

Perception, Discrimination, and Learning of Speech in Newborns

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Abstract

From birth, newborns begin to utilize their well-developed auditory system for neural representation and learning/memory of various speech elements. Investigating the characteristics of speech processing in newborns can not only reveal the cognitive neural mechanisms of language function in the earliest stages of human development, but also provide valuable clues for early warning and clinical diagnosis of neurodevelopmental disorders such as autism. We reviewed and summarized newborns' perception, discrimination, and learning of speech, as well as the predictive role of language development for autism, and found that newborns exhibit perceptual preferences for specific speech; newborns possess unique phonemic discrimination abilities; brain functional or structural indices of language processing in infancy have certain predictive value for autism. We propose that future research should proceed along three directions. In terms of basic research: First, strictly control prosodic factors in speech materials to re-examine characteristics of newborn language processing and the issue of cerebral lateralization; Second, reveal the cognitive neural mechanisms of newborn speech learning and the memory consolidation role of sleep. In terms of clinical translational research, using high-risk autism newborns as longitudinal tracking subjects, establish a disease risk assessment system based on longitudinal multimodal brain observation data to reveal the predictive value of early postnatal language development brain indices for autism.

Full Text

Preamble

Title: Newborn Perception, Discrimination, and Learning of Speech Sounds

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Abstract: From the moment of birth, newborns begin to utilize their mature auditory system to form neural representations and learn the various elements of speech. Investigating the characteristics of speech processing in newborns not only reveals the neurocognitive mechanisms of language function in the earliest stages of human development but also provides valuable clues for the early warning and clinical diagnosis of neurodevelopmental disorders such as autism. This review summarizes research on newborn perception, discrimination, and learning of speech sounds, as well as the predictive value of language development for autism. We found that newborns exhibit perceptual preferences for specific speech sounds, possess unique phoneme discrimination abilities, and that brain functional and structural indices of language processing in infancy have predictive value for autism. We propose that future research should address three key areas. In basic research: first, strictly control the prosodic features of speech materials to re-examine characteristics of newborn language processing and brain lateralization; second, reveal the neurocognitive mechanisms of newborn speech learning and the role of sleep in memory consolidation. In clinical translation research: track high-risk autism newborns longitudinally, establish disease risk assessment systems based on multimodal brain observation data, and reveal the predictive value of early brain indices of language development for autism.

Keywords: newborn, native language preference, left lateralization, language development, autism spectrum disorder

Language is the primary means of human communication. “How does language develop? Which parts of the brain control it?” This question, posed twice by *Science* in 2005 and 2021 among its 125 frontier scientific questions, represents a significant focus for psychologists and linguists. Speech serves as the crucial vehicle for language; individuals must first perceive speech sounds before mastering articulation and using them to convey meaning to others. Human fetuses are typically born at 37–42 weeks gestational age. The period from birth to 28 days is defined as the newborn stage, from 29 days to 12 months as infancy, and 1–3 years as toddlerhood. Within this developmental trajectory of language capacity, newborns occupy a critical stage for speech perception. This article focuses on newborn perception, discrimination, and learning of speech sounds.

The auditory system begins functioning as early as 24 weeks gestational age (Hepper & Shahidullah, 1994), enabling fetuses to ‘hear’ sounds from outside the womb. However, these sounds undergo low-pass filtering by maternal tissues, losing high-frequency characteristics. Only at birth do newborns become directly exposed to the language environment, at which point they begin using their mature auditory system to form neural representations and learn the various elements of language. Newborns possess remarkable phoneme discrimination abilities, enabling them to distinguish vowels and consonants across different languages. Following several months of native language exposure, infants become more sensitive to native phonemes while losing the ability to discriminate

foreign phonemes (Cheour et al., 1998; Kuhl, 2010; Werker et al., 2012). Language learning plays a crucial role in this rapid ‘perceptual narrowing’ process. Prior to perceptual narrowing, newborns’ heightened sensitivity to phonemes across languages represents the most unique language perception and discrimination ability in early human language development. Investigating newborn perception, discrimination, and learning of speech sounds not only reveals the neurocognitive mechanisms of language function in the earliest developmental stages, helping to construct theories in developmental linguistics and psychology, but also provides valuable clues for early warning and clinical diagnosis of neurodevelopmental disorders such as autism.

