maturation and early behavioral outcomes. Our findings highlight motor system maturation as a foundational development event, with social interaction acting like a catalyst that facilitates infants' communicative transition from gross-motor behaviors toward refined fine-motor skills, ultimately supporting the emergence of socialized speech. These results empirically support that speech acquisition is an emergent property arising from extensive neural integration and dynamic interactions among multiple brain systems and behavioral domains. Rather than isolated neural substrates directly driving complex cognitive skills such as speech, their maturation supports these capacities indirectly through precursor skills, particularly motor and social functions.

By employing advanced diffusion neuroimaging techniques — specifically HARDI and robust infant-specific tract extraction methods — our study demonstrates the unique methodological advantages of diffusion neuroimaging for characterizing the microstructural foundations of early speech development. As one of the pioneering efforts utilizing a large-scale, high-quality infant

dataset to elucidate neural mechanisms of speech acquisition, our findings underscore the distinct capacity of diffusion MRI in uncovering integrative and experience-driven processes underlying complex cognitive development. Future research should continue exploring these developmental cascades, particularly emphasizing how prenatal and early-life motor and sensorimotor experiences shape neural substrates, thereby bridging prenatal and postnatal developmental stages as an integrated continuum.

Table 1: Significant correlations between the quadratic term of white matter tract maturation and the total number of phrases understood, as measured by the MacArthur-Bates Communicative Development Inventories - Words and Gestures. Negative estimates indicate inverted-U-shaped (quadratic) relationships, reflecting an initial increase in phrase comprehension with tract maturation that peaks and then slightly declines at higher maturity levels. These associations specifically support the synchronized developmental trajectories of motor and association tracts as illustrated Fig. 2. ($^{**}p < 0.01$)

Total number of phrases understood	*Estimate*	p**-value**	r^2
$\mathbf{AF_L}$	-648.5	0.006^{**}	0.620
$\mathbf{SLF\ II_R}$	-470.0	0.006^{**}	0.614
$\mathbf{CST_L}$	-376.3	0.006^{**}	0.604
$\mathbf{T\ PREC_L}$	-598.4	0.006^{**}	0.596

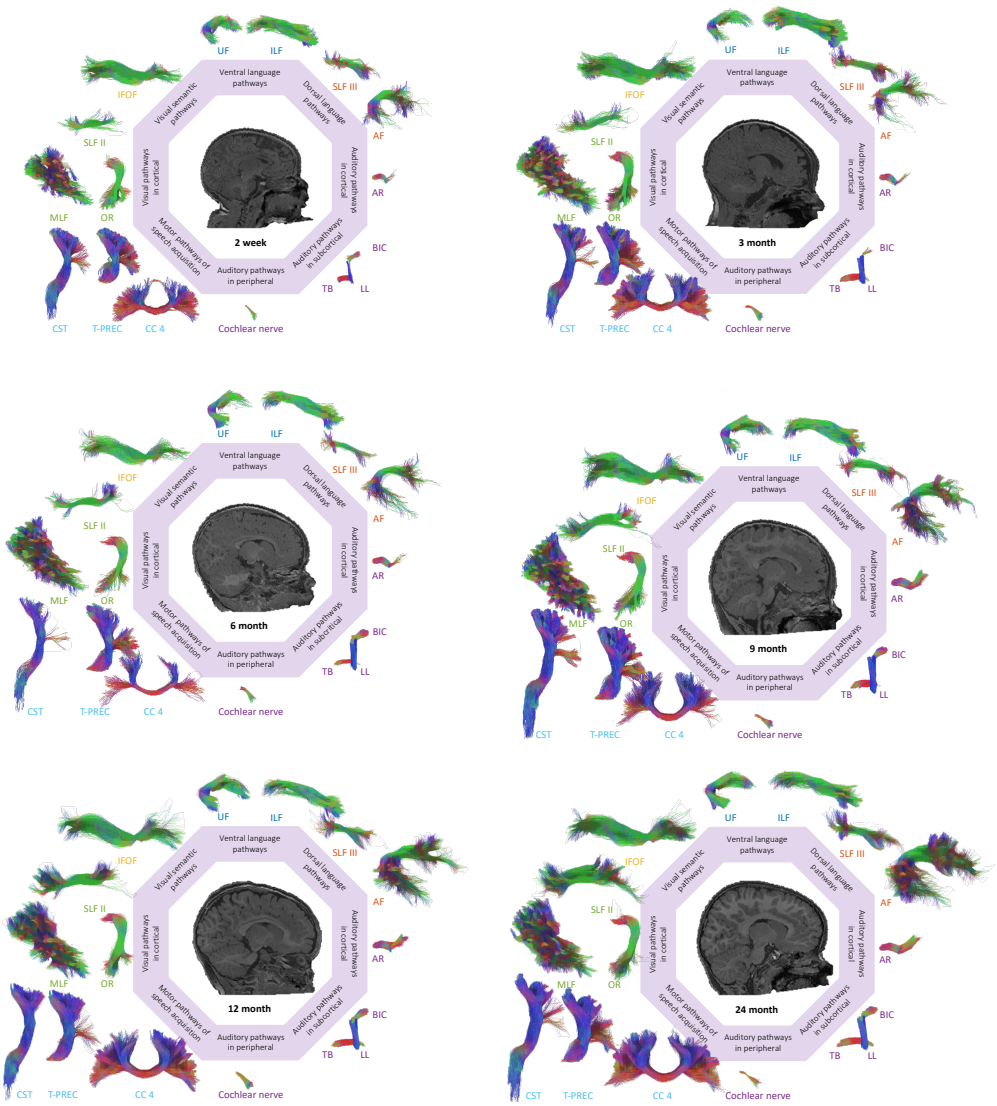

Figure 1: White matter tracts implicated in speech acquisition (left hemisphere), visualized across developmental stages from neonates to 24-month-old infants. Tracts are categorized into five pathways: **motor** (**CST**, **T-PREC**, **CC_4**), **auditory** (**Cochlear nerve**, **TB**, **LL**, **BIC**, **AR**), **visual** (**OR**, **MLF**, **SLF II**), **ventral** language (**UF**, **ILF**, **IFOF**), and **dorsal** language (**AF**, **SLF III**). Consistent with previous findings (*115*,*59*,*46*), **UF** appears relatively mature at birth; and in contrast, **AF**, initially immature at birth, exhibits rapid postnatal maturation[2].

[2] **CST**: **corticospinal tract**; **T-PREC**: **thalamo-precentral**; and **CC_4**: **corpus callosum anterior midbody** (**primary motor**); **TB**: **trapezoid body**; **LL**: **lateral lemniscus**; **BIC**: **brachium of the inferior colliculus**; **AR**: **acoustic radiation**; **OR**: **optic radiation**; **SLF II**: **superior longitudinal fasciculus II**; **MLF**: **middle longitudinal fasciculus**; **UF**: **uncinate fasciculus**; **ILF**: **inferior longitudinal fasciculus**; **IFOF**: **inferior fronto-occipital fasciculus**; **AF**: **arcuate fasciculus**; **SLF III**: **superior longitudinal fasciculus III**.

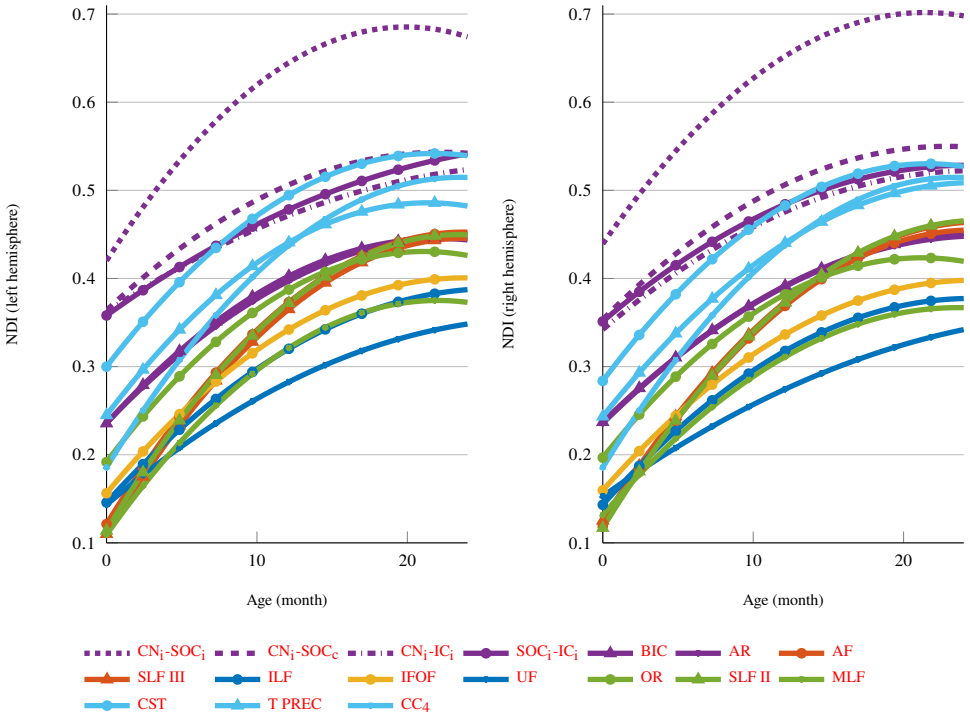

Figure 2: Neurite density index (NDI) based characterization of white-matter development across tracts in both hemispheres from birth to 24 months of age. Tracts demonstrate asynchronous maturity at birth, but association tracts (*e.g.*, **SLF II** and **AF**, **SLF III**) rapidly mature, closely paralleling **motor** tracts (**CST** and **T-PREC**), and reach maturity levels comparable to primary sensory tracts (*e.g.*, **AR** and **OR**) by 24 months. The slight decline observed at higher maturity levels likely reflects the exclusion of data at older ages; extending age beyond 24 months will clarify. (Abbreviations: CN, cochlear nucleus; SOC, superior olivary complex; IC, inferior colliculus; i, ipsilateral; and c, contralateral.)

Table 2: Summary of significant longitudinal mediation pathways from *motor* to *speech* via *social interaction* (*Motor* → *Social* → *Speech*). Predictor variables (motor skills) at approximately 6 months, mediator variables (social skills) at approximately 12 months, and outcome variables (speech abilities) at approximately 24 months are assessed using matched longitudinal data from the BCP cohort. Estimates, standard errors, and significance levels are reported for each pathway, derived from linear models within a piecewise structural equation modeling framework. These pathways highlight the critical role of early gross-motor skills in facilitating later social interactions, which subsequently promote speech development, consistent with prior evidence demonstrating the pivotal role of gross-motor skills in enhancing early social engagement and communicative outcomes (*140, 78*).

