CellPress

Trends in Neurosciences

Review

Infant neuroscience: how to measure brain activity in the youngest minds

Nicholas B. Turk-Browne [1,2,*] and Richard N. Aslin[1,3]

The functional properties of the infant brain are poorly understood. Recent advances in cognitive neuroscience are opening new avenues for measuring brain activity in human infants. These include novel uses of existing technologies such as electroencephalography (EEG) and magnetoencephalography (MEG), the availability of newer technologies including functional near-infrared spectroscopy (fNIRS) and optically pumped magnetometry (OPM), and innovative applications of functional magnetic resonance imaging (fMRI) in awake infants during cognitive tasks. In this review article we catalog these available non-invasive methods, discuss the challenges and opportunities encountered when applying them to human infants, and highlight the potential they may ultimately hold for advancing our understanding of the youngest minds.

Highlights

The first 2 years of life is a period of rapid learning and growth when humans acquire notable motor, perceptual, linguistic, and social capabilities.

Because of challenges in measuring brain activity in human infants, many of the neural mechanisms underlying these capabilities have not been identified.

Advances in neuroimaging technologies, task designs, and data analyses from studies of older children and adults are starting to be translated into studies of infants.

These new methods include frequency tagging designs in electroencephalography (EEG), task-based functional magnetic resonance imaging (fMRI) studies in awake and behaving infants, multivariate analyses of EEG and functional near-infrared spectroscopy (fNIRS), and the emergence of infant-friendly optically pumped magnetometry (OPM).

The resulting neural data provide rich new measures of infant cognition, supplementing the limited behavioral data that can be obtained from preverbal infants.

Why study the infant mind and brain?

A general approach to understanding a complex structure or system is to study how it can be built, or 'reverse engineered' [1–3]. What are the parts, how are they arranged, when do they come online, how are their functions coordinated, what are the resulting emergent properties, and what can go wrong? This captures our perspective on why it is important to study infants to understand the human mind and brain. The first 2 years of human life is a revolutionary period like no other. During this period, the volume and anatomy of the brain change at the fastest rate of our lifespan [4,5] and the foundational capacities of the mind take root [6].

There is a large behavioral literature on the early development of the human mind [7]. This field of **infant cognition** (see Glossary) has revealed the capacities of infants for perception, attention, learning, memory, language, motor control, theory of mind, metacognition, and more, through looking, reaching, and other simple behaviors [8–11]. These studies are clever and insightful, yet the behavioral measures they rely upon are difficult to interpret because each can be influenced by multiple cognitive capacities [10]. In this article, we synthesize research from a related and growing field – infant neuroscience – that focuses on the early development of the human brain. This complements infant cognition research by revealing biological mechanisms that underlie cognitive capacities, which can inform algorithmic understanding of how these developing capacities work and can help to better predict and explain infant behavior.

Linking brain and behavior poses a key challenge in studying infants, especially when they are preverbal: their small behavioral repertoire requires that researchers infer complex cognition from simple actions [12]. Access to the brain dramatically expands the toolkit of infancy researchers [13] by enabling new experimental designs and dependent measures [14]. These neural measures have the potential to address open theoretical issues in infant cognition [15,16]. For example, recent theories posit that infants mentally simulate events in the world

[1]Department of Psychology, Yale University, New Haven, CT 06520, USA
[2]Wu Tsai Institute, Yale University, New Haven, CT 06510, USA
[3]Child Study Center, Yale School of Medicine, New Haven, CT 06520, USA

*Correspondence: nicholas.turk-browne@yale.edu (N.B. Turk-Browne).

© 2024 Elsevier Ltd. All rights reserved.

[17]; this cannot be observed directly in behavior, but **multivariate analyses** of neural data could detect such simulations to validate these hypotheses. The infant neuroscience techniques we review in this article provide rich, dynamic, and implicit measures that may drive a new generation of progress. At the same time, infant neuroscience faces its own unique challenges, which we also consider.

The growing availability of infant neuroscience techniques is the result of dramatic progress over recent decades in research on the adult human brain [18,19][i]. During this time, researchers gained access to new non-invasive technologies for measuring functional brain activity in humans, including **fMRI** [20], **MEG** [21] – both the original cryogenic (superconducting quantum interference device, SQUID) and newer optical (OPM) varieties – and **fNIRS** [22]. These methods complement **EEG** [23], a longer-standing method that is still widely used in infants.

Beyond new tools for data acquisition, there have also been notable advances in the analysis of adult brain imaging data [24]. Whereas early 'univariate' analysis approaches in cognitive neuroscience emphasized the brain activity of individual regions in space or discrete moments in time [25,26], modern 'multivariate' approaches incorporate data-driven machine learning [27] and network science [28] techniques, as well as theory-driven inference from computational models [29]. Such analyses are increasingly being applied to infant data [30–32], and these applications present a major opportunity for unraveling complex neural systems as they emerge during early development.

The infant brain can also be studied from an evolutionary perspective, informed by comparative research from developmental neurobiology in animal model systems [33,34]. Infant rodents and primates have advanced our understanding of, for example, motion detection [35], face recognition [36], and memory replay [37]. These studies add valuable insights by incorporating causal perturbations and invasive recordings that are not applicable in human infants. At the same time, key aspects of the human mind, such as language, theory of mind, and consciousness, are more difficult and sometimes impossible to study in animals [38]. One of our goals in this article is to reveal opportunities to work toward, in humans, a refined mechanistic understanding of early cognitive development.

To outline the scope of this review, we focus on methods for measuring the functional properties of the human brain during infancy, spanning the first 2 years of life. We highlight what types of questions neural measures can help to answer in infants, and discuss unique challenges when interpreting such measures. We describe the landscape of available non-invasive tools for infants, their strengths and weaknesses, and effective practices for acquiring and analyzing data. We target diverse audiences, including new researchers for whom this review can be a primer, infancy researchers looking to expand from behavioral and physiological measures to neural measures, developmental cognitive neuroscientists wishing to learn more about cutting-edge techniques, and cognitive neuroscientists studying the adult brain who are interested in adapting their skill sets to infants. We do not aim to provide a comprehensive account of all empirical and theoretical advances that have been enabled by these tools across content areas of cognitive development, but we do reference several innovative applications of these tools in infants. Many of these innovations have arisen in recent years, including rapid progress in using machine learning and artificial intelligence (AI) for neuroimaging data [39], dramatic growth in the number of awake infant fMRI studies [16], and the arrival of OPM [40]. Our goal is to raise awareness about the availability and feasibility of these methods for rigorous cognitive neuroscience in infants, and to spur interest in using these methods to address fundamental questions about the developmental origins of the human mind and brain.

Glossary

Blood oxygenation level-dependent (BOLD) response: a signal measured by fMRI that reflects an oversupply of oxygenated blood to replenish metabolic resources around sites of increased neuronal population activity, allowing this activity to be localized approximately.
Electroencephalography (EEG): a neuroimaging technique in which an array of electrodes is placed on the scalp, and these electrodes sense volume currents from the brain induced by the electrical activity of neuronal populations.
Event-related potential (ERP): the average change in electrical or magnetic activity evoked by a stimulus or task across trials that is often characterized by peaks or troughs at particular moments in time which reflect specific perceptual or cognitive processes.
Functional magnetic resonance imaging (fMRI): a neuroimaging technique that measures BOLD activity over the whole brain in a volume of voxels every 1–2 s using a head coil in an MRI machine.
Functional near-infrared spectroscopy (fNIRS): an optical neuroimaging technique that emits light at wavelengths matched to oxygenated and deoxygenated blood, and uses an array of detectors to measure absorption and infer neural activity, akin to the BOLD response.
Frequency tagging: an experimental design in which stimuli are presented sequentially at a fixed interval, allowing processing of these stimuli or abstractions to be inferred based on power or coherence at the corresponding frequency.
Functional alignment: an alternative to standard anatomical coregistration across participants in which voxels or channels are aligned based on the similarity of their activity timeseries rather than the location of their anatomical coordinates.
Infant cognition: a subfield of developmental psychology focused on the early presence and development of cognition and behavior in infants.
Looking time: the duration of eye fixations on a stimulus or location; a dependent measure that is widely used in infant cognition research to test habituation, violation of expectation, or stimulus discrimination.

Questions that can be addressed by infant neuroscience research

Neuroscience research in human infants is challenging – so why bother? Indeed, the field of infant cognition has made significant progress by focusing on behavior alone. There are several types of questions that may not only benefit from, but require, neural measures.

One class of questions involves trying to better understand the cognitive processes underlying behavior. Seemingly simple infant-friendly behavioral measures such as **looking time** are influenced by several processes. For example, infants often look longer at things they deem to be novel, except when they do not and instead look more at familiar things [41,42]. This classic reversal – now the subject of a collaborative study[ii] – has been linked to a host of factors, including the salience, complexity, familiarity, and duration of stimuli [43]. These factors may load onto different brain systems (e.g., sensory systems for complexity, attentional systems for salience, and memory systems for familiarity); thus, neural measures indicating the involvement of one or more of these brain systems may help to dissect which process(es) drive looking behavior in a given task. Again, these processes cannot be measured directly in nonverbal behavior; neural measures can therefore serve to enrich the interpretation of infant behavior.