2. Newborn Preferences for Speech Perception

Early studies of newborns and infants typically employed the ‘habituation-dishabituation paradigm’ using ‘pacifier sucking frequency’ as an index. Experimenters first familiarized participants with specific speech materials, during which the ‘habituation’ process was typically accompanied by a gradual decline in pacifier sucking frequency. Subsequently, participants were presented with novel speech materials. If pacifier sucking frequency suddenly increased, it indicated that participants could perceive differences between old and new stimuli, with the new speech material triggering a ‘dishabituation’ process. Using this paradigm, numerous behavioral studies have found that newborns exhibit perceptual preferences for speech sounds, native language, and their mother’s voice (see reviews: Zhou & Zhang, 2017; Yu et al., 2022). In short, during the dishabituation process, newborns show significantly higher pacifier sucking frequencies when listening to speech compared to non-speech sounds, indicating greater attentional preference for the former (Vouloumanos & Werker, 2007). Moreover, newborns exhibit higher sucking frequencies when listening to native language compared to foreign language (Mehler et al., 1988; Moon et al., 1993). Studies comparing mothers’ voices to those of other women have found that newborns prefer the former, showing higher sucking frequencies when listening to their mother’s voice (DeCasper & Fifer, 1980).

Since newborns cannot follow instructions to produce conscious, active behavioral responses, behavioral indices are susceptible to interference from task-irrelevant factors. In contrast to behavioral studies, advances in brain imaging techniques have enabled researchers in recent years to directly observe newborn brain responses to speech perception using methods such as electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS). EEG methods primarily employ event-related potential techniques using the oddball paradigm, focusing on the ‘mismatch response’ (MMR) component, which represents an early form of the adult mismatch negativity (MMN). For example, Beauchemin et al. (2011) found that mothers’ voices elicited larger amplitude and shorter latency MMRs in newborn brains compared to other women’s voices. Compared to EEG, fNIRS helps reveal the sensitivity and specificity of cortical regions involved in newborn speech processing. A meta-analysis based on fNIRS (Chen

et al., 2020) indicates that the brain regions involved in newborn speech perception are primarily the frontal, temporal, and inferior parietal lobes, showing left-hemisphere advantage. This left-lateralized activation is also influenced by experimental contrast conditions: when comparing non-speech sounds (such as whistled communication) to foreign language, newborns show stronger brain activation in temporal and frontal lobes for foreign language, manifesting left lateralization (May et al., 2018). When comparing native to foreign language, although both activate bilateral temporal lobes, activation in the left temporal lobe is stronger than the right under native language conditions (Kotilahti et al., 2010; May et al., 2018; Peña et al., 2003; Sato et al., 2012; Vannasing et al., 2016). The left-lateralization advantage in language processing is evident not only at the functional level but also in the morphology of the temporal lobe in newborns (including preterm infants born after 29 weeks gestation), which shows leftward asymmetry (see review Bisiacchi & Cainelli, 2022). For instance, research has found that language-related brain regions in newborns (primarily superior temporal and inferior frontal areas) exhibit left-lateralization advantages in cortical surface area and thickness (Li et al., 2014). Additionally, language brain networks show more efficient structural connectivity in the left hemisphere (Ratnarajah et al., 2013), and white matter connectivity in the left hemisphere of newborns can predict syntactic and other language abilities at 12 months of age (Sket et al., 2019).