Predictor (Motor)	**Mediator (Social)**	**Outcome (Speech)**	**Motor → Social**			**Social → Speech**		
			Estimate	*Std. Error*	*p*-value	*Estimate*	*Std. Error*	*p*-value
grosssubdomain Raw	interpersrelationsubdom Raw	mcg vc totcom	0.711	0.238	0.003^{**}	8.535	4.343	0.049^{*}
grosssubdomain Raw	interpersrelationsubdom Raw	mcg vc totpr	0.711	0.238	0.003^{**}	18.566	7.190	0.010^{*}
grosssubdomain Raw	interpersrelationsubdom Raw	Receptive Language Raw	0.644	0.227	0.005^{**}	0.562	0.230	0.014^{*}
grosssubdomain Raw	interpersrelationsubdom Raw	Receptive Language T	0.644	0.227	0.005^{**}	1.552	0.672	0.021^{*}
grosssubdomain Raw	interpersrelationsubdom Raw	receptivesubdomain Raw	0.620	0.219	0.005^{**}	0.475	0.235	0.043^{*}
grosssubdomain Raw	interpersrelationsubdom Raw	receptivesubdomain v Scale	0.620	0.219	0.005^{**}	0.289	0.146	0.048^{*}
motorskillsdomain Domain Standard	interpersrelationsubdom Raw	mcg vc totpr	0.121	0.036	0.001^{***}	16.542	7.516	0.028^{*}
motorskillsdomain v Scale	interpersrelationsubdom Raw	mcg vc totpr	0.443	0.125	0.0004^{***}	16.653	7.603	0.028^{*}
grosssubdomain Raw	interpersrelationsubdom v Scale	mcg vc totcom	0.574	0.176	0.001^{**}	11.610	5.923	0.050^{*}
grosssubdomain Raw	interpersrelationsubdom v Scale	mcg vc totpr	0.574	0.176	0.001^{**}	23.284	9.956	0.019^{*}
grosssubdomain Raw	interpersrelationsubdom v Scale	Receptive Language Raw	0.493	0.172	0.004^{**}	0.634	0.312	0.043^{*}
grosssubdomain v Scale	interpersrelationsubdom v Scale	mcg vc totcom	0.397	0.195	0.042^{*}	11.704	5.439	0.031^{*}
grosssubdomain v Scale	interpersrelationsubdom v Scale	mcg vc totpr	0.397	0.195	0.042^{*}	20.824	9.133	0.023^{*}
grosssubdomain Raw	socializationdomain Domain Standard	mcg vc totpr	2.110	0.781	0.007^{**}	5.741	2.277	0.012^{*}
motorskillsdomain Domain Standard	socializationdomain Domain Standard	mcg vc totpr	0.338	0.120	0.005^{**}	4.877	2.322	0.036^{*}
motorskillsdomain v Scale	socializationdomain Domain Standard	mcg vc totpr	1.269	0.418	0.002^{**}	4.912	2.349	0.037^{*}

Note: Significance levels indicated by: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 3: Summary of significant longitudinal mediation pathways from *social interaction* to *speech* via *motor skills* (*Social* → *Motor* → *Speech*). Predictor variables (social skills) were assessed at approximately 6 months, mediator variables (motor skills) at approximately 12 months, and outcome variables (speech abilities) at approximately 24 months, based on paired longitudinal data from the BCP cohort. Estimates, standard errors, and significance levels are reported for each pathway, derived from linear models within a piecewise structural equation modeling framework. These mediation pathways highlight the critical role of early social interactions in facilitating subsequent fine-motor skills, which in turn support later speech development, consistent with two aspects of existing evidence (*i*) social interaction facilitate sensorimotor integration (*7*, *5*), and (*ii*) sensorimotor skills facilitate early communicative outcomes (*77*, *40*).

Predictor (Social)	**Mediator (Motor)**	**Outcome (Speech)**	**Social → Motor**			**Motor → Speech**		
			Estimate	*Std. Error*	*p*-value	*Estimate*	*Std. Error*	*p*-value
interpersrelationsubdom Raw	mcg lg total	Expressive Language Raw	0.790	0.355	0.026*	0.401	0.146	0.006**
interpersrelationsubdom Raw	mcg lg total	Expressive Language T	0.790	0.355	0.026*	1.018	0.370	0.006**
interpersrelationsubdom Raw	mcg lg total	mcg vc totpr	0.927	0.331	0.005**	7.597	3.676	0.039*
interpersrelationsubdom Raw	mcg tg total	Expressive Language Raw	0.923	0.448	0.039*	0.318	0.114	0.005**
interpersrelationsubdom Raw	mcg tg total	Expressive Language T	0.923	0.448	0.039*	0.808	0.287	0.005**
interpersrelationsubdom Raw	motorskillsdomain Domain Standard	mcg ph total	1.255	0.536	0.019*	0.073	0.035	0.038*
interpersrelationsubdom v Scale	mcg lg total	Expressive Language Raw	1.199	0.583	0.040*	0.375	0.147	0.011*
interpersrelationsubdom v Scale	mcg lg total	Expressive Language T	1.199	0.583	0.040*	0.959	0.371	0.010*
interpersrelationsubdom v Scale	mcg lg total	mcg vc totpr	1.356	0.522	0.009**	7.209	3.602	0.045*
interpersrelationsubdom v Scale	motorskillsdomain Domain Standard	mcg ph total	1.808	0.902	0.045*	0.077	0.035	0.025*
playleisuretimesubdom Raw	finesubdomain v Scale	Receptive Language Raw	0.483	0.156	0.002**	0.646	0.309	0.037*
playleisuretimesubdom Raw	finesubdomain v Scale	Receptive Language T	0.483	0.156	0.002**	1.799	0.903	0.046*
playleisuretimesubdom Raw	motorskillsdomain Domain Standard	Receptive Language Raw	1.925	0.961	0.045*	0.121	0.050	0.015*
playleisuretimesubdom Raw	motorskillsdomain Domain Standard	Receptive Language T	1.925	0.961	0.045*	0.337	0.145	0.020*
playleisuretimesubdom v Scale	Fine Motor T	Expressive Language Raw	1.043	0.485	0.031*	−0.263	0.130	0.043*
playleisuretimesubdom v Scale	Fine Motor T	Expressive Language T	1.043	0.485	0.031*	−0.709	0.327	0.030*
playleisuretimesubdom v Scale	finesubdomain v Scale	Receptive Language Raw	0.379	0.124	0.002**	0.620	0.308	0.044*
playleisuretimesubdom v Scale	motorskillsdomain Domain Standard	Receptive Language Raw	1.564	0.764	0.041*	0.118	0.050	0.017*
playleisuretimesubdom v Scale	motorskillsdomain Domain Standard	Receptive Language T	1.564	0.764	0.041*	0.328	0.145	0.024*
socializationdomain Domain Standard	Fine Motor T	Expressive Language T	0.282	0.127	0.026*	−0.710	0.332	0.032*
socializationdomain Domain Standard	motorskillsdomain Domain Standard	Receptive Language Raw	0.359	0.182	0.048*	0.113	0.049	0.022*
socializationdomain Domain Standard	motorskillsdomain Domain Standard	Receptive Language T	0.359	0.182	0.048*	0.311	0.144	0.032*
socializationdomain v Scale	Fine Motor T	Expressive Language T	0.832	0.373	0.026*	−0.707	0.332	0.033*
socializationdomain v Scale	motorskillsdomain Domain Standard	Receptive Language Raw	1.103	0.538	0.040*	0.114	0.049	0.022*
socializationdomain v Scale	motorskillsdomain Domain Standard	Receptive Language T	1.103	0.538	0.040*	0.312	0.145	0.031*

Note: Significance levels indicated by: $^{*}p < 0.05$, $^{**}p < 0.01$.

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Author contributions: F.L. designed the research, wrote the code, and drafted the manuscript. F.L., J.L., and J.G. collected and processed the dataset. F.L. and X.C. provided statistical analysis and interpretation of the data. F.L., Y.W., Z.W., and H.W. made contributions in the areas of anatomical delineation and data analysis. F.L., J.F., H.Z., and D.S. coordinated and supervised the whole work. All authors were involved in critical revisions of the manuscript, and have read and approved the final version.

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Competing interests: There are no competing interests to declare.

Data and materials availability: Baby Connectome Project (BCP) are publicly available (*92*), on URL - https://www.humanconnectome.org/study/lifespan-baby-connectome-project.

Supplementary materials

Materials and Methods

Supplementary Text

Figures S1 to S9

Tables S1 to S14

References *(159-179)*

Supplementary files

`0_summary_matched_t_b_item_number.csv`

`1_significant_relationships_t_b_ordered_by_behavior.csv`

`1_significant_relationships_t_b_ordered_by_tract.csv`

`2_combined_results_with_fdr_and_mediation.csv`

`3_mediation_results_m_s_l.xlsx`

`3_mediation_results_s_m_l.xlsx`

Supplementary Materials for

Diffusion Neuroimaging of Speech Acquisition in Infants

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This PDF file includes:

Materials and Methods

Supplementary Text

Figures S1 to S9

Tables S1 to S14

Supplementary files:

The following supplementary files provide detailed tract-level and behavior-level statistical results:

`0_summary_matched_t_b_item_number.csv` — *Summary of the number of matched tract–behavior item pairs across* 11 *assessments*

`1_significant_relationships_t_b_ordered_by_behavior.csv` — *Significant tract–behavior associations, sorted by behavioral variable names*

`1_significant_relationships_t_b_ordered_by_tract.csv` — *Same as above, sorted by tract variable names*

`2_combined_results_with_fdr_and_mediation.csv` — *Comprehensive cross-sectional mediation results across all* 19 *pathway models*

`3_mediation_results_m_s_l.xlsx` — *Longitudinal mediation results for the motor → social → speech pathway*

`3_mediation_results_s_m_l.xlsx` — *Longitudinal mediation results for the social → motor → speech pathway*

Materials and Methods

Data acquisition and participants

We utilized data from the Baby Connectome Project (BCP), currently the largest available high-quality longitudinal dataset comprising infant neuroimaging and behavioral assessments (*92*). Following quality control (QC) procedures detailed in our previous work (*91*), we retained 246 data samples collected from 164 infants for subsequent analyses. The detailed distribution of data samples across age groups (in months) is provided in Table S1.

For our primary statistical analyses, we selected 5 behavioral assessments, which yielded a larger number of matched tract–behavior data pairs compared to the remaining 6 assessments. Detailed information about these assessments is provided in supplementary file `0_summary_matched_t_b_item_number.csv`, Sections Statistical Analysis and Mediation pathway analysis. Behavioral scores were included only when they were obtained within a one-month interval of the corresponding dMRI scans. Fig. S1 illustrates the distribution of matched subjects specifically for the MacArthur-Bates Communicative Development Inventories (CDI) – Words and Gestures (W & G). This analysis included 90 data samples from a total of 74 infants, consisting of 37 females and 37 males. A small subset of infants older than 24 months was also included in order to fully utilize the available longitudinal follow-up data.

