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Review

Consciousness in the cradle: on the emergence of infant experience

Tim Bayne [1,2,8,*] Joel Frohlich,[3,4,8] Rhodri Cusack,[5] Julia Moser,[6] and Lorina Naci[7]

Although each of us was once a baby, infant consciousness remains mysterious and there is no received view about when, and in what form, consciousness first emerges. Some theorists defend a 'late-onset' view, suggesting that consciousness requires cognitive capacities which are unlikely to be in place before the child's first birthday at the very earliest. Other theorists defend an 'early-onset' account, suggesting that consciousness is likely to be in place at birth (or shortly after) and may even arise during the third trimester. Progress in this field has been difficult, not just because of the challenges associated with procuring the relevant behavioral and neural data, but also because of uncertainty about how best to study consciousness in the absence of the capacity for verbal report or intentional behavior. This review examines both the empirical and methodological progress in this field, arguing that recent research points in favor of early-onset accounts of the emergence of consciousness.

Highlights

The study of infant (and fetal) consciousness is emerging as a distinctive research focus in the science of consciousness.

Converging evidence from studies of functional network connectivity, attention, multimodal integration, and cortical responses to global oddballs suggests that consciousness is likely to be in place in early infancy and may even occur before birth.

Recent research is beginning to provide clues about both the content and structure of infant consciousness.

The onset of experience

Nearly everyone who has held a newborn infant has wondered what, if anything, it is like to be a baby. What kinds of conscious states are characteristic of infant experience? In what ways is infant experience continuous with ordinary adult (or childhood) experience, and in what ways is it unique? Indeed, do newborn infants have any kind of experience at all, or does consciousness emerge only weeks, perhaps months, after birth? Few would doubt that consciousness is generally in place by the age of 1 year, where children have a wide range of perceptual and cognitive capacities and produce a rich suite of communicative behaviors. At the same time, none of the neural machinery required for consciousness is in place immediately after conception (e.g., neurogenesis does not even begin until weeks later [1]). At one developmental timepoint, the human organism lacks the capacity for consciousness; at another timepoint, it has acquired that capacity. When does this change take place?

Although speculation on the emergence of experience dates back to the earliest reflections on the human mind, it is only in the past few decades that such speculation has been informed by detailed understanding of brain development. There is, however, no consensus as to when consciousness first emerges and the range of candidate answers offered here is extremely wide. At one end of the spectrum are accounts that suggest that consciousness might be in place from as early as 24 to 26 weeks **gestational age** (see Glossary), which is when thalamocortical connectivity is first established [2,3]. At the other end of the spectrum are accounts according to which consciousness is unlikely to be in place significantly prior to the child's first birthday [4]. In between, of course, lie a wide range of possible accounts, including the view that consciousness arises soon after birth [5], perhaps even during the process of birth itself.

[1]Monash University, Melbourne, VIC, Australia
[2]Brain, Mind, and Consciousness Program, Canadian Institute for Advanced Research, Toronto, Canada
[3]Institute for Neuromodulation and Neurotechnology, University Hospital and University of Tübingen, Tübingen, Germany
[4]Institute for Advanced Consciousness Studies, Santa Monica, CA, USA
[5]Thomas Mitchell Professor of Cognitive Neuroscience, Trinity College Institute of Neuroscience, Trinity College Dublin, Dublin, Ireland
[6]Masonic Institute for the Developing Brain, University of Minnesota, Minneapolis, MN, USA
[7]Trinity College Institute of Neuroscience and Global Brain Health Institute, Trinity College, Dublin, Ireland
[8]These authors contributed equally (co-first authorship) to this work.

*Correspondence:
timothy.bayne@monash.edu (T. Bayne).

Box 1. Implications of early consciousness

Questions about when (and in what form) consciousness first emerges are widely taken to have clinical, ethical, and potentially even legal implications. For example, until the late 1980s, it was routine for infants to be operated on without the administration of analgesics or anesthetics [106], a practice that presumably reflected the widespread belief that infants could not feel pain. Clinicians now generally assume that even newborns can experience pain [107] and, as a result, are much more likely to administer analgesics to this patient group [108]. However, debates about when the capacity for pain experience might first emerge remain ongoing [109–111].

In addition to the implications associated with the experience of pain, consciousness itself is often taken to have normative significance. On one understanding of this idea (the 'normative significance thesis'), individuals who possess a standing capacity for consciousness have a kind of moral status that is not shared by individuals without such a capacity. Accounts of what that moral status might involve vary, but most agree that it involves protection from a range of harms. If the normative significance thesis is true, then debates about the emergence of consciousness would have important ethical implications.