3. Newborn Discrimination of Speech Elements

In addition to these speech perception preferences, newborns possess remarkable phoneme discrimination abilities, enabling them to distinguish vowels and consonants across different languages (note: phonemes are categorized into vowels and consonants) and, based on this, to discriminate syllables (combinations of vowels and consonants) and syllable sequences (Chen & Zhang, 2020). Newborns can simultaneously discriminate phonemes from both native and foreign languages, representing the most unique language ability at this developmental stage (compared to infants, children, and adults). Using the habituation-dishabituation paradigm, Moon et al. (2013) found in a classic developmental language study that newborns could discriminate vowels in both native and foreign language conditions, with stronger discrimination abilities for native vowels. This latter finding suggests a role for prenatal learning, as fetuses can hear the mother's surrounding environment and her own native language production by 24 weeks gestational age. Behavioral studies have also found that newborns can discriminate sentences from different languages (Ramus et al., 2000), identify syllables (Bertoncini et al., 1987), and detect stress patterns in syllables (Sansavini et al., 1997).

Beyond behavioral observations, numerous brain science studies have directly demonstrated newborns' remarkable abilities to discriminate speech elements. EEG and magnetoencephalography studies using the oddball paradigm and MMR as an index have found that newborn brains can discriminate vowels

(Cheour-Luhtanen et al., 1995; Kostilainen et al., 2020; Kujala et al., 2004; Partanen et al., 2013), vowel pitch (Kujala et al., 2004), and consonants (Mahmoudzadeh et al., 2017; Partanen et al., 2013), with shorter MMR latencies in the left hemisphere compared to the right (Mahmoudzadeh et al., 2017). fNIRS research has revealed that newborns' temporal, frontal, and parietal lobes can discriminate vowels (Benavides-Varela et al., 2012). Even preterm newborns at 30 weeks gestational age demonstrate left-hemisphere advantage for language, with faster and more sustained neural responses to syllables in the left temporal lobe compared to the right, and the left inferior frontal gyrus can discriminate consonants but not speaker gender (Mahmoudzadeh et al., 2013). Furthermore, brain imaging studies have found that newborn brains can perceive and discriminate syllable sequences: they produce larger negative brain waves in response to the first syllable of a sequence (Teinonen et al., 2009); bilateral temporal lobes and left inferior frontal gyrus can distinguish between three different sequences composed of three distinct syllables (designated ABC): ABB, AAB, and ABC (Gervain et al., 2008; 2012); and exchanging the first and last syllables in a sequence activates temporal and frontal lobes more than exchanging middle syllables (Ferry et al., 2016). Newborns' perception and discrimination of syllable sequence structure forms the foundation for lexical segmentation of speech streams and statistical language learning during the newborn and infant stages.

4. Newborn Speech Learning

The aforementioned studies on newborn speech perception and phoneme discrimination either passively observed fetal language learning by leveraging prenatal language exposure (e.g., Moon et al., 2013) or examined newborn speech perception abilities at a single time point (all studies except Moon et al.). To date, only one fetal study (Partanen et al., 2013) has employed speech learning materials and observed learning-induced changes in newborn brain function: experimenters had fetuses listen to an 8-minute syllable sequence daily from 29 weeks gestation until birth (containing standard stimulus /tatata/, vowel variant /tatota/, and pitch variant /tatāta/). Results showed that after birth, newborns in the learning group exhibited larger MMR amplitudes for the learned pitch variant compared to control groups, but no group differences were found for the vowel variant condition. This study demonstrates that prenatal learning can create speech memory representations while also suggesting limitations to prenatal learning.