The BCP data acquisition protocols are detailed in (*92*). In brief, T1-weighted (T1w) and diffusion MRI (dMRI) data were acquired on a 3T Siemens Prisma scanner. T1w data were obtained using a magnetization-prepared rapid gradient-echo (MPRAGE) sequence with parameters: TR = 2400 ms; TE = 2.24 ms; flip angle = 8 degrees, matrix size = 320×320, field of view (FOV) = $256 \times 256\,\text{mm}^2$; and an isotropic voxel size of $0.8\,\text{mm}^3$. The dMRI data were acquired using a multiband spin-echo echo-planar imaging (EPI) sequence with the following parameters: TR = 2640 ms; TE = 88.6 ms; flip angle = 78 degrees; matrix size = 140×105, FOV = $210 \times 210\,\text{mm}^2$; and isotropic voxel size = $1.5\,\text{mm}^3$. The diffusion acquisition included 144 diffusion-weighted directions distributed across 6 diffusion weighting shells (b-values = 500, 1000, 1500, 2000, 2500, and 3000 s/mm^2), along with 6 b_0 volumes. To ensure longitudinal compatibility with the HCP Lifespan Pilot Project data (*160*), two specific shell (b-values = 1500 and 3000 s/mm^2) were explicitly incorporated. Tractography was conducted utilizing both T1w and dMRI data for

all subjects, with detailed procedures provided in Section Data Processing and Tract Extraction. While differences in shell number or acquisition protocols across sites might potentially introduce systematic biases, careful visual inspections of NDI trajectories showed no observable site- or sequence-related differences. Moreover, the robustness of the NODDI model, which estimates microstructural properties rather than relying solely on absolute signal intensities, likely mitigates such scanner or site variations.

Data Processing and Tract Extraction

Infant structural MRI (sMRI) and dMRI data were processed using our previously developed multimodal MRI processing pipeline (*113*), which integrates widely used neuroimaging toolboxes, including FSL (*161*), ANTs (*162*), and MRtrix3 (*108*). Brain tissue segmentation and region-of-interest (ROI) parcellation were performed using our deep-learning–based algorithms, optimized specifically to ensure longitudinal consistency and accuracy across infant imaging data (*112, 111, 90*). These processing steps enabled accurate co-registration between sMRI and dMRI modalities (*163*), precise estimation of fiber orientation distribution functions (fODFs) (*109*), and reliable tractography analyses (*164*).

Building upon our recently developed NeoAudi Tract (NAT) toolbox (*91*), initially designed for individualized auditory tract extraction from infant dMRI data, we extended its capability to systematically identify white matter tracts across multiple brain systems. The tract extraction involved the **motor**, **auditory**, **visual**, **ventral** language, and **dorsal** language pathways. The systematically extracted tracts enabled comprehensive characterization of developmental trajectories, providing critical insights into underlying white matter maturation mechanisms across early infancy.

To extract white matter tracts from the **motor**, **visual**, **ventral** language, and **dorsal** language pathways:

1. We first collected HARDI data from a subset of 105 adult subjects from the high-quality Human Connectome Project (HCP) dataset (*95, 165*), to construct a tract atlas.

2. We initially generated a coarse atlas of speech-related tracts by averaging anatomically aligned tracts from these adult subjects (*166*), following a previously validated method for auditory tract extraction across peripheral, subcortical, and cortical regions (*91*).

3. We then iteratively refined this initial atlas by repeating tract extraction and alignment steps, progressively developing a high-resolution adult reference tract atlas.

4. Finally, this refined adult atlas was subsequently warped to individual infant dMRI data using NAT's dual-branch registration framework, which was specifically optimized to ensure accurate alignment of both cortical and subcortical regions across infants of varying ages.

Statistical Analysis

After tract extraction, we calculated the mean microstructural attributes for each tract and modeled their developmental trajectories using linear mixed-effects models (LMMs) (*114*). To determine the optimal developmental trajectory model for the neurite density index (NDI), we compared *linear*, *logarithmic*, and *quadratic* models, which are commonly utilized in developmental neuroimaging research (*167*, *168*, *49*). All three models demonstrated statistically significant fits for each tracts (all $p < 0.001$; detailed in Tables S2, S3, and S4). The quadratic model consistently provided superior fits, yielding higher r^2 values and lower Akaike Information Criterion (AIC) scores compared to the linear and logarithmic models. Moreover, the logarithmic model occasionally yielded negative predicted values at birth, which are physiologically implausible given that NDI values typically range between 0 and 1. Therefore, we selected the quadratic model for modeling NDI developmental trajectories.

To examine associations between white matter tracts and behavioral outcomes, and to identify potential mediation pathways, we implemented a three-stage statistical analysis framework: *1*) tract–behavior correlation analysis, *2*) cross-sectional mediation analysis, and *3*) longitudinal mediation analysis. In stage *1*) and *2*), we employed LMMs (*114*), incorporating quadratic effects on tract variables. For stage *3*), we applied standard linear models, in line with established methods for longitudinal mediation analyses (*7*). Missing data for variables of interest were excluded in stages *1*) and *3*). In contrast, we in stage *2*) adopted a more flexible strategy for handling missing data: participants who lacked data for at most one of the three variables — predictor (X), mediator (M), or outcome (Y) — were retained. Missing values for these cases were imputed using the `mice` package in `R`, generating 100 imputed datasets. Model parameters were estimated separately for each imputed dataset and subsequently pooled following Rubin's rules (*132*), effectively account-

ing for both within- and between-imputation variability. Pooled p-values were calculated from the corresponding t-statistics, using the combined standard errors and degrees of freedom according to Rubin's combination formula.

In both cross-sectional and longitudinal mediation analyses (stages *2* and *3*), we employed piecewise structural equation modeling implemented via the `psem` package in `R` (*131*), as defined by Equations S1 and S2. The cross-sectional mediation analysis (stage 2) was specified as:

$$\begin{cases} M_{i,j} = \beta_0 + \beta_1 X_{i,j} + \beta_2 X_{i,j}^2 + \beta_3 \text{Age}_{i,j} + \beta_4 \text{Sex}_i + b_{0,i} + \epsilon_{i,j} \\ Y_{i,j} = \gamma_0 + \gamma_1 X_{i,j} + \gamma_2 X_{i,j}^2 + \gamma_3 M_{i,j} + \gamma_4 \text{Age}_{i,j} + \gamma_5 \text{Sex}_i + c_{0,i} + \zeta_{i,j} \end{cases} \tag{S1}$$

where $X_{i,j}$, $M_{i,j}$, and $Y_{i,j}$ represent predictor, mediator, and outcome variables for subject i at measurement j. Age and sex were covariates; $b_{0,i}$ and $c_{0,i}$ denote random intercepts for each subject, $\epsilon_{i,j}$ and $\zeta_{i,j}$ denote residual errors, and β and γ are fixed-effect parameters to be estimated. Each mediation model comprised two linear mixed-effects submodels: the first predicts the mediator M from the predictor X, and the second predicts the outcome Y from both X and M. Quadratic term (X^2) were included when tract variables served as predictors to model nonlinear developmental effects.

The longitudinal mediation analysis (stage *3*) employed the following two-step modeling approach:

$$\begin{cases} M_{i,(12\sim14m)} = \alpha_0 + \alpha_1 X_{i,(4\sim6m)} + \alpha_2 \text{Age}_{X,i} + \alpha_3 \text{Age}_{M,i} + \alpha_4 \text{Sex}_i + \varepsilon_i \\ Y_{i,(24\sim26m)} = \delta_0 + \delta_1 X_{i,(4\sim6m)} + \delta_2 M_{i,(12\sim14m)} + \delta_3 \text{Age}_{X,i} + \delta_4 \text{Age}_{M,i} + \delta_5 \text{Age}_{Y,i} + \delta_6 \text{Sex}_i + \eta_i \end{cases} \tag{S2}$$

where $X_{i,(4\sim6m)}$, $M_{i,(12\sim14m)}$, and $Y_{i,(24\sim26m)}$ represent predictor, mediator, and outcome variables measured within specified age windows (4–6, 12–14, and 24–26 months). Age at each measurement and sex were controlled; ε_i and η_i denote residual errors, and α and δ represent the fixed-effect parameters to be estimated. Specifically, we first modeled M, assessed at the 12-14 month window, as a function of X, assessed at 4-6 month window, while controlling for age at each respective time point. Subsequently, we modeled Y, assessed at the 24–26 month window, as a function of earlier X and M, again controlling for age at each time point. Both models were collectively analyzed using the `psem` package to estimate standardized path coefficients and mediation effects. This framework is sensitive to the temporal ordering inherent in longitudinal data collection, allowing the approximation of realistic developmental mediation pathways.

Mediation pathway analysis

We utilized a total of 11 behavioral assessments from the BCP dataset, categorized into two groups — *Primary* and *Supplementary* — as summarized in Table S5. The *Primary* group comprised 5 assessments consistently employed across all analytical stages: (*1*) tract–behavior correlation analysis, (*2*) cross-sectional mediation analysis, and (*3*) longitudinal mediation analysis. Each primary assessment provided over 70 samples with valid matches to tract data in stage (1). The *Supplementary* group included 6 additional assessments, exclusively employed in tract–behavior correlation analyses due to limited matched sample sizes. The detailed number of matched tract–behavior sample pairs for each assessment is available in the supplementary file *0_summary_matched_t_b_item_number.csv*. Matching between behavioral and neuroimaging data was conducted using a consistent temporal criterion: retaining only behavioral scores collected within a one-month interval of the corresponding dMRI scans. Statistical significance assessed using a Benjamini-Hochberg false discovery rate (FDR) correction to adjust for multiple comparisons across the 33 white matter tracts (*133*), with significance threshold set at $p < 0.05$. Significant results following correction are reported comprehensively in supplementary files `1_significant_relationships_t_b_ordered_by_behavior.csv` and `1_significant_relationships_t_b` differing only in their organization by *tract* or *behavior* variables.

In stage *(2)*, we formulated a total of 19 theoretical hypotheses, each corresponding to a distinct mediation pathway model, as detailed in Table S6. Each model followed a three-variable mediation structure, represented as Predictor (X) $\rightarrow$ Mediator (M) $\rightarrow$ Outcome (Y). Variables were systematically selected from behavioral assessments across seven domains. The complete list of variables within each domain is provided in Tables S8, S9, S10, S11, S12, S13, and S14. Across the 19 specified pathway models, we identified a total of 74, 276 valid $X \rightarrow M \rightarrow Y$ combinations. After applying rigorous FDR correction for multiple comparisons across all 74, 276 combinations, we identified 849 statistically significant mediation pathways. Significant mediation was defined by the presence of significant paths both from X to M and M to Y, with FDR-adjusted $p < 0.05$. Detailed results are provided in the supplementary file `2_combined_results_with_fdr_and_mediation.csv`.