Neuroscience can also help to answer questions about cognitive processes in infants that have yet to manifest in overt behavior. Akin to the competence versus performance distinction in language acquisition [44], whereby infants know more about language than they can articulate at first, protracted motor development may not allow infants to act on the neural representations they possess [45], such as those related to (in addition to language) semantic knowledge, episodic memory, spatial navigation, or consciousness. In this situation, directly studying these neural representations may be a more sensitive approach [38]. Relatedly, many infant behavioral paradigms produce one or a small number of dependent measures that are collected at the end of a protocol [12] (e.g., the outcome of learning or the violation of a habituated expectation). By contrast, infant neuroscience allows online, incidental measurement of processes throughout a task (e.g., learning curves). Moreover, obtaining multiple neural measurements – patterns of brain activity across thousands of points in space and time – dramatically increases the amount of data obtained per infant.

Another class of questions concerns how regions of the infant brain are specialized and organized for different cognitive processes. Where in the brain are functions instantiated? What information is represented in those regions? When in time is this information processed in relation to stimulus events or other processes? Answering such questions can address vexing issues about nature and nurture, namely whether there are dedicated, even experience-independent functional modules in the brain for domains of core knowledge, and/or whether functions instead emerge and adapt in infancy through experience and across more distributed networks in the brain [46–50].

Finally, studying the youngest brains can guide our understanding of the mature brain and behavior – a developmental, within-species analog to how animal models can help to advance our understanding of the human brain. For example, developing brains have dramatically different volume, folding, connectivity, and other structural properties [4], but still can implement some sophisticated, adult-like functions [51]. Indeed, several infant neuroscience studies have observed functional properties more similar to adults than not [52,53]. The fact that a qualitatively different biological architecture can achieve these functions puts important constraints on explanations in adult cognitive neuroscience about how and why specific brain systems have particular functional specializations and connectivity. In turn, knowing the range of functional organizations that allow the brain to implement normative behavioral and psychological phenotypes during development opens up new clinical applications such as diagnostic methods and pharmacological treatments.

Magnetoencephalography (MEG): a neuroimaging technique that measures magnetic fields created by electrical activity in the brain using an array of superconducting quantum interference device (SQUID) or optically pumped magnetometer (OPM) sensors placed around the head.

Multivariate analysis: a set of analysis approaches, often implemented using machine-learning algorithms, in which the spatiotemporal patterns of brain activity over voxels or channels are used as the input for training and testing classification, regression, and similarity models to decode or predict stimuli or tasks.

Interpretation of neural measures

Perhaps one of the most challenging tasks faced by an infancy researcher is how to interpret neuroscience results. Measures obtained using non-invasive neuroimaging tools are too coarse to assess single units or local circuits and are therefore an indirect proxy for the neural population dynamics used by the brain to perform computations relevant to behavior. Even if a future tool provides more direct and precise neural measures, changes in brain activity during development can reflect several factors that are nearly impossible to control experimentally, including age-related differences in task difficulty and instructability, motor control and language ability, neural selectivity and tuning, and attention, motivation, and interest [54–57]. Thus, caution is warranted when drawing conclusions about cognitive development from infant neuroscience data alone.

There are several possible ways to enrich interpretation and mitigate such pitfalls, including validation in participants with developmental disorders or deficits affecting specific brain mechanisms [58,59]. Moreover, computational models can simulate brain mechanisms that are linked to behavior and can then safely be 'lesioned' to test causality [60,61]. Finally, multimodal neuroimaging studies that combine tools may help to address the limitations or interpretational challenges of any individual tool [62–64].

Nevertheless, conclusions about how to interpret infant neuroimaging data should avoid assumptions of developmental homology. By this we mean that there could be qualitative changes during infancy in the extent, localization, connectivity, and modularity of key functional mechanisms in the brain [51,65]. Developmental studies often implicitly assume that the functional neuroanatomy of the human brain is relatively static, such that task activation (or inactivation) of a region previously linked to a cognitive process in adults provides evidence of maturity (or immaturity) of that process in children. This assumption is reasonable in some cases [53,66], but violations affect how the timing and trajectory of developmental change are characterized [67]. Analysis techniques based on **functional alignment** [24,68], which can track function agnostic to anatomy, may provide a more accurate estimate of how the functional properties of the infant brain change with age [69] (Box 1).

These considerations reveal a developmental form of 'reverse inference' – when activity in a brain region alone is used to infer a cognitive process because prior studies linked that region to the process [70]. This potential fallacy is problematic even among studies of adults, given that brain regions can serve multiple cognitive processes, but it seems especially dangerous when relying on adult studies to infer a cognitive process that infants may or may not have. That said, given a paucity of infant data, such adult-based reasoning may still be useful for generating hypotheses about infants that can then be tested experimentally [70].

Why is it challenging to study infants?

A first major challenge when studying infants is task design. Infants have a relatively short attention span and typically cannot be given instructions, both of which result in small amounts of data and high attrition rates. This has not deterred researchers from assessing infant behaviors, but much of that work has focused on spontaneous or easily elicited measures rather than on noisy signals from the brain [71]. For example, a mainstay in the infant literature since the 1950s has been how infants orient to stimuli, typically measured by the speed and duration of looking [10]. Such measures of visual attention can be coarse (i.e., attentive vs. looking away) or fine (i.e., precise fixations with an eye-tracker). Looking behavior has been used widely in habituation and violation-of-expectation paradigms to infer the cognitive capabilities of infants to represent objects, numbers, agents, and more [8]. Other behaviors (e.g., sucking) and

Box 1. Functional alignment across development

A common assumption in developmental neuroimaging is that adult anatomical and functional atlases are a reasonable approximation of the infant brain. This assumption is often false [67], but persists because of the challenge of mapping adult functions to the developmentally homologous anatomy in infants. It is difficult to know what counts as the 'same' region across infants and adults given differences in global volume, relative size, cortical folding, and landmarks. Even worse, there is no guarantee that a function that maps to one anatomical region in adults will map to the same region in infants.

Shared response modeling (SRM) and the related approach of hyperalignment [68] offer a data-driven solution [24]. SRM is a functional alignment method that takes as its input brain activity over time across voxels (fMRI) or channels (EEG, MEG, fNIRS) from a group of participants with the same task timing (e.g., watching the same movie). SRM finds a projection of the data that captures their shared responses in a lower-dimensional (e.g., fewer than the number of voxels/channels) set of feature timecourses. After this procedure, new data from the same participants can be transformed from their anatomical space to the shared functional space, even if they have a different number of voxels/channels or variable mapping of functions to anatomy.

SRM could be used in infant neuroscience in several ways [69], for example, to predict infant brain activity from adult brain activity while avoiding homological assumptions inherent to anatomical alignment. This 'signal reconstruction' approach has been applied in older children [51]: first, SRM learns a functional space across a group of adults watching a movie, akin to a group average of their shared temporal response features, as well as weight matrices that transform each individual's anatomical voxels/channels into these functional features. The brain responses of a child to the same movie are then regressed onto these adult functional features to obtain their weight matrix. This determines the loading of adult features onto the voxels/channels of each child. The adult and child weight matrices are combined so that voxel/channel activity evoked by a new stimulus in adults can be translated into the brain anatomy of the child. This provides a prediction of how the brain of the child would respond if it had adult-like function. This predicted activity is compared to the actual child brain activity, resulting in a measure of functional similarity between the child and the adults. This similarity can predict the age of the child and reveals that some adult functions are absent in the child brain; some are localized to the same regions, and others are present but reorganized to different regions [51]. The growing availability of infant movie data will allow similar analyses in infants [31,32,69,135].

physiological measures (e.g., heart rate) vary with stimulus conditions and can be used in operant and classical conditioning paradigms to assess stimulus discrimination, memory, and the process of learning [72].

A second challenge is that behavior undergoes developmental changes. For example, reaction times and conditioning get faster with age [73], and the salience of stimuli is affected by prior experience [74]. In other words, the dependent measures used to assess development – the 'yardstick' for measuring age-related changes – are confounded with the developmental mechanisms that they have been used to reveal. This motivates the use of physiological measures that do not require a behavioral response, such as heart rate, galvanic skin response, and pupil size [75]. However, these physiological responses have an indirect relationship with the underlying neural mechanisms and may also undergo developmental changes. Indeed, changes in pupil size are correlated with stimulus prediction, but they are also influenced by variations in luminance, arousal, and sympathetic/parasympathetic balance [76].

These challenges have motivated infancy researchers to seek more direct neural measures [13,15,16]. The natural place to start was EEG, a non-invasive technique amenable to small infant heads that requires minimal restraint to mitigate movement artifacts. In adults, EEG captures neural activity precisely in time, although it can only localize this activity in the brain approximately [77]. The advent of fMRI in the 1990s offered a non-invasive way to localize functional signals in space precisely across the whole brain. However, fMRI was not readily usable with infants because it requires rigid head stabilization during image acquisition. Achieving immobilization with an awake infant was initially viewed as a fool's errand. Indeed, until recently nearly all fMRI studies in infants were conducted during sleep without a task or with auditory stimuli [15,78–81]. Further, the sluggish hemodynamic response in fMRI limits the number of experimental trials that can be acquired within the short 'window of cooperation' of infants, relative to EEG or behavioral tasks.