To date, only two studies have revealed learning-induced brain plasticity changes by observing and comparing newborn brain activity before and after speech learning. The first study (Cheour et al., 2002) had newborns listen to vowel materials (/y/ and /i/) for 2.5–5 hours during nighttime sleep and tested learning effects using EEG with standard stimulus /y/ and deviant stimuli /i/ and /y/i/ in an oddball paradigm. Results showed that although newborns could discriminate the single vowels /y/ and /i/ before learning, only after nighttime learning could they discriminate /y/ and the complex vowel /y/i/ the following

morning. Additionally, MMR amplitudes elicited by vowel /i/ were larger after learning than before. The study also found that this learning effect in newborns could be maintained until the following evening and generalized to the same vowels at different pitches, but not to unlearned vowel materials. The second study (Wu et al., 2022) used fNIRS to examine plastic changes in newborn cerebral cortex following vowel learning (listening to forward-played and reversed vowel materials). Results showed that compared to control groups, newborns in the learning group exhibited faster neural responses in bilateral frontal lobes (inferior frontal gyrus) to learned vowels at the end of the 5-hour learning period (compared to learned control sounds—reversed vowels). After 2 hours of sleep following learning, bilateral superior temporal gyri, supramarginal gyri, and left inferior parietal regions showed stronger activation to learned vowels (compared to control sounds).

Notably, Wu et al. (2022) also found that newborns could not discriminate between vowels and control sounds before speech learning, which appears contradictory to previous studies (e.g., Moon et al., 2013) that found newborns possess vowel discrimination abilities. This discrepancy may arise because previous studies employed speech materials containing prosodic information (note: prosody, also called the ‘music of language,’ comprises features such as pitch, loudness, speech rate, and pauses). For example, some studies used vowels differing in pitch (e.g., Moon et al., 2013) or prosodically rich ‘motherese’ (Peña et al., 2003; Sato et al., 2012), the latter being the sing-song, exaggerated speech style adults use when communicating with infants (containing abundant prosodic information). Given newborns’ high sensitivity to speech prosody (Zhang et al., 2019; Zhang et al., 2019, 2023), vowel discrimination observed in these studies may actually reflect prosody discrimination. In contrast, Wu et al. (2022) strictly controlled prosodic features in their speech materials (see supplementary materials of that study) and found that newborn infants could not discriminate forward-played versus reversed vowels at birth, but acquired vowel discrimination abilities after several hours of speech learning.

Furthermore, the three aforementioned speech learning studies (Cheour et al., 2002; Partanen et al., 2013; Wu et al., 2022) examined only vowel learning. Although two newborn studies suggested that sleep has an important influence on speech learning (Cheour et al., 2002; Wu et al., 2022), because these experiments did not manipulate sleep, the memory consolidation role of sleep in newborn language learning remains unconfirmed.

5. Potential Predictive Value of Early Language Development for Autism

Autism spectrum disorder (ASD) is the most prevalent neurodevelopmental disorder in early childhood, characterized primarily by impairments in social interaction, communication deficits including language difficulties, and repetitive, stereotyped behaviors, which severely impact lifelong social functioning and quality of life (American Psychiatric Association, 2013). The current reported

global average prevalence is 1–2% (Hirota & King, 2023; World Health Organization, 2023; Zeidan et al., 2022). Language development impairment constitutes one of the primary concerns in ASD, as affected children often exhibit deficits in both receptive and expressive language abilities (Belteki et al., 2022), and show significant structural and functional abnormalities in language processing brain networks located in the temporal and frontal lobes (Tryfon et al., 2018). Early diagnosis and intervention can improve symptoms and prognosis to varying degrees, yet no studies have directly examined the relationship between newborn language development and autism. This section primarily reviews relevant research from infancy, focusing on longitudinal studies with predictive value for autism diagnosis. Participants in these longitudinal studies are typically infants at high risk for autism (HRA), defined as infants with genetic risk (family history), brain structural or functional abnormalities, or adverse prenatal factors (advanced maternal age, threatened abortion, viral infection, drug abuse, birth asphyxia, etc.) (Hirota & King, 2023).