The number of significant mediation pathways identified for each model, summarized in Table S6, can be categorized into two primary groups: (*1*) models with tract variables as predictors,

and (*2*) models with behavioral variables (*e.g.*, motor or social skills) as predictors. In the first group, motor skills emerged as the most consistent mediators, yielding the highest number of significant mediation pathways. Conversely, pathways involving emotional regulation or social interaction as mediators rarely yielded significant mediation pathways. In the second group — where behavioral variables such as social and motor skills served as predictors — we assessed their mediated effects on speech acquisition through other developmental domains. Our mediation analyses collectively suggest that neural substrates preferentially support foundational motor-skill development, subsequently facilitating broader developmental outcomes, including speech. This interpretation is supported by the notable mediation patterns of living-skills variables: tract maturation indirectly facilitated living-skill development primarily via motor skills (Table S6, pathway B5: 24 significant pathways), but with minimal direct mediation effects on speech (pathway C2: only 1 significant pathway). Moreover, early motor and social experiences prominently supported later speech outcomes indirectly through living skills (pathways D5: 171 significant pathways; D6: 164 significant pathways). Additionally, visual variables emerged as robust mediators (D1: 80 significant pathways; D2: 3 significant pathways), likely reflecting fundamental perceptual skills — such as visual attention to caregivers' articulator movements during early communicative interactions — rather than advanced literacy-related abilities (*e.g.*, reading or writing). Thus, motor maturation, interacting dynamically with social experiences, provides an integrative foundation for cognitive and linguistic development, effectively linking to speech capacities.

Given our observations in stage (*2*), which suggested reciprocal facilitation between social interactions and motor skill development, we further explored their temporal relationships in stage (*3*) to clarify developmental cascades linking speech acquisition with motor and social development. Specifically, we conducted longitudinal mediation analyses examining two alternative developmental pathways: (*i*) a *motor* → *social* → *speech* model, and (*ii*) a *social* → *motor* → *speech* model.

Specifically, in the first pathway (*motor* → *social* → *speech*), motor skills assessed within the 4-6-month age window were used to predict social interaction at 12-14 months, which subsequently predicted speech outcomes at 24–26 months. In the second pathway (*social* → *motor* → *speech*), early social interactions at 4–6 months predicted motor skill development at 12–14 months, which in turn influenced speech outcomes at 24–26 months. Given the focused nature of our analysis

on a limited set of theoretically predefined mediation pathways, we did not apply the Benjamini-Hochberg false discovery rate (FDR) correction (*133*) in this stage. Instead, we reported uncorrected p-values to individually assess the significance of each mediation pathway. Detailed results for both pathways are provided in supplementary files: `3_mediation_results_m_s_l.xlsx` (motor → social → speech) and `3_mediation_results_s_m_l.xlsx` (social → motor → speech).

Supplementary Text

Additional Results

As part of our preliminary analyses, we also evaluated standard diffusion tensor imaging (DTI)-derived metrics — namely, radial diffusivity (RD), mean diffusivity (MD), and fractional anisotropy (FA) — to explore their potential associations with early speech development. These metrics were examined alongside neurite density index (NDI) to provide a comprehensive characterization of tract microstructure. However, the RD values of white matter tracts showed no significant correlation with scores from the MacArthur–Bates Communicative Development Inventories (CDI) – Words and Gestures (W & G). This lack of correlation likely results from inherent limitations of the DTI model, particularly its inadequate handling of crossing fibers, which introduces systematic bias in FA metrics.

Notably, as depicted by FA trajectories in Fig. S7 (with detailed illustrations in Fig. S9), auditory brainstem tracts (*e.g.*, **CN–IC** and **SOC–IC**) appeared less mature than the acoustic radiation (**AR**). This finding contrasts with well-established neuroanatomical and histological evidence regarding auditory pathway maturation (*66*). MD trajectories (shown in Fig. S6, with detailed illustrations in Fig. S8) closely mirrored this developmental patterns observed with FA. However, MD and RD trajectories demonstrated more consistent maturation patterns for dorsal and ventral language pathways (Fig. S4, detailed in Fig. S5). Interestingly, FA trajectories displayed hemispheric asymmetries and inconsistencies that were not clearly present in either MD or RD trajectories, further highlighting the methodological limitations inherent to traditional DTI-derived metrics. Given these constraints, our primary analyses utilized NDI, which provides a more robust and biologically interpretable measure of tract microstructure relevant to early speech acquisition.

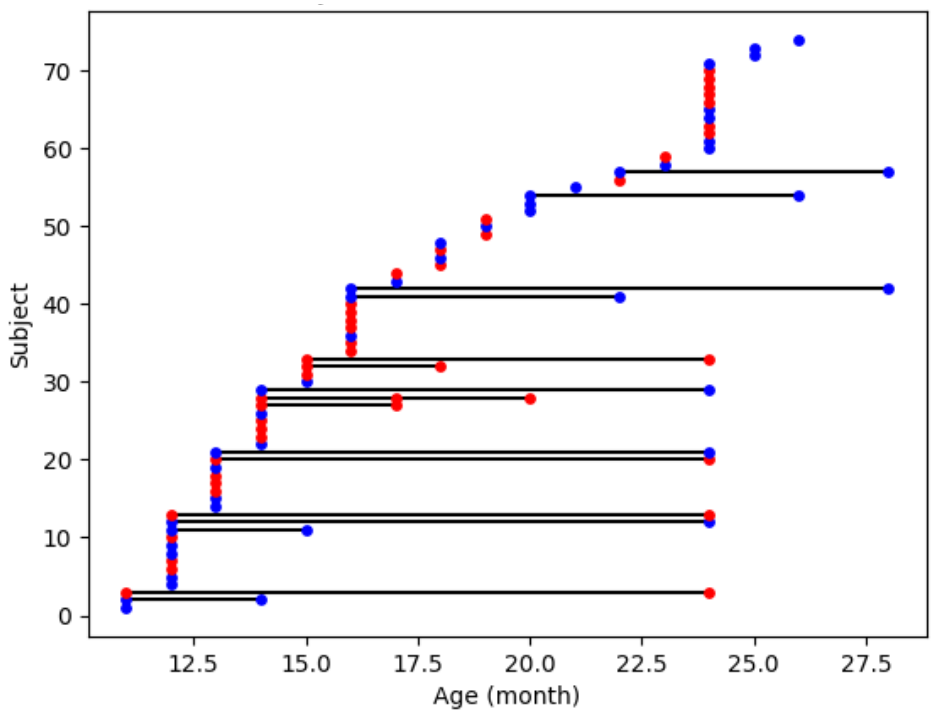

Figure S1: The paired MacArthur–Bates CDI - W & G scores and longitudinal scans of participants with different ages. For each male subject, each scan is demonstrated as a blue point, while red point denotes female infants. The scans from the same subjects are connected by a horizontal black line.

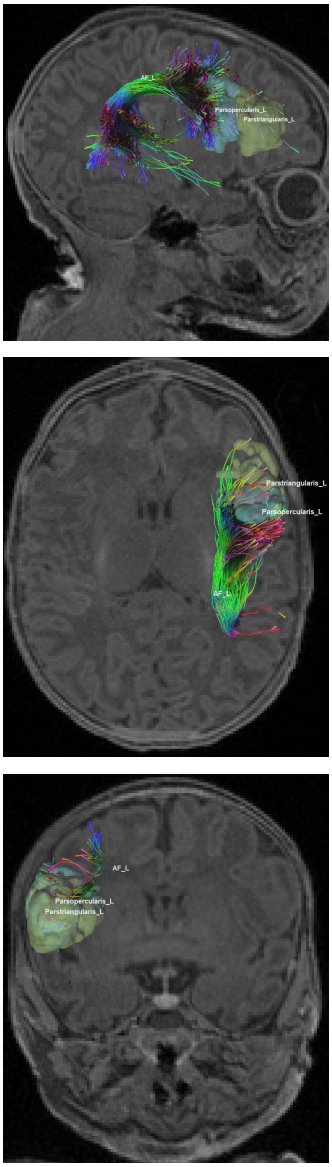

Figure S2: The extracted **AF** in the left hemisphere of a neonate reaches BA 44 (Parsopercularis_L, denoted by light blue) and BA 45 (Parstriangularis_L denoted by light green). While earlier studies of infant brain connectivity primarily utilized diffusion tensor imaging (DTI) approaches (*105*, *106*), our analysis employed constrained spherical deconvolution (CSD) and high-angular-resolution diffusion imaging (HARDI), which offer improved sensitivity and specificity in resolving crossing fibers and sparse connectivity patterns. Furthermore, we applied adaptive streamline termination thresholds and infant-specific, anatomically constrained tractography protocols (see detailed description in Supplementary Methods), which likely contributed to our observation of subtle **AF** connectivity reaching inferior frontal regions in neonates.