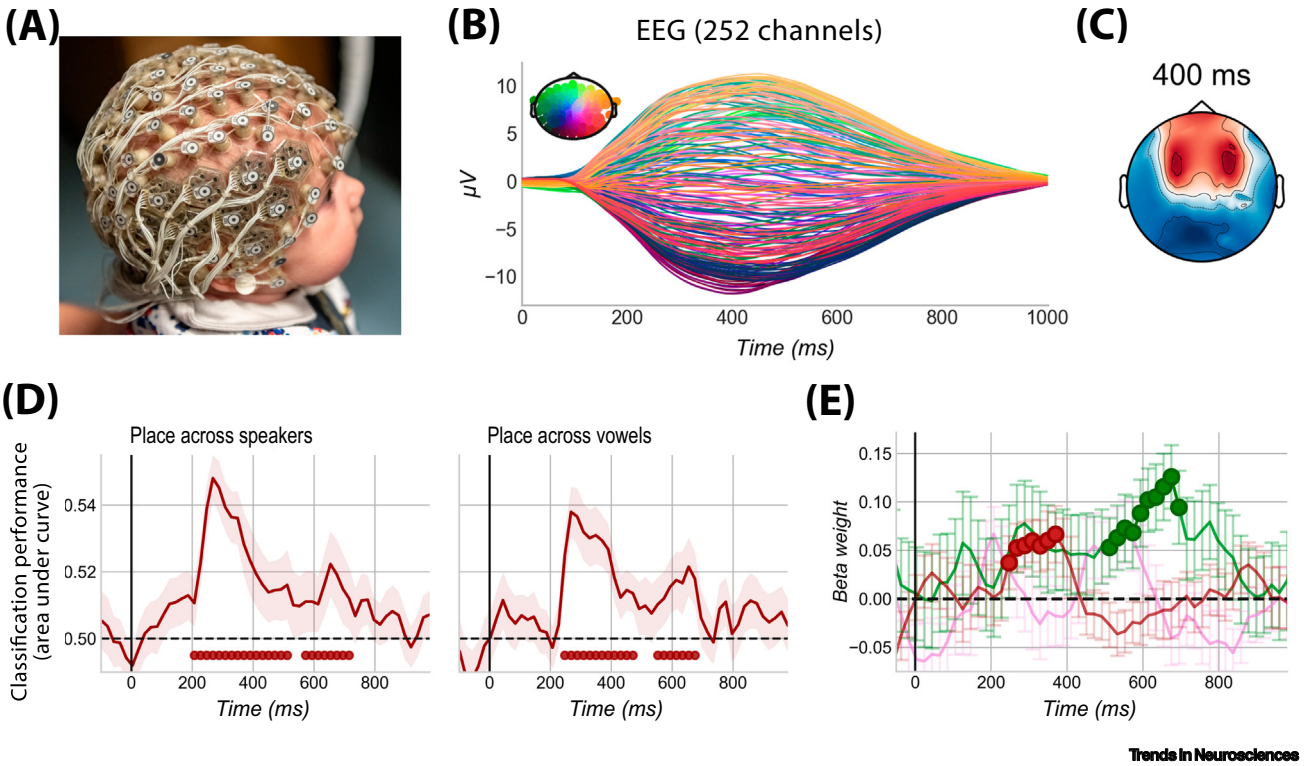

Figure 1. An example of an infant electroencephalography (EEG) study of speech perception of phonetic categories. Speech perception requires the listener to form phonetic categories that ignore variation across talkers, speaking rate, and the surrounding acoustic context. Linguists have characterized these phonetic categories based on the principles of parsimony and universal properties across thousands of natural languages. This study asked whether 3-month-old infants encode phonetic categories according to these linguistic principles by examining patterns of EEG activity from 256 channels using multivariate analysis. (A) An array of electrodes with saline sponges establish low-impedance contact with the scalp. The cap combines whole-head coverage (128 electrodes) with high-density coverage (another 128 electrodes) over temporal cortices. (B) Grand mean event-related potentials (ERPs) from all 256 electrodes. (C) The topography of mean ERPs across stimulus conditions, showing peak amplitudes over frontocentral scalp locations. (D) Speech syllables varied in place of articulation (labial, alveolar, velar) and were spoken by different talkers (male, female) in different vowel contexts (bi-bo, di-do, gi-go). A classifier model trained on neural patterns evoked by syllables generalized across male/female and /i/-/o/ vowels, as shown by the timecourse of classification accuracy after syllable onset; this indicates the existence of phonetic categories. (E) Classification accuracy also indicated generalization to novel examples of consonants that varied in place of articulation. Moreover, category-level decoding was evident earlier in time than identity-level decoding. Figure adapted from [49] with permission.

The conclusion one might draw is that the widespread deployment of neuroimaging in studies of awake infants, with the sophistication obtainable from adults, remains an aspiration. We offer a more optimistic outlook, bolstered by the recent availability for infants of (i) new protocols that enable more data to be gathered, (ii) new neuroimaging technologies with unique strengths, and (iii) new computational analysis methods to extract richer insights. These advances have put the field of infant neuroscience on the cusp of major breakthroughs.

Neuroscience tools suitable for human infants

Electroencephalography

EEG measures electrical fields emanating from the brain through electrodes placed on the scalp. Active neurons serve as dipoles that induce volume currents in nearby brain tissue and fluid, and radiate out into the skull and scalp [23]. These signals are sampled with high temporal resolution, whereas the spatial resolution of EEG is limited by differences in conductivity across tissue types and blurring by the skull. Even if transmitted faithfully, sources cannot be localized exactly because of the inverse problem: the impossibility of reconstructing 3D brain activity from 2D

measurements on the scalp; however, approximations suitable for source localization, such as 'beamforming', have proven useful [82].

The electrodes in EEG are embedded in caps that fit on the head. These caps can be sized for infants, are light and comfortable, stay in place during head movement, and allow the child to sit on the parent's lap. The connection between the electrodes and the scalp is made either with conductive gel or with sponges soaked in saline solution; the latter is faster because all electrodes are prepared at once but can lead to worse connections and to interference between channels. EEG is the most established tool for infant neuroscience, and there has been recent progress in domains such as visual categorization [83], symbolic labeling [84], maternal odor recognition [85], statistical learning [86], and music and speech perception [87,88] (Figure 1).

Magnetoencephalography

MEG is the magnetic counterpart of EEG [21]. The volume currents induced by neuronal activity create perpendicular magnetic fields. These fields are extremely weak: detecting them requires advanced magnetic shielding and highly sensitive sensors. The most common sensor is a SQUID that converts magnetic flux into voltage. A key advantage of MEG over EEG is that it is less distorted by conductivity differences and by variation in skull thickness and fontanels [89]. As a result, MEG has higher spatial resolution than EEG while retaining the same temporal resolution and quiet operation suitable for infant testing. SQUID-based MEG requires a large and expensive instrument with helium cooling that can be difficult to use in infants unless customized. The SQUID sensors are arranged into a fixed array that accommodates an adult-sized head; this presents an issue for infants whose smaller heads do not fill the array, given that sensitivity falls off with distance from brain tissue. These drawbacks may be addressed in the near future with the increasing availability of OPM, a new form of MEG [40]. This may be the most promising addition to the toolbox for infant neuroscience (and cognitive neuroscience more generally) since fMRI (Box 2).

Box 2. The prospect of optically pumped magnetometry (OPM) for MEG research with infants

MEG may soon become more infant-friendly with the arrival of OPM [136]. Optical pumping refers to the use of a light source to change the quantum state of an atom and make it sensitive to weak magnetic fields, in this case those induced by the activity of neurons. OPM sensors contain a laser diode as the light source, the atoms being pumped are typically in an alkali metal vapor (^{87}rubidium), photoreceptors are used to measure magnetic resonance, and electromagnetic coils control the surrounding magnetic field. OPM-MEG eliminates the need in SQUID-MEG for a large machine with cryogenic cooling. Advances in miniaturization have resulted in small sensors that can be arrayed on a semi-rigid cap worn by participants [40], including infants [90] and children [137]. OPM-MEG arrays on the horizon may have dozens to hundreds of channels on the cap.

OPM-MEG has several advantages in general, and for infants in particular [138]. By removing cryogens, the sensors can be brought into closer contact with the head. Given that magnetic fields dissipate exponentially with distance from the source, this can increase signal strength. Moreover, the self-contained nature of sensors means they can be arranged flexibly in different configurations to fit infant-sized caps. The proximity and fit of sensors also make OPM-MEG more robust to head motion, in principle. The technology of the sensors themselves is developing rapidly, and new triaxial sensors are coming on the market that measure magnetic fields in three axes as opposed to a single axis with SQUID-MEG, thus alleviating geometric blind spots [138,139]. Although current OPM-MEG systems must be installed inside a magnetically shielded room (like SQUID-MEG), future iterations may include built-in or portable shielding around the head. The ability to record human brain activity with high fidelity in space and time from participants while they engage in naturalistic tasks would enable powerful, new experimental paradigms.

At the moment, however, OPM-MEG for infant research is still far from widespread adoption, and there have so far been only a handful of deployments of OPM equipment worldwide. Ongoing technical refinements will be necessary to address crucial practical issues (e.g., heat dissipation).

Beyond recent proof-of-concept OPM studies (e.g., [90]), most MEG research in infants has been conducted using SQUID systems, including studies of speech processing [91], word recognition [92], face processing [93], and rule learning [94] (Figure 2). There are several challenges when collecting MEG data in infants [95], but there is also growing convergence regarding best practices, especially when the participants are awake, which enables naturalistic tasks [96,97].

Functional magnetic resonance imaging

fMRI is used widely in adult cognitive neuroscience because it localizes regions and patterns of activity across the whole brain (including deep-brain and subcortical structures) [20]. Relative to other signals that can be recorded non-invasively, the **blood oxygenation level-dependent (BOLD) response** that fMRI measures has high spatial resolution but low temporal resolution, peaking 4–5 s after neural activity and decaying after 15–20 s (the hemodynamic response function).