Existing longitudinal tracking studies of HRA infants indicate that behavioral indices of language typically show predictive value for autism only after 12 months of age, whereas brain functional or structural indices of language processing demonstrate predictive value as early as 3 months of age or even earlier (Ayoub et al., 2022; Clairmont et al., 2022; Molnar-Szakacs et al., 2021). To date, four longitudinal tracking studies have investigated brain observations of language development in HRA infants, three of which demonstrate the predictive value of infant language brain indices for autism. Liu et al. (2020) used resting-state functional magnetic resonance imaging (fMRI) and found that functional connectivity in language brain networks was weaker in 1.5-month-old HRA infants compared to healthy controls. By 9 months, healthy infants showed enhanced functional connectivity primarily between auditory cortex and hippocampus, whereas HRA infants showed enhanced connectivity between auditory cortex and somatosensory cortex. Subsequently, this research group used fMRI to examine brain activity in 9-month-old infants listening to speech containing statistical and prosodic cues (Liu et al., 2021), finding reduced activation in left temporal lobe and amygdala and weakened functional connectivity between bilateral primary auditory cortex and right anterior insula in the HRA group compared to healthy controls. These neural indices during speech processing tasks could predict autism symptoms in the HRA group at 3 years of age. Pecukonis et al. (2021) used fNIRS to examine brain activity in 6-month-old infants listening to syllable sequences, finding that HRA infants later diagnosed with autism at 3 years showed weaker activation in bilateral frontal and anterior temporal lobes compared to both healthy controls and HRA infants not diagnosed with autism at 3 years. This suggests that frontal and temporal activation during speech processing at 6 months can effectively predict autism. Righi et al. (2014) used EEG to examine functional connectivity between frontal and temporal/parietal lobes in 12-month-old infants listening to speech, finding that language brain network connectivity strength decreased sequentially across three groups: healthy controls, HRA infants not diagnosed with autism at 3 years, and HRA infants

diagnosed with autism at 3 years. This study indicates that language brain network connectivity strength during speech processing at 12 months can provide valuable predictive information for autism diagnosis and symptom severity at 3 years. Additionally, non-longitudinal studies have found reduced habituation to repeated syllables in HRA infants: unlike healthy control infants who show habituation, repeated syllables continue to activate bilateral temporal lobes in 3-month-old HRA infants (Edwards et al., 2017) and elicit non-decremental P150 components in frontal lobes of 9-month-old HRA infants (Seery et al., 2014).

Additionally, fMRI studies using non-speech materials have found that 4–7-month-old HRA infants are less sensitive to human voices, showing weaker activation in right temporal lobe and medial frontal lobe in response to human vocal sounds compared to healthy control infants (Blasi et al., 2015; Braukmann et al., 2018).

Brain lateralization of language processing also has predictive value for autism. Reviews of children and adults indicate that left lateralization of language processing in individuals with autism is often reduced or absent (Lindell, 2020), sometimes even showing right lateralization in core language areas (superior temporal gyrus and inferior frontal gyrus) (Herringshaw et al., 2016). To date, five longitudinal tracking studies of HRA infants have investigated language lateralization, three of which demonstrate the predictive value of infant language lateralization indices for autism. Seery et al. (2013) found in an EEG study that syllable-evoked slow waves developed typical left lateralization in healthy control infants between 6 and 12 months, whereas HRA infants showed no such change over the six-month period. Similarly, Keehn et al. (2013) used fNIRS to examine changes in brain functional connectivity during syllable sequence processing in infants from 3 to 12 months, finding that functional connectivity in left-hemisphere language regions of 3-month-old HRA infants gradually weakened with age, becoming significantly weaker than healthy controls by 12 months. Finch et al. (2017) found that in a consonant discrimination task with 12-month-old infants, HRA infants later diagnosed with autism at 3 years showed right-lateralized MMR at 12 months, whereas healthy controls showed left-lateralized MMR. Thus, MMR lateralization during phoneme discrimination tasks in infancy may serve as an effective predictor of autism. The arcuate fasciculus is the neural pathway connecting core language regions Broca's area (in inferior frontal gyrus) and Wernicke's area (in superior temporal gyrus). Two MRI diffusion-weighted imaging studies found that at 1.5 months, healthy controls showed left lateralization of the arcuate fasciculus, whereas the HRA group showed right lateralization, and arcuate fasciculus lateralization could predict autism symptoms at 3 years (Liu et al., 2019). From 6 months onward, HRA infants later diagnosed with autism at 2 years already showed weaker language brain network connectivity centered on the arcuate fasciculus compared to healthy controls, and connectivity strength in HRA infants could predict autism symptoms at 2 years (Lewis et al., 2017). Additionally, fNIRS studies using non-speech materials found that compared to healthy controls and HRA infants not diagnosed with depression at 3 years, HRA infants diagnosed with