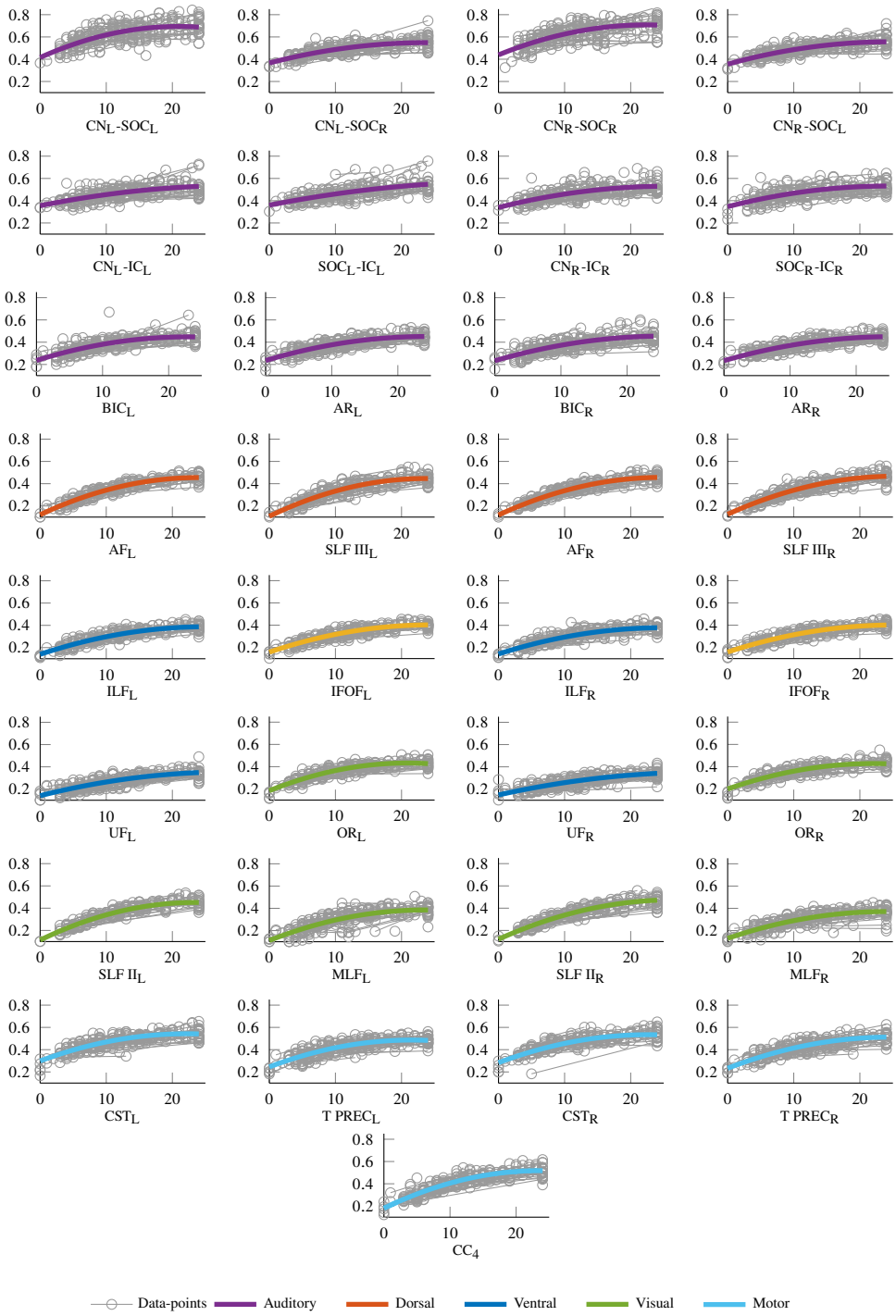

Figure S3: Individual NDI data points and fitted curves across both hemispheres from neonatal to 24 months. The solid colored lines represent fitted population-level developmental trajectories using LMMs, illustrating both inter-subject variability and consistent maturation patterns. Some tracts exhibit slight declines at higher maturity levels, likely due to excluding data points at older ages (> 24 months), and including later developmental data could potentially clarify these patterns.

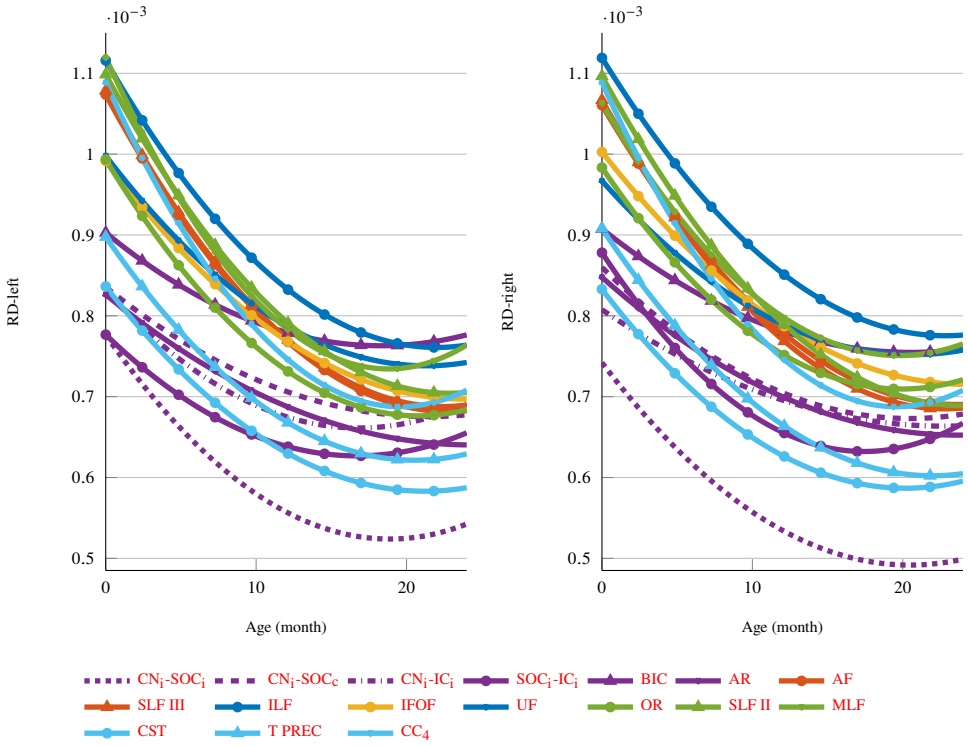

Figure S4: Developmental trajectories of white matter microstructure characterized by radial diffusivity (RD) across both hemispheres from neonatal to 24-month-old infants.

Table S1: Summary of infant dMRI data samples employed after applying quality control procedures to exclude scans with acquisition issues or severe artifacts.

Age	**2 wk**	**1 mo**	**2 mo**	**3 mo**	**4 mo**	**5 mo**	**6 mo**	**7 mo**	**8 mo**	**9 mo**	**10 mo**	**11 mo**	**12 mo**
Sample size (N)	5	2	1	9	9	17	14	10	14	17	7	13	17
Age		**13 mo**	**14 mo**	**15 mo**	**16 mo**	**17 mo**	**18 mo**	**19 mo**	**20 mo**	**21 mo**	**22 mo**	**23 mo**	**24 mo**
Sample size (N)		10	10	15	10	5	8	7	6	5	5	6	24

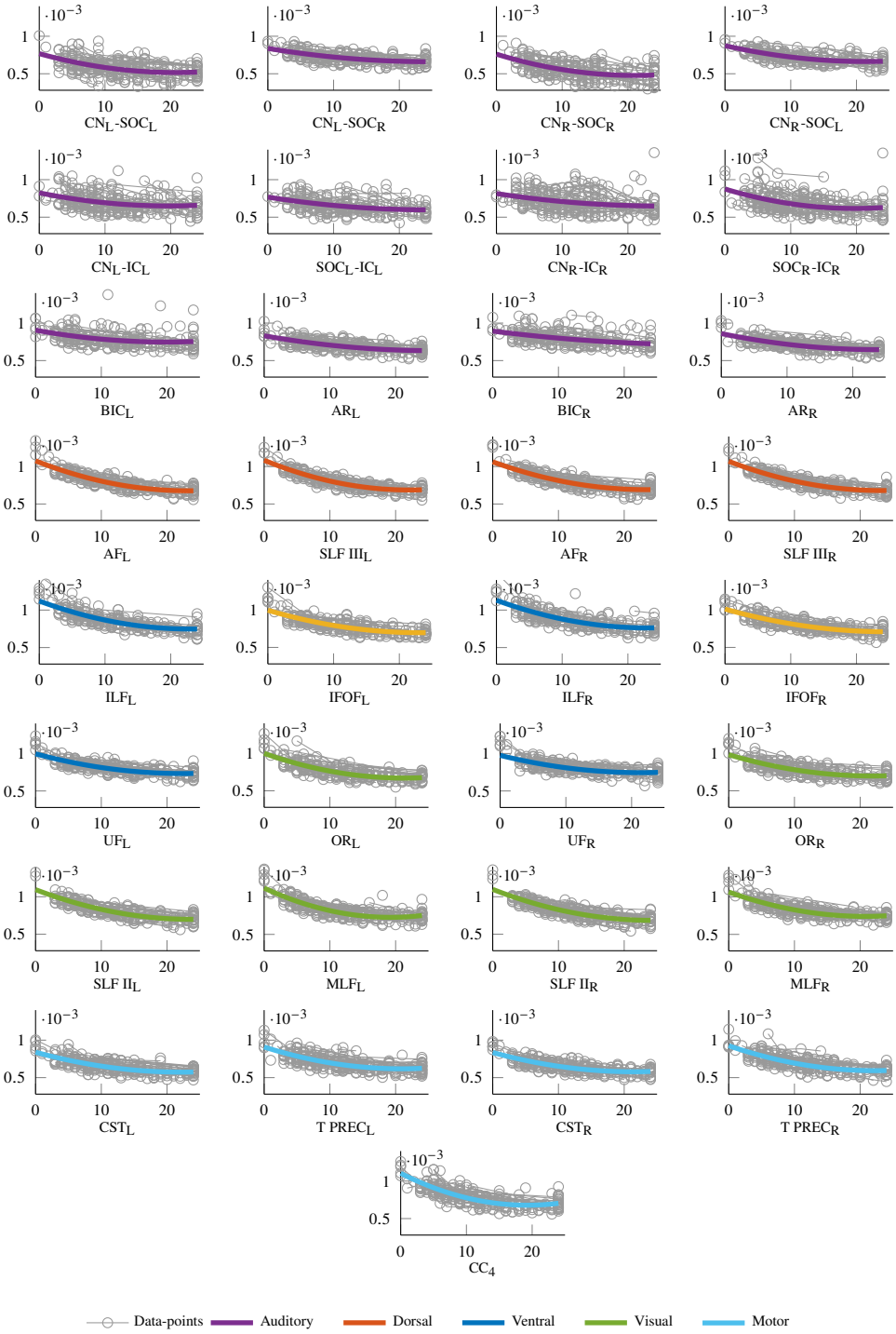

Figure S5: Individual data points and fitted curves representing radial diffusivity (RD) across both hemispheres, from birth through 24 months. Data points reflect measured mean RD values, and fitted curves show the estimated developmental trajectory of each tract.