Although fMRI has great potential for studying infant cognition [15,16], its use for this purpose has been relatively limited. Key challenges include the inhospitality of the MRI environment (loud noises, confined space, separation from parent, adult-sized head coils, etc.), difficulty in instructing infants to stay still, artifacts from minor head motion, age-related differences in the shape, timing, and amplitude of the BOLD response, and the need for substantial amounts of data to overcome the low signal-to-noise ratio [98–100]. One solution has been to collect fMRI data while infants are asleep [81] – a state in which they spend more than half of their time. This has led to important

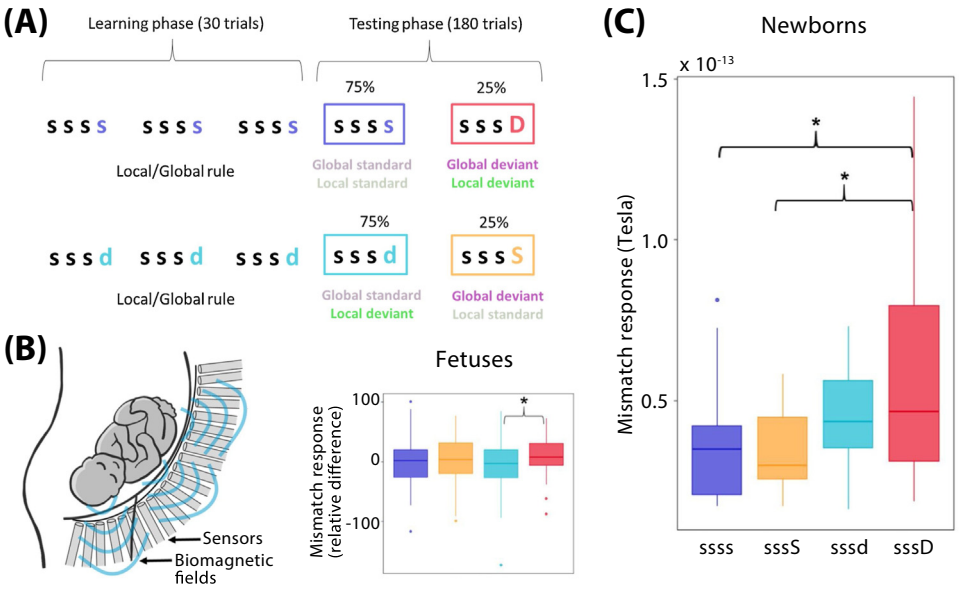

Figure 2. Examples of infant magnetoencephalography (MEG) studies of local and global structure detection. Behavioral studies have revealed that infants can detect changes in the structure of sensory input. Novel structures can be defined at a variety of levels, including local changes and global changes. These two MEG studies, one in fetuses ranging in gestational age from 28 to 35 weeks, and the other in newborns, embedded local and global structure changes in sequences of tones. (A) After an initial learning phase in which four-note sequences were repeated, a test phase assessed changes in the familiar sequence. The changes were either local (within a four-note sequence) or global (across four-note sequences), and they occurred on 25% of test trials. (B) Fetuses were sensitive to global but not local structure, and peak MEG differences occurred 350–650 ms after sequence onset. (C) Newborns were sensitive to both local and global structure, and peak MEG differences occurred in an earlier 200–400 ms time window. Panels (A) and (C) are adapted from [94] with permission; panel (B) is adapted from [140] with permission.

insights, especially about the early development of functional networks [101–105]. Clever task-based experimental designs with somatosensory or auditory stimulation during sleep, and/or with behavioral measures before or after sleep scanning, have also proven effective [80], including in studies of acoustic processing [106], vocal interaction [107], and memory retrieval [108]. Other aspects of cognition are impossible to study while the infant is unconscious during sleep because, for example, they depend on visual input, conscious processing, or concurrent behavior. Building on one early pioneering study of speech perception [79], there has been a recent surge of fMRI studies in awake infants [16,80,100], including on retinotopic organization [52], motion perception [109], face perception [47,53,110], attentional orienting [111], event segmentation [31], and statistical learning [112] (Figure 3). Laboratories differ in the techniques they use to overcome the challenges of awake infant fMRI, including custom versus stock head coils, whether a parent enters the bore with the infant, and the stringency of motion exclusion [53,100]. However, all share a general emphasis on involving parents as a partner; applying strong and redundant hearing protection; using blankets, foam pads, or vacuum pillows for comfort and to limit body movements; and designing short and robust tasks with engaging stimuli to maintain attention.

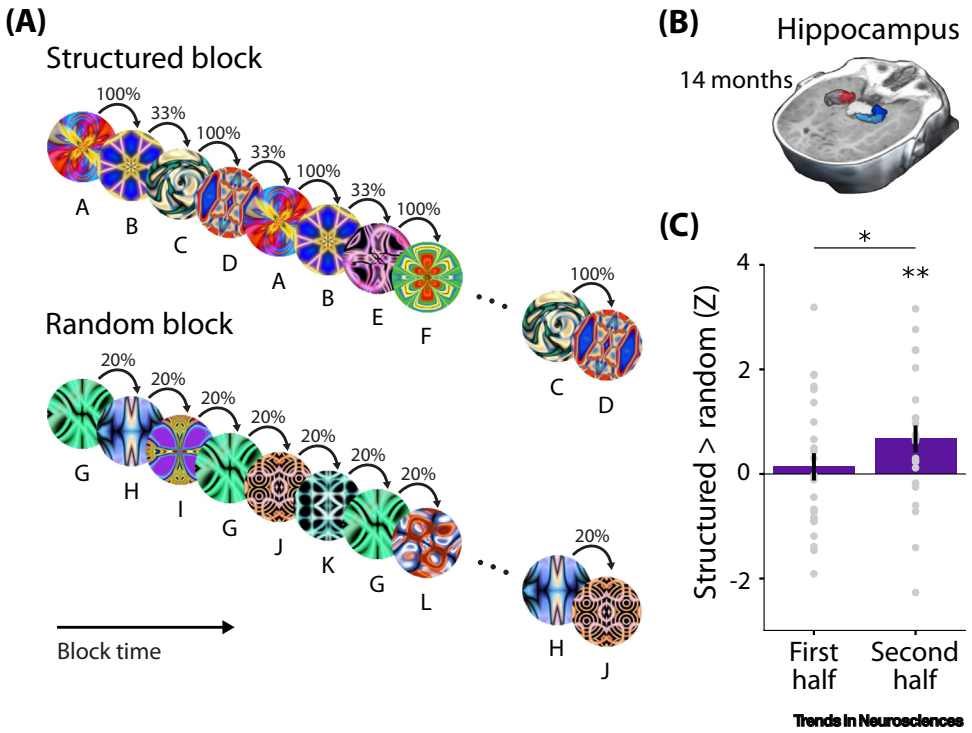

Figure 3. An example of an infant functional magnetic resonance imaging (fMRI) study of statistical learning in the hippocampus. Statistical learning relies on the hippocampus in adults and is a robust behavioral ability in infants, but the hippocampus is typically thought to be immature in infancy (based on the slow development of episodic memory and associated infantile amnesia). This study tested the hypothesis that the hippocampus may contribute earlier in development to statistical learning than to episodic memory. (A) Awake infants aged 3–24 months were exposed to continuous blocks of fractal patterns that appeared one at a time during fMRI. In the structured condition, blocks were generated from embedded pairs (AB, CD, EF), allowing statistical learning of the higher transition probability within (100%) versus across (33%) pairs. In the random condition, blocks were generated from a random order of fractals with uniform transition probabilities (20%) that did not allow the extraction of regularities. (B) The bilateral hippocampus of each infant was segmented manually from an anatomical scan and used as a region of interest (ROI). (C) There was a stronger blood oxygenation level-dependent (BOLD) response in the hippocampal ROI to the structured than random blocks by the end of sequence exposure, growing from the first to the second half of the blocks. This study provides evidence of hippocampal learning in human infants. Figure adapted from [112] with permission.

Functional near-infrared spectroscopy

fNIRS is a diffuse optical imaging technique related to fMRI [22]. Two wavelengths of light, each optimized for absorption by chromophores of either oxygenated or deoxygenated blood, are delivered to the skull via emitters, and returning photons are captured by detectors. By taking advantage of the near-infrared optical window in which skin, bone, and tissue are mostly transparent, the light reaches the surface of the brain, and part of it is reflected and measured. Because the infrared emitters and detectors are attached to a cap worn by the infant, there is less need to immobilize the head and fewer restrictions on body positioning than in most other techniques, enabling more naturalistic studies, including about motor control and social interaction [113]. One notable limitation of fNIRS is that the light-scattering properties of brain tissue mean that it is only sensitive to neural activity near the cortical surface (up to a depth of ~2 cm). Another limitation is the relatively low spatial resolution of fNIRS; high-density systems are being developed that can provide resolution at the scale of fMRI parcels [114].