Although the normative significance thesis is often assumed without argument, it is in fact controversial [112,113]. Some theorists deny that there is anything normatively significant about consciousness at all [114]. Others argue that although certain kinds of conscious states, such as those that are affectively valenced or involve self-consciousness, are normatively significant, consciousness as such is not [115]. It is also worth noting that those who take consciousness to be widely distributed throughout the natural world have reason to resist the normative significance thesis. It is one thing to think that, for example, mammals, birds, and cephalopods have a basic kind of moral status in virtue of possessing the capacity for consciousness, but there are also those who ascribe some form of consciousness to insects, plants, and even elementary particles [116]. Rather than extend the notion of moral status to include these entities, one might instead reconsider the assumption that mere consciousness suffices for basic moral status.

Understanding when (and in what form) consciousness first emerges should be high on the agenda of consciousness science. Not only would it have important implications for debates about the mechanisms underlying consciousness [6], it would also have important clinical, ethical, and perhaps even legal implications (Box 1). Drawing on advances that have been made in detecting consciousness in other challenging contexts, including in patients with severe brain damage [7], this paper examines what we know about the first of glimmerings of human awareness. Although it would be premature to make definitive claims about when consciousness first emerges, we suggest that current evidence indicates that consciousness is likely to be in place by early infancy, and may even begin before birth. Our primary aim, however, is not to provide a definitive answer to the question of when (and in what form) consciousness first emerges, but to present recent developments within a compelling framework that will advance discussion of this important issue.

Methodological challenges

The notion of consciousness with which we are concerned in this article involves the possession of an experiential point of view. An organism is conscious if (and only if) it has a subjective perspective – if there's 'something that it's like' to be that organism [8]. Different kinds of conscious states (or 'contents') are distinguished from each other in terms of what it's like to be in them. What it's like to see a face is distinct from what it's like to hear a melody and each of those experiences is itself distinct from what it's like to feel pain. Note that here we treat 'consciousness' as a synonym for 'awareness'. Our focus here is on the development of 'core' [9] or 'primary' [10] consciousness and not on the development of forms of consciousness that require reflection, self-consciousness, or off-line cognition [11,12]. These features can be absent even in adult states of consciousness [13,14] and are unlikely to be present in the earliest stages of experience.

Because consciousness is a subjective phenomenon, attempts to identify its presence in infancy confront serious methodological challenges. Clearly, the standard tools for studying consciousness in adults and older children, such as the capacity to produce verbal reports or follow

Glossary

Auditory oddball paradigm: the experimental presentation of auditory tones in which one auditory stimulus (the 'oddball') is assigned a low probability relative to other stimuli. In a variant known as the local-global oddball paradigm, each trial consists of a sequence of multiple stimuli and two types of oddballs exist: 'local' oddballs, which have a low probability of occurring within a sequence, and 'global' oddballs, which have a low probability of occurring across sequences.

Gestational age: the age of a fetus as determined by the time since the pregnant woman's last menstruation (as opposed to the time since conception).

Global workspace theory (GWT): in its most influential version, known as the global neuronal workspace theory, GWT holds that consciousness depends on ignition and broadcast within a global workspace that is instantiated in frontoparietal cortical regions.

Higher-order representation theories (HOTs): higher-order theories take consciousness to depend on higher-order representations of first-order mental states.

Integrated information theory (IIT): IIT equates an individual's consciousness with the cause-effect structure specified by a substrate that is maximally irreducible.

Local re-entry theory (LRT): also known as the local recurrent processing theory, LRT holds that consciousness depends on recurrent processing within cortex. LRT has been developed primarily in relation to visual consciousness.

McGurk effect: a multisensory effect in which simultaneously presenting the phoneme /ba/ (auditory input) with the lip movements for /ga/ (visual input) produces a percept of the phoneme /da/.

Ontogenesis: the process by which an organism develops from conception to adulthood. The ontogenesis of consciousness refers to the development of consciousness during the early life of an organism.

P300: an EEG/MEG response to an unexpected stimulus. Note that while the name 'P300' implies a 300 millisecond latency, this response occurs substantially later in infants.