autism at 3 years showed reduced left temporal lobe activation to human voices and enhanced activation to non-human voices at 4–6 months, with this lateralization abnormality predicting autism symptoms at 3 years (Lloyd-Fox et al., 2018).

The aforementioned HRA infant studies have fully demonstrated the predictive value of early language development for autism. Simultaneously, we note that the brain indices and speech perception/discrimination tasks employed in these infant studies can be readily implemented during the newborn stage (see reviews in Sections 2–4 of this article). Given that younger age is associated with greater brain plasticity, obtaining neurobiological indices of language processing during the newborn period to construct the earliest behavioral-brain characteristic index system reflecting individual language capacity formation and development could provide the most temporally beneficial individualized early warning parameters for early autism diagnosis.

4. Research Outlook

In summary, current research on newborn speech perception, discrimination, and learning indicates that: 1) newborns exhibit speech perception preferences, showing greater preference for speech, native language, and mother’s voice, along with left-hemisphere brain lateralization; 2) newborns possess unique phoneme discrimination abilities, with brains capable of distinguishing vowels and consonants across all languages and already able to discriminate relatively complex syllables and syllable sequences; 3) speech learning during the newborn stage induces plastic changes in brain language neural networks. Additionally, numerous infant studies have found that brain indices of early language development have significant early warning and diagnostic value for autism. Based on existing research limitations, we identify three key issues requiring resolution in basic and clinical translation research on newborn language processing.

First, prosodic features of speech materials have not received adequate attention. The vast majority of existing newborn studies have not controlled for differences in prosodic features across conditions, potentially confounding results and conclusions in at least three ways. 1) Newborn phoneme discrimination may be confounded by prosody perception. As previously mentioned, some newborn studies used vowels differing in pitch (e.g., Moon et al., 2013) or prosodically rich ‘motherese’ as experimental materials (e.g., Peña et al., 2003; Sato et al., 2012) and found vowel discrimination abilities in newborns. However, Wu et al. (2022), after controlling for prosodic factors, found that newborn infants could not discriminate vowels at birth but could rapidly form neural representations and discriminate vowels after 5 hours of vowel learning. 2) Prosodic information in speech also raises questions about the effectiveness of fetal language learning. The only fetal speech learning study (Partanen et al., 2013) found that fetuses showed learning effects only for pitch, not for vowels, suggesting that fetuses may learn only prosodic rather than phonemic information. Similarly, newborns prefer native language over foreign language and also prefer