Two further challenges with fNIRS are anatomical coregistration and surface vascular noise. fMRI studies include structural scans from the same infant, thereby providing coregistration of brain activity to anatomy. fNIRS relies on photometric techniques to obtain 3D coordinates of the emitter and detector locations and to align them with the anatomy of either age-specific MRI templates or a structural scan of the same infant from a separate MRI session. Nevertheless, many existing fNIRS studies in infants have reported spatially diffuse results that are, in part,

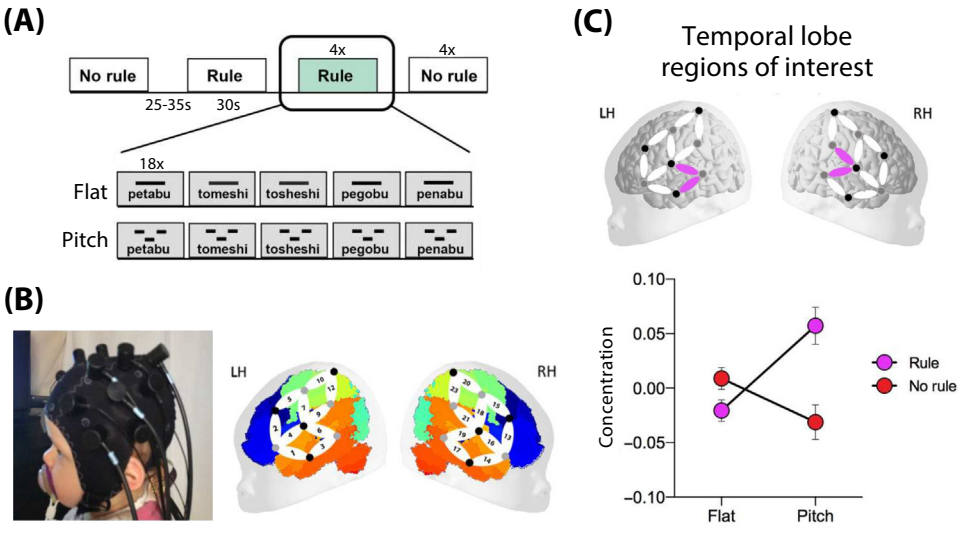

Figure 4. Example of an infant functional near-infrared spectroscopy (fNIRS) study of non-adjacent dependency learning. Behavioral and fNIRS studies of newborns have documented their ability to detect immediate repetitions (e.g., AAB vs. ABC) in sequences of speech syllables. However, non-adjacent dependencies, where A and B are separated by one of many intervening syllables (i.e., x), have proved to be more difficult for infants to learn. This study asked whether non-adjacent dependency learning can be facilitated by a secondary cue that is correlated with the AxB structure. (A) Rule-based structure in sequences of three syllables consisted of two non-adjacent dependencies (i.e., AxB and CxD, where A, B, C, and D were specific syllables and x was one of the 18 syllables randomly assigned to each triplet). In the flat pitch condition, the three syllables had the same fundamental frequency. In the high pitch condition, the first and third syllables had a higher pitch than the middle syllable. These rule conditions were contrasted with a no-rule control in which the first and third syllable identities were unpaired. (B) fNIRS optodes were placed over frontal-temporal regions of the brain in 9-month-old infants. (C) fNIRS responses in temporal lobe regions of interest (ROIs) from both hemispheres showed greater activation in the rule than no-rule blocks, but only when the pitch cue was present. Abbreviations: LH, left hemisphere; RH, right hemisphere. Figure adapted from [141] with permission.

confounded by surface vascular noise resulting from the fact that photons must traverse the scalp, skull, cerebrospinal fluid, and vascular web on the cortical surface twice to provide neural measures. Statistical algorithms and direct measurements of non-cortical noise can provide a more accurate measure of cortical hemodynamics [115,116].

Infant research using fNIRS is burgeoning, and recent studies have explored predictive signals in rapid learning [117], visual working memory in typical [118] and atypical populations [119], face and scene processing [120], synchrony between infants and parents [121], and bilingualism [122,123] (Figure 4).

Strengths and weaknesses of different tools

Researchers have an ethical responsibility to minimize the risk of harm, especially for a vulnerable population such as infants. When studying healthy infants, this mandates the use of non-invasive methods that measure neural activity indirectly, either at a distance through the scalp or through proxies such as blood oxygenation. Thankfully, these methods have complementary strengths that capture most research needs. Which tool is most appropriate for a particular study depends on the research question. Ultimately, a combination of tools, acquired in parallel experiments – or better, simultaneously [62–64] – may yield the greatest insight.

As a guide, we have mapped out several dimensions of how these tools differ (Table 1): (i) temporal scale, the granularity at which signals can be resolved in time; (ii) spatial scale, the granularity at which neural signals can be localized in space; (iii) coverage sensitivity, how broadly and deeply the brain can be resolved with confidence; (iv) motion tolerance, robustness to head movements; (v) body posture, whether there is flexibility in positioning the infant; (vi) acoustic noise, sound pressure level during data collection; (vii) parental involvement, whether parents can interact with the infant during data collection; and (viii) behavioral constraints, how the apparatus physically limits which behaviors are possible.

The tools are similar on other dimensions: (i) age, all tools can be used throughout infancy from birth (fMRI and MEG can even be performed *in utero*); (ii) state, all tools work during sleep or wake states (although the latter is especially difficult in fMRI); (iii) data quantity, most studies recruit small sample sizes and collect limited data per participant because of the complexity of the procedures and the short attention span of infants, respectively; and (iv) data quality, infant data are generally noisier.

The limited amount and greater noise of data from infants, compared to adults, raises concerns about statistical power and replicability, as well as about representativeness across populations [124]. These concerns are partly addressed through multi-site consortia and data sharing, which are bringing infant neuroscience into the exciting era of open science (Box 3). However, such efforts cannot bypass the

Table 1. Strengths and weaknesses of non-invasive techniques for measuring infant brain activity[a]

	Temporal scale	Spatial scale	Coverage sensitivity	Motion tolerance	Body posture	Acoustic noise	Parental involvement	Behavioral constraints
EEG	ms	cm	Superficial structures	Moderate	Adjustable	Quiet	Full	Minor
MEG (SQUID)	ms	cm	Superficial and deeper structures	Low	Supine or seated	Quiet	Partial	Moderate
MEG (OPM)	ms	cm	Superficial and deeper structures	Moderate	Adjustable	Quiet	Full	Minor
fMRI	s	mm	Whole brain	Low	Supine	Loud	Limited	Severe
fNIRS	s	cm	Superficial structures	Moderate	Adjustable	Quiet	Full	Minor

[a]Summary of attributes (columns) by technique (rows) in research on human subjects.

Box 3. Open science: datasets and software

The complexity of neuroimaging studies, especially in infants, often necessitates a team approach for data collection and analysis in which psychologists, statisticians, physicists, engineers, computer scientists, and others combine their expertise. The expense and difficulty of fMRI and MEG, in particular, have extended such collaborative efforts to the creation of computing and informatics platforms for data sharing. Similar sharing practices have also begun to emerge for EEG and fNIRS data, with the long-term goal of aggregating data across laboratories to improve their demographic representation and address nuanced questions in the face of substantial between-subject variability across infants and children. A parallel sharing effort is also underway for task and analysis software in terms of custom, laboratory-specific code and the creation of standardized tools.

In the same way that the neuroimaging technologies described in this review are more standardized in adults and older children, so too are data- and code-sharing practices. Below we list many of the resources available for infant research, as well as a sampling of broader resources that may be useful to infancy researchers. We focus primarily on non-commercial resources for functional neuroimaging.

Open functional datasets

EEG and MEG (aggregated lists, mostly adult)[iv,v]
fMRI (consortia, resting-state infant)[iii,vi,vii]
fMRI (studies, task-based infant)[viii,ix]
fMRI (repositories, mostly adult)[x,xi]
fNIRS (nascent efforts)[xii,xiii]
Multimodal[xiv,xv,xvi]

Non-commercial analysis software

EEG and MEG[xvii,xviii,xix,xx,xxi,xxii]
fMRI[xxiii,xxiv,xxv,xxvi,xxvii,xxviii]
fNIRS[xxix,xxx,xxxi]

short timeframe during which infants are cooperative in any given session, nor the difficulty of performing multiple sessions at a specific age (because the infant grows older than the selected age group), both of which limit the number of measures that can be collected. Moreover, because these measures need to be collected at multiple research sites with varying equipment and expertise, such studies tend to be conservative and focus on simple measures that can be deployed at scale. Indeed, a major new National Institutes of Health (NIH)-funded longitudinal study (birth to age 5), known as the Healthy Brain and Child Development (HBCD) project[iii], is not collecting awake task-based fMRI data until after infancy (at around age 4). Thus, many questions about infant brain function will, for now, only be addressed at a smaller scale through laboratory-specific data collection. Open science practices, with public sharing of datasets and software, are further improving the rigor of infant neuroscience by helping the field to coalesce around conventions, and by enabling reanalysis and meta-analysis of difficult-to-collect infant data.

Design and analysis of experiments

The tools available for infant neuroscience can be used with a variety of task designs and analysis techniques to draw inferences about the functional properties of the early developing brain. At root, almost all such experiments present stimuli with a prescribed timing that allows synchronization with concurrent neural and behavioral measures. These designs often draw as much from adult cognitive neuroscience as from infant cognition research; the latter behavioral studies can yield insufficient data (e.g., one test trial in the violation-of-expectation paradigm) or involve kicking, reaching, or other actions that would cause head motion. These classical tasks were optimized for overt behavioral measures, whereas more covert neural measures enable different and sometimes longer task designs.

In event-related designs, stimuli are presented one at a time in a discrete 'trial' separated by blank intervals that are fixed in duration or jittered to allow trial onsets to be decorrelated.