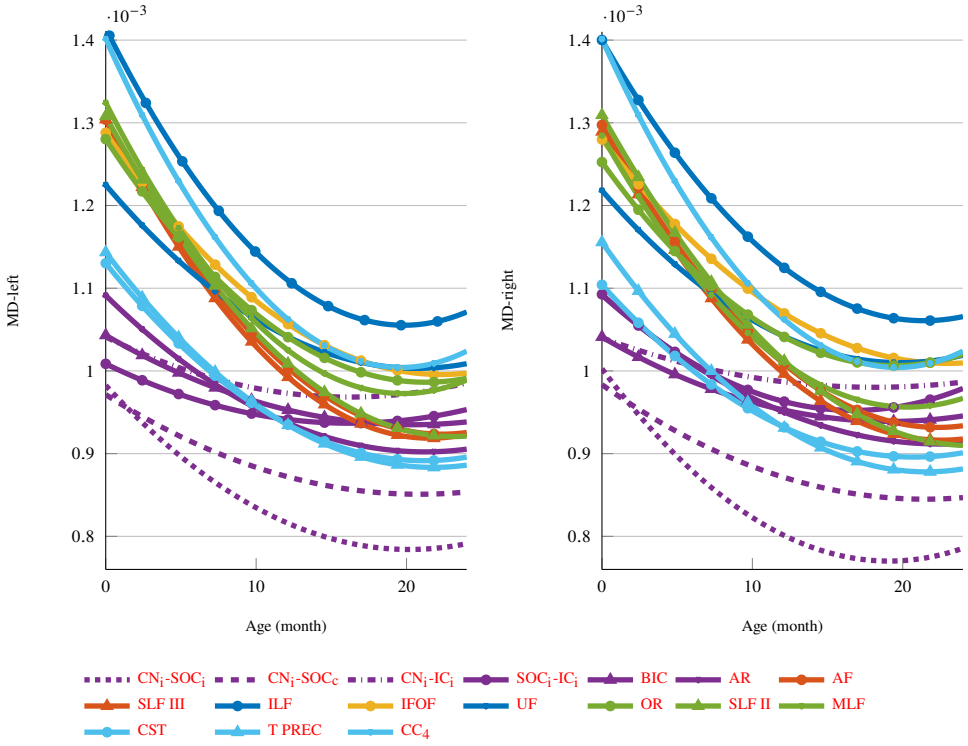

Figure S6: Developmental trajectories of white matter microstructure characterized by mean diffusivity (MD) across both hemispheres from neonatal to 24-month-old infants.

Table S2: Comparison of linear, logarithmic, and quadratic models in LMMs based on adjusted r-squared and AIC performance among for auditory tracts.

Tract name		CN_L-SOC_L	CN_L-SOC_R	CN_R-SOC_R	CN_R-SOC_L	CN_L-IC_L	SOC_L-IC_L	CN_R-IC_R	SOC_R-IC_R	BIC_L	AR_L	BIC_R	AR_R
Linear	p	4.79e-26	1.89e-35	1.70e-26	3.05e-41	1.47e-27	1.69e-33	1.44e-33	6.43e-28	3.71e-41	6.47e-56	2.03e-41	1.48e-60
	$r^2 \uparrow$	0.7140	0.8796	0.8074	0.8909	0.8818	0.7923	0.7408	0.7946	0.9068	0.8892	0.9011	0.8476
	AIC $\downarrow$	-514.23	-816.07	-519.94	-836.21	**-716.33**	**-718.99**	-694.47	-694.17	-770.46	-874.04	-747.59	-871.90
Logarithm	$p \downarrow$	5.04e-36	3.79e-46	8.38e-39	2.30e-53	2.21e-27	3.49e-31	4.74e-31	1.37e-36	3.23e-43	1.83e-56	4.35e-39	2.93e-55
	$r^2 \uparrow$	0.7812	0.8794	0.8318	0.8580	0.8395	0.7609	**0.7758**	0.7900	0.9072	0.9113	**0.9141**	0.8895
	AIC $\downarrow$	**-555.17**	**-847.69**	**-561.43**	**-857.30**	-707.14	-712.44	**-703.52**	**-722.32**	**-795.78**	**-906.62**	**-764.61**	**-896.21**
Quadratic	p	6.90e-17	2.00e-19	3.39e-12	3.65e-24	1.64e-09	6.97e-08	3.17e-12	9.87e-11	2.90e-25	3.28e-26	1.43e-16	7.84e-26
	$r^2 \uparrow$	**0.8211**	**0.9319**	**0.8747**	**0.9032**	**0.9013**	**0.8110**	0.7675	**0.8038**	**0.9410**	**0.9254**	0.9055	**0.8950**
	AIC $\downarrow$	-524.66	-820.68	-528.20	-838.97	-704.00	-698.70	-683.24	-690.49	-793.89	-900.76	-750.89	-890.55

AIC=akaike information criterion; L=left; R=right; **CN=cochlear nucleus**; **SOC=superior olivary complex**; **IC=inferior colliculus**; **BIC=brachium of the inferior colliculus**; **AR=acoustic radiation**.

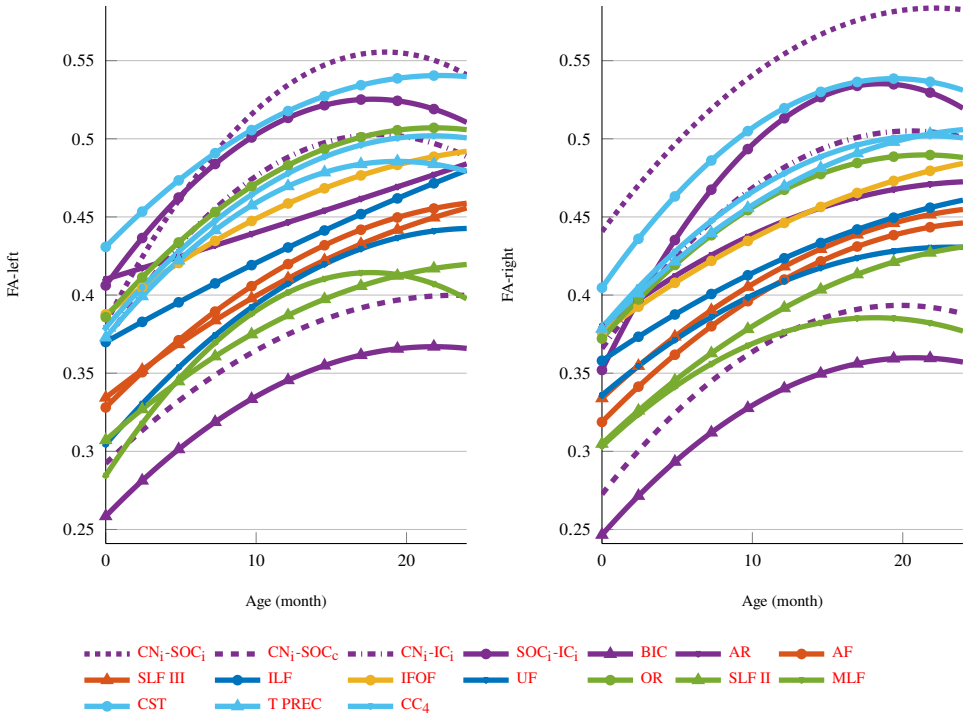

Figure S7: Developmental trajectories of white matter microstructure characterized by fractional anisotropy (FA) across both hemispheres from neonatal to 24-month-old infants.

Table S3: Comparison of linear, logarithmic, and quadratic models in LMMs based on adjusted r-squared and AIC performance for major tracts in left hemisphere.

Tract name		AF	SLF III	ILF	IFOF	UF	OR	SLF II	MLF	CST	T PREC	CC 4
Linear	p	8.38e-81	2.25e-72	7.59e-63	1.11e-71	1.75e-57	1.47e-49	3.70e-78	6.63e-51	8.66e-46	4.49e-46	2.85e-66
	$r^2 \uparrow$	0.9515	0.9426	0.9469	0.9530	0.9549	0.9256	0.9669	0.8200	0.9125	0.7691	0.9193
	AIC $\downarrow$	-832.38	-751.84	-867.01	-909.85	-896.60	-834.53	-810.49	-652.56	-776.55	-771.07	-735.43
Logarithm	p	1.90e-90	3.62e-77	2.67e-67	2.21e-75	4.83e-48	3.56e-76	1.42e-100	6.21e-43	1.34e-68	2.58e-55	2.21e-67
	$r^2 \uparrow$	0.9807	0.9747	**0.9561**	**0.9708**	0.9443	0.9565	0.9932	0.8935	0.9236	0.8223	**0.9635**
	AIC $\downarrow$	-936.45	-818.96	**-908.26**	-963.81	-880.99	**-949.98**	-943.79	-672.10	**-850.82**	**-828.91**	-797.66
Quadratic	p	1.10e-71	2.80e-53	7.62e-42	1.48e-47	3.18e-20	1.12e-52	3.65e-71	1.36e-22	1.32e-27	7.00e-32	2.05e-45
	$r^2 \uparrow$	**0.9809**	**0.9837**	0.9233	0.9647	**0.9797**	**0.9628**	**0.9959**	**0.9027**	**0.9379**	**0.8250**	0.9534
	AIC $\downarrow$	**-961.34**	**-833.29**	-904.68	**-979.13**	**-907.79**	-937.37	**-966.21**	**-673.90**	-819.47	-816.58	**-807.99**

AIC=akaike information criterion; **AF**: **arcuate fasciculus**; **SLF III**: **superior longitudinal fasciculus III**; **ILF**: **inferior longitudinal fasciculus**; **IFOF**: **inferior fronto-occipital fasciculus**; **UF**: **uncinate fasciculus**; **OR**: **optic radiation**; **SLF II**: **superior longitudinal fasciculus II**; **MLF**: **middle longitudinal fasciculus**; **CST**: **corticospinal tract**; **T PREC**: **thalamo-precentral**; and **CC 4**: **corpus callosum anterior midbody** (**primary motor**).