low-pass filtered native language (Mehler et al., 1988), suggesting that native language preference may result from fetal learning of prosodic cues in native language (note: fetuses hear low-pass filtered speech dominated by prosodic information). 3) Left lateralization of language processing in newborn brains may be influenced by prosodic factors. Lateralization reflects functional specialization of the brain, and left-hemisphere advantage for language is one of the most widely accepted conclusions in language science (Friederici, 2011; Hickok & Poeppel, 2007). Is left-hemisphere specialization for language innate? If newborn studies fail to find left-lateralization advantage for language, this may result from interference by prosodic factors in speech materials, as newborns process prosody with right-hemisphere lateralization (Cheng et al., 2012; Telkemeyer et al., 2009; Zhang et al., 2019; Zhang et al., 2023). For example, Perani et al. (2011) used ‘motherese’ storytelling materials to examine newborn language processing and found that speech conditions (compared to resting state) activated bilateral brains with right lateralization. May et al. (2011) low-pass filtered speech materials and found that native language (compared to foreign language) activated bilateral language regions in newborns. The failure of these two studies to find left lateralization for language may stem from prosodic features being highlighted and amplified in the speech materials. Notably, Arimitsu et al. (2011) separated phonemic and prosodic features of speech materials, finding that the newborn left brain (supramarginal gyrus) was primarily sensitive to vowel discrimination, whereas the right brain (temporal lobe) was primarily sensitive to prosody discrimination. In summary, given prosody’s interference in these three aspects of language research, we strongly recommend that future studies strictly control prosodic factors in speech materials to re-examine and validate existing conclusions regarding newborn speech perception preferences, phoneme discrimination abilities for vowels and consonants, brain lateralization of language processing, and fetal speech learning. Beyond excluding prosody’s influence on language research, we can also investigate how prosodic processing affects language learning. For example, research has found that prosodically rich ‘motherese’ facilitates effective speech encoding in 7-month-old infants (Kalashnikova et al., 2018) and promotes vocabulary learning in adults (Ma et al., 2020). Can prosodically rich speech materials help newborns learn language faster and better? This represents a valuable research direction.

Second, the neurocognitive mechanisms of newborn speech learning remain unclear. Nearly all newborn speech processing studies mentioned in this review employed either the habituation-dishabituation paradigm (behavioral and fNIRS studies) or the oddball paradigm (EEG and MEG studies using MMR as an index) to examine speech perception and discrimination abilities at single time points. Regarding speech learning, only two studies have investigated vowel learning in newborns (Cheour et al., 2002; Wu et al., 2022). Given that newborns show certain differences in perceiving vowels versus consonants (Benavides-Varela et al., 2012), how do newborns learn consonants? What neural plasticity changes occur in their brains during consonant learning? We recommend that future studies adopt the experimental paradigm of Wu et al. (2022),

using speech materials with strictly controlled prosodic features and employing EEG and fNIRS to investigate consonant learning in newborns. Beyond consonant learning, an equally important question concerns the role of sleep in newborn speech learning. Newborns sleep nearly 20 hours per day—can neural representations of speech elements formed during wakefulness be consolidated and strengthened through sleep? Research shows that sleep in adults helps consolidate new knowledge and skills, producing stable and durable memory representations (Diekelmann & Born, 2010), a process termed sleep-dependent memory consolidation (Stickgold, 2005). Numerous studies have found that brief periods of non-rapid eye movement (NREM) sleep have significant consolidation effects on declarative memory (including episodic and semantic memory) (Rasch et al., 2007), with consolidation effects closely related to sleep slow waves (Diekelmann et al., 2009). However, newborns possess only a rudimentary form of NREM sleep (called the ‘quiet sleep’ stage) and have not yet developed sleep slow waves (note: sleep slow waves can first be observed in infants at 2–4 months; Fattinger et al., 2014). The earliest reported sleep-dependent memory consolidation occurs at 3 months (Horváth et al., 2018), while sleep consolidation effects on language learning have been found as early as 6 months (Friedrich et al., 2017; Simon et al., 2017). We recommend that future studies manipulate sleep or use EEG to analyze the proportion of different sleep stages to reveal the memory consolidation role of sleep, particularly quiet sleep, in newborn language learning. Further, what are the neural mechanisms through which newborn sleep consolidates language learning? Targeted memory reactivation (TMR; Rudoy et al., 2009) is an effective method for regulating memory processing during sleep, significantly activating memory-related brain regions including parahippocampal gyrus, thalamus, and medial temporal lobe (van Dongen et al., 2012), and has been widely used in recent years to investigate neural mechanisms of sleep-dependent memory consolidation (Hu et al., 2020). The TMR paradigm has been successfully applied to episodic memory (Prabhakar et al., 2018) and word learning (Johnson et al., 2021) in 2-year-old toddlers. We suggest that future studies adopt the TMR paradigm to regulate memory processing of speech learning during newborn sleep, using EEG or fMRI indices to reveal the neural mechanisms of sleep-dependent memory consolidation in newborns. Understanding and mastering the mechanisms and characteristics of newborn language learning can provide scientific foundations for interventions targeting language learning at this developmental stage.