This is a useful approach for linking brain responses to individual stimuli or to variance in behavior (e.g., reaction time), such as when studying attention and awareness [111,125]. In block designs, multiple stimuli are presented sequentially with minimal separation for longer periods of time, followed by a blank interval before the next block. This evokes larger responses that are summated over the stimuli in each block, such as for localizing category-selective regions of visual cortex [47,53,110]. In event-related and block designs, the amplitude of the evoked response in a channel (EEG, MEG, fNIRS) or voxel (fMRI) can be quantified by averaging the peristimulus activity or fitting the activity with a general linear model. This is referred to as an **event-related potential (ERP)** in EEG/MEG or a mass univariate response in fMRI/fNIRS. By contrast, multivariate analysis approaches [24] model patterns of brain activity across channels or voxels, typically using machine-learning algorithms for classification or regression to decode (and encode) stimulus properties or behaviors, or to assess the similarity of representations. Such approaches have begun to be used in infant neuroscience with EEG [126–128] and fNIRS [129].

The presentation of stimuli in continuous streams rather than discrete events/blocks allows **frequency tagging** designs in which multiple stimuli or higher-order features in the stream appear at different frequencies. During analysis, the raw neural data (typically from EEG or MEG) are converted with a Fourier transform or wavelet decomposition, and the power or coherence at these frequencies quantifies the processing of the corresponding features [130]. This approach has proven useful for studying infant perception, language, and learning [86,88,131,132]. Another continuous design involves viewing movies [32,133], listening to songs/stories [106,134], or interacting with a social partner [121]. The resulting timeseries data can be correlated across individuals to assess reliability, used to align individuals into a common functional space, and/or labeled with stimulus features for further univariate or multivariate analysis [24,69]. Although not a controlled experiment in a traditional sense, continuous stimuli can help to investigate naturalistic processes in infants [135], such as event segmentation [31], and are highly engaging for infants, thereby enhancing the amount of data collected from each participant.

Concluding remarks

This review provides a guide to exciting new approaches for infant neuroscience. Advances in adult cognitive neuroscience and behavioral studies of infant cognition have made it possible to ask fundamental questions about how the functional properties of the human brain develop (see Outstanding questions). In this way, infants are a fertile ground for a new generation of human neuroscience research. The resulting discoveries will inform a broader understanding of the relationship between mind and brain across the lifespan, and lead to eventual real-world applications in sectors concerned with learning and development, including education, healthcare, and AI.

Acknowledgments

We thank members of our laboratories for many inspiring discussions, and we dedicate this work to the memory of Dr Sheri Choi. We are grateful to the Canadian Institute for Advanced Research, the James S. McDonnell Foundation (https://doi.org/10.37717/2020-1208), and the National Science Foundation (BCS 2323360) for funding that supports our current developmental research.

Declaration of interests

The authors declare no competing interests.

Resources

[i]https://www.cogneurosociety.org/cns-2023-videos/

[ii]https://manybabies.github.io/MB5

Outstanding questions

What are the best approaches for awake infant fMRI? For example, some studies use custom infant-sized head coils whereas others use the bottom portion of stock coils. The former may be more sensitive to activity in frontal cortex; the latter allows panoramic visual stimuli and easy observation of infant comfort and gaze behavior.

How does vascular noise contribute to infant fNIRS? This is important to know for ensuring that measured signals originate in cortex but – given the small distance from scalp to cortex in infants – requires short channels (<5 mm) that are not yet implemented in commercial instruments.

How can EEG and fNIRS sensors on the scalp be coregistered to the infant brain? Surface-based methods combined with average age-specific templates may not capture individual variation in cortical anatomy. Low-field MRI makes collecting anatomical scans from individual infants more feasible because of its lower cost and flexible use in unshielded environments.

What is the clinical utility of studying infant brain activity? For example, fMRI in a neonatal intensive care unit (NICU) could be used to predict outcomes and detect functional anomalies. This may be particularly crucial in the perinatal period when higher plasticity allows more treatment options and better recovery.

How might functional ultrasound complement other methods? Recent technical advances have made it possible to measure blood volume in newborn cerebral microvasculature. This could enrich fNIRS studies of infant cortical responses.

How can the infant brain be modeled computationally? Cognitive models provide hypotheses about latent variables and processes that can be fit to brain activity. Machine-learning models can decode brain activity and simulate developmental architectures and learning algorithms.

How can multiple methods be combined? Multimodal data, collected simultaneously or separately, can balance the pros and cons of different methods and reveal insights about spatial-temporal patterning of activity in distributed brain networks.

[iii]https://hbcdstudy.org
[iv]https://github.com/openlists/ElectrophysiologyData
[v]https://www.fieldtriptoolbox.org/faq/open_data/
[vi]https://nda.nih.gov/edit_collection.html?id=2848
[vii]https://www.developingconnectome.org
[viii]https://datadryad.org/search?q=turk-browne+infant
[ix]https://osf.io/jnx5a/
[x]https://openneuro.org/search/modality/mri
[xi]https://neurovault.org
[xii]https://manybabies.org/MB3N/
[xiii]https://openfnirs.org/data/
[xiv]https://things-initiative.org
[xv]https://data.donders.ru.nl/collections/di/dccn/DSC_3011020.09_236
[xvi]https://fcon_1000.projects.nitrc.org/indi/cmi_healthy_brain_network/sharing.html
[xvii]https://sccn.ucsd.edu/eeglab
[xviii]https://www.fieldtriptoolbox.org
[xix] https://neuroimage.usc.edu/brainstorm
[xx] https://mne.tools/stable
[xxi]https://www.plasticityinneurodevelopmentlab.com/implementing-happe
[xxii]https://github.com/ChildDevLab/MADE-EEG-preprocessing-pipeline
[xxiii]https://afni.nimh.nih.gov
[xxiv]https://fsl.fmrib.ox.ac.uk/fsl/fslwiki
[xxv]https://www.fil.ion.ucl.ac.uk/spm/
[xxvi]https://fmriprep.org/en/stable/
[xxvii]https://brainiak.org
[xxviii]https://github.com/ntblab/infant_neuropipe
[xxix]https://openfnirs.org/software/homer
[xxx]https://www.nitrc.org/projects/nirskit/
[xxxi]https://www.nitrc.org/projects/neurodot

References

1. Csete, M.E. and Doyle, J.C. (2002) Reverse engineering of biological complexity. *Science* 295, 1664–1669
2. Cauwenberghs, G. (2013) Reverse engineering the cognitive brain. *Proc. Natl. Acad. Sci. U. S. A.* 110, 15512–15513
3. Dupoux, E. (2018) Cognitive science in the era of artificial intelligence: a roadmap for reverse-engineering the infant language-learner. *Cognition* 173, 43–59
4. Bethlehem, R.A.I. *et al.* (2022) Brain charts for the human lifespan. *Nature* 604, 525–533
5. Gilmore, J.H. *et al.* (2018) Imaging structural and functional brain development in early childhood. *Nat. Rev. Neurosci.* 19, 123–137
6. Spelke, E.S. and Newport, E.L. (1998) Nativism, empiricism, and the development of knowledge. In *Handbook of Child Psychology: Theoretical Models of Human Development* (5th edn) (Damon, W. and Lerner, R.M., eds), pp. 275–340, John Wiley & Sons
7. Arterberry, M.E. and Kellman, P.J. (2016) *Development of Perception in Infancy: The Cradle of Knowledge Revisited*, Oxford University Press
8. Spelke, E.S. and Kinzler, K.D. (2007) Core knowledge. *Dev. Sci.* 10, 89–96
9. Smith, L.B. (2005) Cognition as a dynamic system: principles from embodiment. *Dev. Rev.* 25, 278–298
10. Aslin, R.N. (2007) What's in a look? *Dev. Sci.* 10, 48–53
11. Gelman, S.A. (2009) Learning from others: children's construction of concepts. *Annu. Rev. Psychol.* 60, 115–140
12. Aslin, R.N. and Fiser, J. (2005) Methodological challenges for understanding cognitive development in infants. *Trends Cogn. Sci.* 9, 92–98
13. Dehaene-Lambertz, G. and Spelke, E.S. (2015) The infancy of the human brain. *Neuron* 88, 93–109
14. Nelson, C.A. and Luciana, M. (2008) *Handbook of Developmental Cognitive Neuroscience* (2nd edn), MIT Press
15. Ellis, C.T. and Turk-Browne, N.B. (2018) Infant fMRI: a model system for cognitive neuroscience. *Trends Cogn. Sci.* 22, 375–387
16. Yates, T.S. *et al.* (2021) The promise of awake behaving infant fMRI as a deep measure of cognition. *Curr. Opin. Behav. Sci.* 40, 5–11
17. Ullman, T.D. *et al.* (2017) Mind games: game engines as an architecture for intuitive physics. *Trends Cogn. Sci.* 21, 649–665
18. Kriegeskorte, N. and Douglas, P.K. (2018) Cognitive computational neuroscience. *Nat. Neurosci.* 21, 1148–1160
19. Tibon, R. *et al.* (2022) Bridging the big (data) gap: levels of control in small- and large-scale cognitive neuroscience research. *Trends Neurosci.* 45, 507–516
20. Bandettini, P.A. (2012) Twenty years of functional MRI: the science and the stories. *NeuroImage* 62, 575–588
21. Baillet, S. (2017) Magnetoencephalography for brain electrophysiology and imaging. *Nat. Neurosci.* 20, 327–339
22. Ferrari, M. and Quaresima, V. (2012) A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage* 63, 921–935
23. Michel, C.M. and Murray, M.M. (2012) Towards the utilization of EEG as a brain imaging tool. *NeuroImage* 61, 371–385
24. Cohen, J.D. *et al.* (2017) Computational approaches to fMRI analysis. *Nat. Neurosci.* 20, 304–313