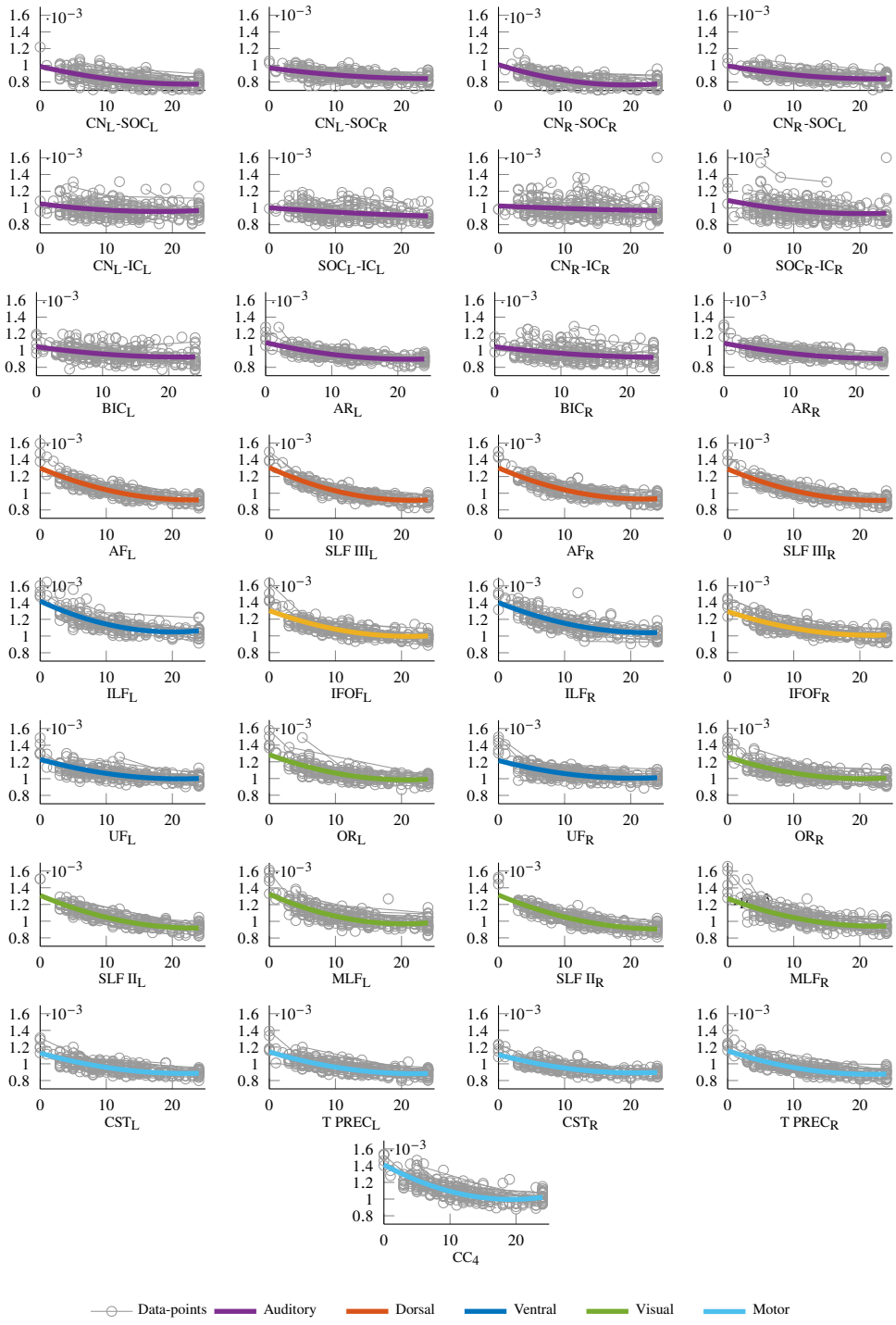

Figure S8: Individual data points and fitted curves representing mean diffusivity (MD) across both hemispheres, from birth through 24 months. Data points reflect measured mean MD values, and fitted curves show the estimated developmental trajectory of each tract.

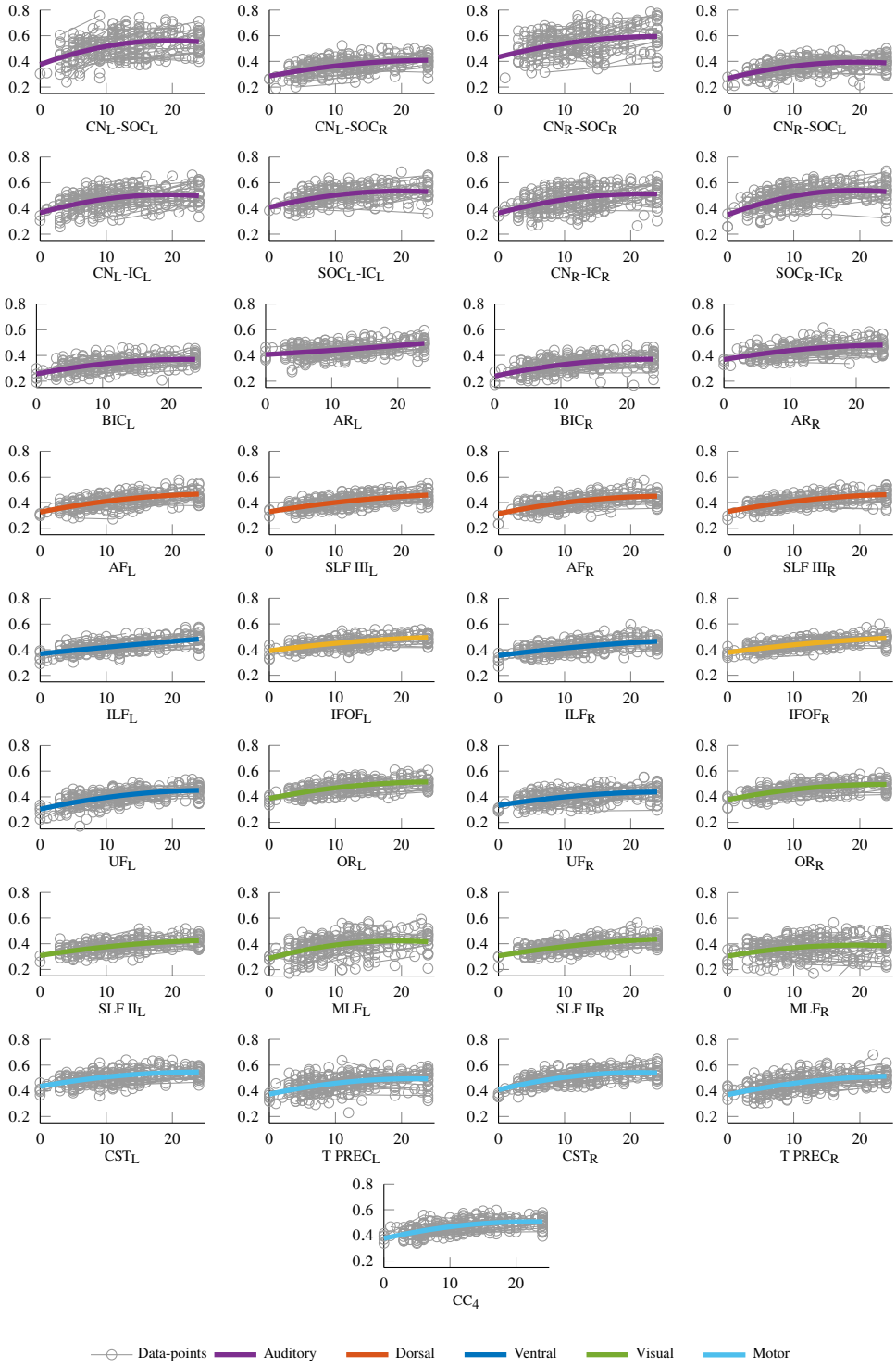

Figure S9: Individual data points and fitted curves representing fractional anisotropy (FA) across both hemispheres, from birth through 24 months. Data points reflect measured mean FA values, and fitted curves show the estimated developmental trajectory of each tract.

Table S4: Comparison of linear, logarithmic, and quadratic models in LMMs based on adjusted r-squared and AIC performance for major tracts in right hemisphere.

Tract name		AF	SLF III	ILF	IFOF	UF	OR	SLF II	MLF	CST	T PREC	CC 4
Linear	p	1.15e-86	1.87e-85	2.48e-63	1.17e-68	6.98e-53	3.54e-50	1.40e-88	1.26e-49	1.15e-86	1.70e-62	2.85e-66
	$r^2 \uparrow$	0.9494	0.9386	0.9208	0.9354	0.9410	0.9688	0.9766	0.9211	0.9279	0.8413	0.9193
	AIC $\downarrow$	-873.23	-827.82	-843.14	-918.38	-912.78	-839.25	-865.23	-793.70	-776.44	-774.12	-735.43
Logarithm	p	3.03e-94	9.26e-85	9.14e-63	3.21e-70	2.48e-44	1.56e-77	3.32e-93	2.53e-51	3.03e-94	1.78e-59	2.21e-67
	$r^2 \uparrow$	0.9769	**0.9694**	**0.9348**	0.9613	0.9127	0.9584	0.9848	0.9229	0.9197	0.9256	**0.9635**
	AIC $\downarrow$	-963.30	-882.94	-869.48	-962.88	-888.58	**-923.97**	-924.86	**-820.15**	**-837.81**	-811.35	-797.66
Quadratic	p	2.27e-66	4.00e-52	3.82e-40	1.94e-40	4.15e-15	5.15e-37	8.98e-60	4.04e-31	2.27e-66	3.70e-27	2.05e-45
	$r^2 \uparrow$	**0.9774**	0.9686	0.9207	**0.9726**	**0.9812**	**0.9751**	**0.9878**	**0.9580**	**0.9543**	**0.9462**	0.9534
	AIC $\downarrow$	**-981.34**	**-899.23**	**-877.80**	**-968.36**	**-916.90**	-897.93	**-946.34**	-818.08	-822.88	**-816.36**	**-807.99**

AIC=akaike information criterion; **AF**: **arcuate fasciculus**; **SLF III**: **superior longitudinal fasciculus III**; **ILF**: **inferior longitudinal fasciculus**; **IFOF**: **inferior fronto-occipital fasciculus**; **UF**: **uncinate fasciculus**; **OR**: **optic radiation**; **SLF II**: **superior longitudinal fasciculus II**; **MLF**: **middle longitudinal fasciculus**; **CST**: **corticospinal tract**; **T PREC**: **thalamo-precentral**; and **CC_4**: **corpus callosum anterior midbody** (**primary motor**).

Table S5: Eleven behavioral assessments used in this study

Assessment	Abbreviation	Usage in Analysis
MacArthur-Bates Communicative Development Inventories – Words and Gestures Form (*169*)	_mci_wg	Primary in all analyses
Mullen Scales of Early Learning (*170*)	_mullen	Primary
Vineland Adaptive Behavior Scales (*171*)	_vine	Primary
Infant-Toddler Social and Emotional Assessment (*172*)	_itsea	Primary
Repetitive Behavior Scale–Revised (*173*)	_rbsr	Primary
Child Behavior Checklist (*174*)	_cbcl	Supplementary only in tract - behavior analysis
Dimensional Joint Attention Assessment (*175*)	_djaa	Supplementary
Early Childhood Behavior Questionnaire (*176*)	_ecbq	Supplementary
Infant Behavior Questionnaire (*177*)	_ibq	Supplementary
Minnesota Executive Function Scale (*178*)	_mefs	Supplementary
Rating of Reciprocal Social Behavior (*179*)	_rrsb	Supplementary

Table S6: Summary of significant cross-sectional mediation pathways identified via piecewise structural equation modeling. Potential developmental cascades were evaluated across $74,409$ possible mediation pathway Combinations using tract-specific NDI mean values and behavioral measures. Pathways were rigorously screened by applying Benjamini-Hochberg False Discovery Rate correction, resulting in 849 significant mediation pathways from $74,276$ testable cases (excluded null pathways). Predictors (X), mediators (M), and outcomes (Y) include white matter tract maturation and behavioral measures across motor skills, social interaction, visual awareness, emotional regulation, living skills, and speech domains. Hypotheses for each model reflect the expected indirect contributions of early developmental factors to later speech and cognitive outcomes.