Third, clinical translation research on newborn language development remains largely unexplored. Can brain indices of newborn language processing predict autism? This review suggests that language sensitivity in newborns and infants may be innate. Using language-related brain indices may enable detection of signs of neurodevelopmental disorders such as autism during infancy or even the newborn stage (whereas behavioral indices of language have predictive value only at 1–2 years), thereby enabling early diagnosis and intervention for autism. Currently, only one study has found that language brain indices before 6 months can predict autism diagnosis and symptoms at 3 years (1.5 months: Liu et al.,

2019). Several other HRA infant studies have either identified predictive indicators at 6 months or later (Finch et al., 2017; Lewis et al., 2017; Liu et al., 2021; Pecukonis et al., 2021; Righi et al., 2014) or only identified differences between high- and low-risk autism groups without providing predictive information for autism diagnosis (Edwards et al., 2017; Keehn et al., 2013; Liu et al., 2020; Seery et al., 2013; 2014). Although no reports have examined language processing in HRA newborns to date, we believe that these identified language-related brain indices from infancy (e.g., activation levels and connectivity strength of language brain networks during speech processing, MMR lateralization during phoneme discrimination, arcuate fasciculus lateralization) can be obtained during the newborn stage. Therefore, we recommend that future studies use HRA newborns as longitudinal tracking subjects, attempting to predict and provide early warning for neurodevelopmental disorders such as autism using the earliest brain indices of language development after birth, advancing the time window for disease prevention and treatment to the first months of life. Two challenges currently exist for this clinical translation research. First, China's rapidly declining birth rate has led to insufficient numbers of high-risk newborns available for tracking, substantially extending research duration—this might be addressed through large-scale, multi-center clinical trial coordination. Second, the predictive efficacy of single brain indices from the newborn period for disease diagnosis at 3 years may be limited, necessitating collection of multimodal brain observation data during the newborn stage—including speech preferences, phoneme discrimination, and language lateralization advantages—combined with clinical assessment data from infancy to establish a comprehensive disease risk assessment system.

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Language processing in the newborn: Potential biomarkers for autism spectrum disorder LI Sijin, WANG Tingdong, PENG Zhilin, ZHANG Dandan (Institute of Brain and Psychological Sciences, Sichuan Normal University, Chengdu, 610066) Abstract: Newborns utilize their auditory system to process and learn the various elements of language from birth. Examining the characteristics of language processing in newborns not only reveals the neurocognitive mechanisms of language function in the earliest stages of human development, but also provides valuable clues for an early warning and clinical diagnosis of neurodevelopmental disorders such as autism. This review article summarized the perception, discrimination, and learning of phonemes in newborns, as well as the potential role in predicting autism spectrum disorder. It was found that newborns have preferences for specific languages and possess unique phoneme discrimination

abilities. Furthermore, brain functional and structural indices of language processing in infancy have predictive values for autism. Future research should focus on the following three issues: 1) Controlling the rhythm factors of materials, re-examining the characteristics of newborn language processing and brain lateralization issues; 2) Revealing the neurocognitive mechanisms of newborn language learning and the role of sleep in memory consolidation; 3) Tracking the language development of high-risk newborns with autism and establishing a disease risk assessment system so as to reveal the potential biomarkers for autism.

Key words: newborn, native language preference, left lateralization, language development, autism spectrum disorder

Note: Figure translations are in progress. See original paper for figures.

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