25. Poline, J-B. and Brett, M. (2012) The general linear model and fMRI: does love last forever? *NeuroImage* 62, 871–880
26. Groppe, D.M. *et al.* (2011) Mass univariate analysis of event-related brain potentials/fields I: a critical tutorial review. *Psychophysiology* 48, 1711–1725
27. Haxby, J.V. *et al.* (2014) Decoding neural representational spaces using multivariate pattern analysis. *Annu. Rev. Neurosci.* 37, 435–456
28. Barabási, D.L. *et al.* (2023) Neuroscience needs network science. *J. Neurosci.* 43, 5989–5995
29. Yamins, D.L.K. and DiCarlo, J.J. (2016) Using goal-driven deep learning models to understand sensory cortex. *Nat. Neurosci.* 19, 356–365
30. Zaadnoordijk, L. *et al.* (2022) Lessons from infant learning for unsupervised machine learning. *Nat. Mach. Intell.* 4, 510–520
31. Yates, T.S. *et al.* (2022) Neural event segmentation of continuous experience in human infants. *Proc. Natl. Acad. Sci. U. S. A.* 119, e2200257119
32. Yates, T.S. *et al.* (2023) Functional networks in the infant brain during sleep and wake states. *Cereb. Cortex* 33, 10820–10835
33. Werker, J.F. and Hensch, T.K. (2015) Critical periods in speech perception: new directions. *Annu. Rev. Psychol.* 66, 173–196
34. Pascalis, O. and Kelly, D.J. (2009) The origins of face processing in humans: phylogeny and ontogeny. *Perspect. Psychol. Sci.* 4, 200–209
35. Ge, X. *et al.* (2021) Retinal waves prime visual motion detection by simulating future optic flow. *Science* 373, eabd0830
36. Arcaro, M.J. and Livingstone, M.S. (2017) A hierarchical, retinotopic proto-organization of the primate visual system at birth. *eLife* 6, e26196
37. Farooq, U. and Dragoi, G. (2019) Emergence of preconfigured and plastic time-compressed sequences in early postnatal development. *Science* 363, 168–173
38. Bayne, T. *et al.* (2023) Consciousness in the cradle: on the emergence of infant experience. *Trends Cogn. Sci.* 27, 1135–1149
39. Kumar, M. *et al.* (2021) BrainIAK: the brain imaging analysis kit. *Aperture Neuro* 1, 1–19
40. Brookes, M.J. *et al.* (2022) Magnetoencephalography with optically pumped magnetometers (OPM-MEG): the next generation of functional neuroimaging. *Trends Neurosci.* 45, 621–634
41. Hunter, M.A. and Ames, E.W. (1988) A multifactor model of infant preferences for novel and familiar stimuli. *Adv. Infancy Res.* 5, 69–95
42. Turk-Browne, N. *et al.* (2008) Babies and brains: habituation in infant cognition and functional neuroimaging. *Front. Hum. Neurosci.* 2, 16
43. Kidd, C. *et al.* (2012) The Goldilocks effect: human infants allocate attention to visual sequences that are neither too simple nor too complex. *PLOS ONE* 7, e36399
44. Kuhl, P.K. (2004) Early language acquisition: cracking the speech code. *Nat. Rev. Neurosci.* 5, 831–843
45. Köster, M. *et al.* (2020) Motor cortex activity during action observation predicts subsequent action imitation in human infants. *NeuroImage* 218, 116958
46. Li, J. *et al.* (2020) Innate connectivity patterns drive the development of the visual word form area. *Sci. Rep.* 10, 18039
47. Deen, B. *et al.* (2017) Organization of high-level visual cortex in human infants. *Nat. Commun.* 8, 13995
48. Xie, S. *et al.* (2022) Visual category representations in the infant brain. *Curr. Biol.* 32, 5422–5432
49. Gennari, G. *et al.* (2021) Orthogonal neural codes for speech in the infant brain. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2020410118
50. Liu, J. *et al.* (2023) Longitudinal developmental trajectories of functional connectivity reveal regional distribution of distinct age effects in infancy. *Cereb. Cortex* 33, 10367–10379
51. Yates, T.S. *et al.* (2021) Emergence and organization of adult brain function throughout child development. *NeuroImage* 226, 117606
52. Ellis, C.T. *et al.* (2021) Retinotopic organization of visual cortex in human infants. *Neuron* 109, 2616–2626
53. Kosakowski, H.L. *et al.* (2022) Selective responses to faces, scenes, and bodies in the ventral visual pathway of infants. *Curr. Biol.* 32, 265–274
54. Adolph, K.E. and Hoch, J.E. (2019) Motor development: embodied, embedded, enculturated, and enabling. *Annu. Rev. Psychol.* 70, 141–164
55. Lucca, K. *et al.* (2019) Keep trying!: parental language predicts infants' persistence. *Cognition* 193, 104025
56. Suarez-Rivera, C. *et al.* (2019) Multimodal parent behaviors within joint attention support sustained attention in infants. *Dev. Psychol.* 55, 96–109
57. Kostović, I. *et al.* (2019) Neural histology and neurogenesis of the human fetal and infant brain. *NeuroImage* 188, 743–773
58. Jones, W. and Klin, A. (2013) Attention to eyes is present but in decline in 2–6-month-old infants later diagnosed with autism. *Nature* 504, 427–431
59. Elward, R.L. *et al.* (2021) When the brain, but not the person, remembers: cortical reinstatement is modulated by retrieval goal in developmental amnesia. *Neuropsychologia* 154, 107788
60. Zhuang, C. *et al.* (2021) Unsupervised neural network models of the ventral visual stream. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2014196118
61. Zhuang, C. *et al.* (2022) How well do unsupervised learning algorithms model human real-time and life-long learning? *Adv. Neural Inf. Proces. Syst.* 35, 22628–22642
62. Siddiqui, M. *et al.* (2023) Using multi-modal neuroimaging to characterise social brain specialisation in infants. *eLife* 12, e84122
63. Arichi, T. *et al.* (2017) Localization of spontaneous bursting neuronal activity in the preterm human brain with simultaneous EEG-fMRI. *eLife* 6, e27814
64. Cabrera, L. and Gervain, J. (2020) Speech perception at birth: the brain encodes fast and slow temporal information. *Sci. Adv.* 6, eaba7830
65. Edde, M. *et al.* (2021) Functional brain connectivity changes across the human life span: from fetal development to old age. *J. Neurosci. Res.* 99, 236–262
66. Goksan, S. *et al.* (2015) fMRI reveals neural activity overlap between adult and infant pain. *eLife* 4, e06356
67. Richards, J.E. *et al.* (2016) A database of age-appropriate average MRI templates. *NeuroImage* 124, 1254–1259
68. Haxby, J.V. *et al.* (2020) Hyperalignment: modeling shared information encoded in idiosyncratic cortical topographies. *eLife* 9, e56601
69. Ellis, C.T. *et al.* (2023) Movies reveal the fine-grained organization of infant visual cortex. *eLife* 12
70. Poldrack, R.A. (2011) Inferring mental states from neuroimaging data: from reverse inference to large-scale decoding. *Neuron* 72, 692–697
71. Teller, D.Y. (1979) The forced-choice preferential looking procedure: a psychophysical technique for use with human infants. *Infant Behav. Dev.* 2, 135–153
72. Rovee-Collier, C.K. and Cuevas, K. (2009) Multiple memory systems are unnecessary to account for infant memory development: an ecological model. *Dev. Psychol.* 45, 160–174
73. Canfield, R.L. *et al.* (1995) Age-related change and stability of individual differences in infant saccade reaction time. *Infant Behav. Dev.* 18, 351–358
74. Kaldy, Z. *et al.* (2006) A new method for calibrating perceptual salience across dimensions in infants: the case of color vs. luminance. *Dev. Sci.* 9, 482–489
75. Lansink, J.M. and Richards, J.E. (1997) Heart rate and behavioral measures of attention in six-, nine-, and twelve-month-old infants during object exploration. *Child Dev.* 68, 610–620
76. Hepach, R. and Westermann, G. (2016) Pupillometry in infancy research. *J. Cogn. Dev.* 17, 359–377
77. Fu, X. and Richards, J.E. (2022) Evaluating head models for cortical source localization of the face-sensitive n290 component in infants. *Brain Topogr.* 35, 398–415
78. Anderson, A.W. *et al.* (2001) Neonatal auditory activation detected by functional magnetic resonance imaging. *Magn. Reson. Imaging* 19, 1–5
79. Dehaene-Lambertz, G. *et al.* (2002) Functional neuroimaging of speech perception in infants. *Science* 298, 2013–2015
80. Nielsen, A.N. *et al.* (2023) Baby brains at work: how task-based functional magnetic resonance imaging can illuminate the early emergence of psychiatric risk. *Biol. Psychiatry* 93, 880–892