ID	Pathways model	Combinations	Significant pathways	Purpose and theoretical hypothesis
A1	Tract → Motor → Speech	6,006	44	Tract maturation supports speech development indirectly via enhanced motor skills.
A2	Tract → Social → Speech	5,148	0	Tract maturation supports speech development indirectly via enhanced social interactions.
A3	Tract → Visual → Speech	1,287	7	Tract maturation supports speech development indirectly via visual processing.
B1	Tract → Social → Motor	5,544	0	Tracts maturation supports motor skills indirectly via enhanced social interactions.
B2	Tract → Motor → Social	5,544	42	Tracts maturation supports social interactions indirectly via enhanced motor skills.
B3	Tract → Motor → Emotional	7,854	0	Tracts maturation supports emotional regulation indirectly via motor skills.
B4	Tract → Social → Emotional	6,732	0	Tracts maturation supports emotional regulation indirectly via social interactions.
B5	Tract → Motor → Living Skills	5,082	24	Tracts maturation supports living skills indirectly via enhanced motor skills.
B6	Tract → Social → Living Skills	4,356	0	Tracts maturation supports living skills indirectly via enhanced social interactions.
C1	Tract → Emotional → Speech	7,293	0	Tracts maturation supports speech indirectly via enhanced emotional regulation.
C2	Tract → Living Skills → Speech	4,719	1	Tracts maturation supports speech indirectly via enhanced living skills.
D1	Motor → Visual → Speech	546	80	Early motor skills support speech indirectly via improved visual processing.
D2	Social → Visual → Speech	468	3	Early social interactions support speech indirectly via improved visual processing.
D3	Motor → Emotional → Speech	3,094	4	Early motor skills support speech indirectly via improved emotional regulation.
D4	Social → Emotional → Speech	2,652	1	Early social interactions support speech indirectly via improved emotional regulation.
D5	Motor → Living Skills → Speech	2,002	171	Early motor skills support speech indirectly via improved living skills.
D6	Social → Living Skills → Speech	1,716	164	Early social interactions support speech indirectly via improved living skills.
E1	Social → Motor → Speech	2,184	145	Early social interactions facilitate speech indirectly through enhanced motor skills.
E2	Motor → Social → Speech	2,184	163	Early motor skills facilitate speech indirectly through enhanced social interactions.
	$74,409$ **Combinations in Total**			849 **out of** $74,276$ **potential pathway using FDR correction**

Table S7: Regions of interest (ROIs) defined along the auditory pathway, used in Tables S8 and supplementary files (`0_summary_matched_t_b_item_number.csv`, `1_significant_relationships_t_b_ordered_by_behavior.csv`, `1_significant_relationships_t_b_ordered_by_tract.csv`, `2_combined_results_with_fdr_and_mediation.csv`).

ROI	Cortical region
roi1	cochlear nucleus (CN) left
roi2	cochlear nucleus right
roi3	superior olivary complex (SOC) left
roi4	superior olivary complex right
roi5	inferior colliculus (IC) left
roi6	inferior colliculus right
roi7	medial geniculate body (MGB) left
roi8	medial geniculate body right
pacl	primary auditory cortex (PAC) left
pacr	primary auditory cortex right

Table S8: Group 1: Tract Variables

Variable	Source
avg_AF_l	Tract Extraction (NDI mean)
avg_AF_r	Tract Extraction (NDI mean)
avg_SLF3_l	Tract Extraction (NDI mean)
avg_SLF3_r	Tract Extraction (NDI mean)
avg_ILF_l	Tract Extraction (NDI mean)
avg_ILF_r	Tract Extraction (NDI mean)
avg_IFO_l	Tract Extraction (NDI mean)
avg_IFO_r	Tract Extraction (NDI mean)
avg_UF_l	Tract Extraction (NDI mean)
avg_UF_r	Tract Extraction (NDI mean)
avg_OR_l	Tract Extraction (NDI mean)
avg_OR_r	Tract Extraction (NDI mean)
avg_SLF2_l	Tract Extraction (NDI mean)
avg_SLF2_r	Tract Extraction (NDI mean)
avg_MLF_l	Tract Extraction (NDI mean)
avg_MLF_r	Tract Extraction (NDI mean)
avg_CST_l	Tract Extraction (NDI mean)
avg_CST_r	Tract Extraction (NDI mean)
avg_TPREC_l	Tract Extraction (NDI mean)
avg_TPREC_r	Tract Extraction (NDI mean)
avg_CC_4	Tract Extraction (NDI mean)
avg_roi1toroi4	Tract Extraction (NDI mean)
avg_roi2toroi3	Tract Extraction (NDI mean)
avg_roi1toroi5	Tract Extraction (NDI mean)
avg_roi2toroi6	Tract Extraction (NDI mean)
avg_roi5toroi7	Tract Extraction (NDI mean)
avg_roi6toroi8	Tract Extraction (NDI mean)
avg_roi7topacl	Tract Extraction (NDI mean)
avg_roi8topacr	Tract Extraction (NDI mean)
avg_roi1toroi3	Tract Extraction (NDI mean)
avg_roi2toroi4	Tract Extraction (NDI mean)
avg_roi3toroi5	Tract Extraction (NDI mean)
avg_roi4toroi6	Tract Extraction (NDI mean)

See Table S7 for the definitions of pacl, pacr, and roi1 to roi8.

Table S9: Group 2: Speech Variables

Variable	Source
mcg ph total mci wg	MacArthur-Bates CDI - W & G
mcg vc totcom mci wg	MacArthur-Bates CDI - W & G
mcg vc totpr mci wg	MacArthur-Bates CDI - W & G
Receptive Language T Score	Mullen Scales of Early Learning
Expressive Language T Score	Mullen Scales of Early Learning
Receptive Language Raw Score	Mullen Scales of Early Learning
Expressive Language Raw Score	Mullen Scales of Early Learning
receptive subdomain Raw Score	Vineland Adaptive Behavior Scales
expressive subdomain Raw Score	Vineland Adaptive Behavior Scales
receptive subdomain v Scale Score	Vineland Adaptive Behavior Scales
expressive subdomain v Scale Score	Vineland Adaptive Behavior Scales
communication domain Domain Standard Score	Vineland Adaptive Behavior Scales
communication domain v Scale Score	Vineland Adaptive Behavior Scales

Table S10: Group 3: Social Variables

Variable	Source
interpersrelationsubdom v Scale Score	Vineland Adaptive Behavior Scales
playleisuretimesubdomain v Scale Score	Vineland Adaptive Behavior Scales
interpersrelationsubdom Raw Score	Vineland Adaptive Behavior Scales
playleisuretimesubdomain Raw Score	Vineland Adaptive Behavior Scales
socializationdomain v Scale Score	Vineland Adaptive Behavior Scales
socializationdomain Domain Standard Score	Vineland Adaptive Behavior Scales
Competence domain compliance mean raw score	Infant-Toddler Social and Emotional Assessment
Competence domain imitation play mean raw score	Infant-Toddler Social and Emotional Assessment
Competence domain empathy mean raw score	Infant-Toddler Social and Emotional Assessment
Internalizing domain inhibition to novelty mean raw score	Infant-Toddler Social and Emotional Assessment
Social relatedness item cluster mean raw score	Infant-Toddler Social and Emotional Assessment
Hours spend with other children weekly	Infant-Toddler Social and Emotional Assessment

Table S11: Group 4: Motor Variables

Variable	Source
mcg eg total mci wg	MacArthur-Bates CDI - W & G
mcg lg total mci wg	MacArthur-Bates CDI - W & G
mcg tg total mci wg	MacArthur-Bates CDI - W & G
Gross motor T Score	Mullen Scales of Early Learning
Fine Motor T Score	Mullen Scales of Early Learning
Gross Motor Raw Score	Mullen Scales of Early Learning
Fine Motor Raw Score	Mullen Scales of Early Learning
gross subdomain Raw Score	Vineland Adaptive Behavior Scales
fine subdomain Raw Score	Vineland Adaptive Behavior Scales
gross subdomain v Scale Score	Vineland Adaptive Behavior Scales
fine subdomain v Scale Score	Vineland Adaptive Behavior Scales
motorskills domain v Scale Score	Vineland Adaptive Behavior Scales
motorskills domain Domain Standard Score	Vineland Adaptive Behavior Scales
Repetitive Motor Mean frequency score	Repetitive Behavior Scale-Revised

Table S12: Group 5: Visual & Cognitive Variables

Variable	Source
Visual Reception T Score	Mullen Scales of Early Learning
Visual Reception Raw Score	Mullen Scales of Early Learning
Cognitive T Score Sum	Mullen Scales of Early Learning

Table S13: Group 6: Daily Living Skills Variables

Variable	Source
personal subdomain Raw Score	Vineland Adaptive Behavior Scales
domestic subdomain Raw Score	Vineland Adaptive Behavior Scales
community subdomain Raw Score	Vineland Adaptive Behavior Scales
coping skills subdomain Raw Score	Vineland Adaptive Behavior Scales
personal subdomain v Scale Score	Vineland Adaptive Behavior Scales
domestic subdomain v Scale Score	Vineland Adaptive Behavior Scales
community subdomain v Scale Score	Vineland Adaptive Behavior Scales
coping skills subdomain v Scale Score	Vineland Adaptive Behavior Scales
living skills domain v Scale Score	Vineland Adaptive Behavior Scales
living skills domain Domain Standard Score	Vineland Adaptive Behavior Scales
Sum of Domain Standard Scores	Vineland Adaptive Behavior Scales

Table S14: Group 7: Emotional and Regulatory Behavior Variables

Variable	Source
Total Competence T Score	Infant-Toddler Social and Emotional Assessment
Dysregulation domain sleep mean raw score	Infant-Toddler Social and Emotional Assessment
Dysregulation domain eating mean raw score	Infant-Toddler Social and Emotional Assessment
Competence domain mastery motivation mean raw score	Infant-Toddler Social and Emotional Assessment
Externalizing domain mean raw score	Infant-Toddler Social and Emotional Assessment
Internalizing domain mean raw score	Infant-Toddler Social and Emotional Assessment
Externalizing domain activity impulsivity mean score	Infant-Toddler Social and Emotional Assessment
Internalizing domain depression withdrawal mean score	Infant-Toddler Social and Emotional Assessment
Externalizing domain aggression defiance mean raw score	Infant-Toddler Social and Emotional Assessment
Externalizing domain peer aggression mean raw score	Infant-Toddler Social and Emotional Assessment
Competence domain prosocial peer relations mean raw score	Infant-Toddler Social and Emotional Assessment
Maladaptive item cluster mean raw score	Infant-Toddler Social and Emotional Assessment
Atypical item cluster mean raw score	Infant-Toddler Social and Emotional Assessment
Self Directed Self Injurious Mean frequency score	Repetitive Behavior Scale-Revised
Restricted Behavior Mean frequency score	Repetitive Behavior Scale-Revised
Ritual Routine Behavior Mean frequency score	Repetitive Behavior Scale-Revised
Composite Score Mean frequency score	Repetitive Behavior Scale-Revised