81. Copeland, A. *et al.* (2021) Infant and child MRI: a review of scanning procedures. *Front. Neurosci.* 15, 666020
82. Conte, S. and Richards, J.E. (2022) Cortical source analysis of event-related potentials: a developmental approach. *Dev. Cogn. Neurosci.* 54, 101092
83. Bayet, L. *et al.* (2020) Temporal dynamics of visual representations in the infant brain. *Dev. Cogn. Neurosci.* 45, 100860
84. Kabdebon, C. and Dehaene-Lambertz, G. (2019) Symbolic labeling in 5-month-old human infants. *Proc. Natl. Acad. Sci. U. S. A.* 116, 5805–5810
85. Rekow, D. *et al.* (2021) Odor-driven face-like categorization in the human infant brain. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2014979118
86. Choi, D. *et al.* (2020) Preverbal infants discover statistical word patterns at similar rates as adults: evidence from neural entrainment. *Psychol. Sci.* 31, 1161–1173
87. Gibbon, S. *et al.* (2021) Machine learning accurately classifies neural responses to rhythmic speech vs. non-speech from 8-week-old infant EEG. *Brain Lang.* 220, 104968
88. Lenc, T. *et al.* (2023) Infants show enhanced neural responses to musical meter frequencies beyond low-level features. *Dev. Sci.* 26, e13353
89. Chen, Y-H. *et al.* (2019) Magnetoencephalography and the infant brain. *NeuroImage* 189, 445–458
90. Zahran, S. *et al.* (2022) Performance analysis of optically pumped ^{4}He magnetometers vs. conventional squids: from adult to infant head models. *Sensors* 22, 3093
91. Zhao, T.C. and Kuhl, P.K. (2022) Development of infants' neural speech processing and its relation to later language skills: a MEG study. *NeuroImage* 256, 119242
92. Bosseler, A.N. *et al.* (2021) Using magnetoencephalography to examine word recognition, lateralization, and future language skills in 14-month-old infants. *Dev. Cogn. Neurosci.* 47, 100901
93. Chen, Y. *et al.* (2021) Maturation of hemispheric specialization for face encoding during infancy and toddlerhood. *Dev. Cogn. Neurosci.* 48, 100918
94. Moser, J. *et al.* (2020) Magnetoencephalographic signatures of hierarchical rule learning in newborns. *Dev. Cogn. Neurosci.* 46, 100871
95. Kao, C. and Zhang, Y. (2019) Magnetic source imaging and infant MEG: current trends and technical advances. *Brain Sci.* 9, 181
96. Clarke, M.D. *et al.* (2022) Infant brain imaging using magnetoencephalography: challenges, solutions, and best practices. *Hum. Brain Mapp.* 43, 3609–3619
97. Lin, J.F.L. *et al.* (2022) Dual-MEG interbrain synchronization during turn-taking verbal interactions between mothers and children. *Cereb. Cortex* 33, 4116–4134
98. Korom, M. *et al.* (2022) Dear reviewers: responses to common reviewer critiques about infant neuroimaging studies. *Dev. Cogn. Neurosci.* 53, 101055
99. Cusack, R. *et al.* (2015) Optimizing stimulation and analysis protocols for neonatal fMRI. *PLOS ONE* 10, e0120202
100. Ellis, C.T. *et al.* (2020) Re-imagining fMRI for awake behaving infants. *Nat. Commun.* 11, 4523
101. Gao, W. *et al.* (2017) Functional connectivity of the infant human brain: plastic and modifiable. *Neuroscientist* 23, 169–184
102. Zhang, H. *et al.* (2019) Resting-state functional MRI studies on infant brains: a decade of gap-filling efforts. *NeuroImage* 185, 664–684
103. Graham, A.M. *et al.* (2015) The potential of infant fMRI research and the study of early life stress as a promising exemplar. *Dev. Cogn. Neurosci.* 12, 12–39
104. Bruchhage, M.M.K. *et al.* (2020) Functional connectivity correlates of infant and early childhood cognitive development. *Brain Struct. Funct.* 225, 669–681
105. Hu, D. *et al.* (2022) Existence of functional connectome fingerprint during infancy and its stability over months. *J. Neurosci.* 42, 377–389
106. Wild, C.J. *et al.* (2017) Adult-like processing of naturalistic sounds in auditory cortex by 3- and 9-month old infants. *NeuroImage* 157, 623–634
107. King, L.S. *et al.* (2021) Naturalistic language input is associated with resting-state functional connectivity in infancy. *J. Neurosci.* 41, 424–434
108. Prabhakar, J. *et al.* (2018) Memory-related hippocampal activation in the sleeping toddler. *Proc. Natl. Acad. Sci. U. S. A.* 115, 6500–6505
109. Biagi, L. *et al.* (2015) BOLD response selective to flow-motion in very young infants. *PLOS Biol.* 13, e1002260
110. Yates, T.S. *et al.* (2023) Face processing in the infant brain after pandemic lockdown. *Dev. Psychobiol.* 65, e22346
111. Ellis, C.T. *et al.* (2021) Attention recruits frontal cortex in human infants. *Proc. Natl. Acad. Sci. U. S. A.* 118, e2021474118
112. Ellis, C.T. *et al.* (2021) Evidence of hippocampal learning in human infants. *Curr. Biol.* 31, 3358–3364
113. Hakim, U. *et al.* (2023) Quantification of inter-brain coupling: a review of current methods used in haemodynamic and electrophysiological hyperscanning studies. *NeuroImage* 280, 120354
114. Frijia, E.M. *et al.* (2021) Functional imaging of the developing brain with wearable high-density diffuse optical tomography: a new benchmark for infant neuroimaging outside the scanner environment. *NeuroImage* 225, 117490
115. Yücel, M.A. *et al.* (2021) Best practices for fNIRS publications. *Neurophotonics* 8, 012101
116. Gemignani, J. and Gervain, J. (2021) Comparing different preprocessing routines for infant fNIRS data. *Dev. Cogn. Neurosci.* 48, 100943
117. Emberson, L.L. *et al.* (2015) Top-down modulation in the infant brain: learning-induced expectations rapidly affect the sensory cortex at 6 months. *Proc. Natl. Acad. Sci. U. S. A.* 112, 9585–9590
118. Delgado Reyes, L. *et al.* (2020) The functional brain networks that underlie visual working memory in the first two years of life. *NeuroImage* 219, 116971
119. Wijeakumar, S. *et al.* (2023) Stunting in infancy is associated with atypical activation of working memory and attention networks. *Nat. Hum. Behav.* 7, 2199–2211
120. Powell, L.J. *et al.* (2018) Using individual functional channels of interest to study cortical development with fNIRS. *Dev. Sci.* 21, e12595
121. Piazza, E.A. *et al.* (2020) Infant and adult brains are coupled to the dynamics of natural communication. *Psychol. Sci.* 31, 6–17
122. Arredondo, M.M. *et al.* (2022) Bilingualism alters infants' cortical organization for attentional orienting mechanisms. *Dev. Sci.* 25, e13172
123. Blanco, B. *et al.* (2021) Group-level cortical functional connectivity patterns using fNIRS: assessing the effect of bilingualism in young infants. *Neurophotonics* 8, 025011
124. Azhari, A. *et al.* (2020) A decade of infant neuroimaging research: what have we learned and where are we going? *Infant Behav. Dev.* 58, 101389
125. Kouider, S. *et al.* (2013) A neural marker of perceptual consciousness in infants. *Science* 340, 376–380
126. Ashton, K. *et al.* (2022) Time-resolved multivariate pattern analysis of infant EEG data: a practical tutorial. *Dev. Cogn. Neurosci.* 54, 101094
127. Ng, B. *et al.* (2022) A practical guide to applying machine learning to infant EEG data. *Dev. Cogn. Neurosci.* 54, 101096
128. Sommer, V.R. *et al.* (2022) Spectral pattern similarity analysis: tutorial and application in developmental cognitive neuroscience. *Dev. Cogn. Neurosci.* 54, 101071
129. Emberson, L.L. *et al.* (2017) Decoding the infant mind: multivariate pattern analysis (MVPA) using fNIRS. *PLOS ONE* 12, e0172500
130. Morales, S. and Bowers, M.E. (2022) Time-frequency analysis methods and their application in developmental EEG data. *Dev. Cogn. Neurosci.* 54, 101067
131. de Heering, A. and Rossion, B. (2015) Rapid categorization of natural face images in the infant right hemisphere. *eLife* 4, e06564
132. Kabdebon, C. *et al.* (2022) The power of rhythms: how steady-state evoked responses reveal early neurocognitive development. *NeuroImage* 254, 119150
133. Jessen, S. *et al.* (2019) Quantifying the individual auditory and visual brain response in 7-month-old infants watching a brief cartoon movie. *NeuroImage* 202, 116060
134. Kosakowski, H.L. *et al.* (2023) Preliminary evidence for selective cortical responses to music in one-month-old infants. *Dev. Sci.* 26, e13387
135. Vanderwal, T. *et al.* (2019) Movies in the magnet: naturalistic paradigms in developmental functional neuroimaging. *Dev. Cogn. Neurosci.* 36, 100600

136. Boto, E. *et al.* (2018) Moving magnetoencephalography towards real-world applications with a wearable system. *Nature* 555, 657–661
137. Feys, O. *et al.* (2022) On-scalp optically pumped magnetometers versus cryogenic magnetoencephalography for diagnostic evaluation of epilepsy in school-aged children. *Radiology* 304, 429–434
138. Boto, E. *et al.* (2022) Triaxial detection of the neuromagnetic field using optically-pumped magnetometry: feasibility and application in children. *NeuroImage* 252, 119027
139. Brookes, M.J. *et al.* (2021) Theoretical advantages of a triaxial optically pumped magnetometer magnetoencephalography system. *NeuroImage* 236, 118025
140. Moser, J. *et al.* (2021) Magnetoencephalographic signatures of conscious processing before birth. *Dev. Cogn. Neurosci.* 49, 100964
141. Martinez-Alvarez, A. *et al.* (2023) Prosodic cues enhance infants' sensitivity to nonadjacent regularities. *Sci. Adv.* 9, eade4083