Perturbational complexity index (PCI): a method for identifying the presence of consciousness using the spatiotemporal complexity of the cortical response to a perturbation, such as a commands, are unavailable and we are forced to rely on less direct markers (or indicators) of consciousness. A theorist's choice of markers is crucially important here, and much of the debate surrounding the emergence of consciousness stems from more fundamental disagreement about the kinds of states and capacities that function as markers of consciousness.

transcranial magnetic stimulation (TMS) pulse. In infants and fetuses, sensory perturbations might be substituted for electromagnetic perturbations.

Late-onset views versus early-onset views

Some theorists take consciousness to require capacities which are almost certainly not available to young infants. According to Perner and Dienes [4], consciousness requires the capacity to represent mental states as such and is thus (they conclude) unlikely to be in place before the age of 1 year. Frith [15] equates the contents of consciousness with 'shareable knowledge', suggesting that consciousness involves representations that are 'coded independently of egocentric coordinates'. Although Frith draws no inferences about when consciousness is likely to first emerge, his position would also seem to suggest that consciousness is unlikely to be acquired prior to the child's first birthday. Perhaps the most radical of the 'late-onset' proposals is due to Carruthers [16], who argues that consciousness does not emerge until the age of 3 years on the grounds that this is when children first acquire the concepts that he takes to be required for consciousness, such as 'appears' and 'seems'.

At the same time, many potential markers of consciousness can be found in early infancy. Full-term neonates exhibit visual pursuit and fixation [17] and they produce a rich suite of reactions in response to noxious stimuli, including increased heart-rate and skin conductance, limb-withdrawal, grimacing, and brain activity distinctive to noxious stimuli [18]. Indeed, neonates can distinguish their mother's voice from that of a stranger's [19,20] and can discriminate dynamic facial expressions of happiness from disgust [21]. This capacity for basic environmental responsiveness distinguishes young infants from brain-injured patients in the unresponsive wakefulness syndrome (UWS) ('vegetative state'), who do not respond appropriately to their surroundings and who do not strike us as subjects of awareness. The question, of course, is whether behavioral indicators of consciousness in young infants are to be trusted. A related question is whether there are reasons to think that consciousness might emerge even before these behavioral indicators do.

The theory-first approach

Clearly, methodological questions are of crucial importance here. Without guidance as to which cognitive, behavioral, or neural responses we ought to employ as markers of consciousness, the debate over when consciousness first emerges threatens to become a stand-off between those who favor cognitively demanding measures of consciousness (and thus orient towards 'late-onset' views) and those who favor relatively undemanding measures (and thus orient towards 'early-onset' views).

In response to this dilemma, one might be tempted to begin with a theory of consciousness, and ask what that theory implies with respect to infant consciousness. Although it is certainly useful to consider what particular theories might imply with respect to the emergence of consciousness, the theory-first approach faces serious challenges. For one, there is little agreement as to which theories of consciousness are most likely to be correct (or even plausible). A recent review [6] identified more than 20 neurobiological accounts, many of which have importantly different variants. This failure of theoretical convergence would not be problematic if the field were moving towards consensus, but that does not appear to be the case [22,23]. Worse, rival theories, including those that are some of the most influential, suggest very different accounts of when (and in what form) consciousness first emerges (Box 2).

Box 2. Infant consciousness through a theoretical lens

Although few theories make unambiguous predictions about when consciousness first emerges, it is possible to draw a rough-and-ready distinction between 'early-onset' and 'late-onset' theories. Here, we consider this point with reference to four influential theories of consciousness: **higher-order representation theories (HOTs)**; the **local re-entry theory (LRT)**, **integrated information theory (IIT)**, and the **global workspace theory (GWT)**.

Traditional HOTs suggest a late onset of consciousness (Figure I), as they require the capacity to make one's first-order representations the objects of conceptually structured metarepresentational states. However, more recent HOTs hold that perceptual consciousness requires only the presence of a nonconceptual generative model of the reliability of first-order representations [117,118], and thus allow that consciousness might emerge significantly before conceptual thought does.

LRT holds that visual experience requires recurrent processing within visual cortex, a process that is central to the formation of integrated visual objects [119]. It appears to be a 'late-onset' theory of (visual) consciousness (Figure I), for anatomical evidence suggests that the visual system is unable to support recurrent processing prior to 7 months after birth. Furthermore, backwards masking (which requires recurrent processing) is not effective before 7 months of age [120].

In contrast to HOTs and LRT, IIT [121] suggests an early onset of infant consciousness (Figure I). Although the quantity with which IIT identifies consciousness (Max-Φ) cannot be directly measured, findings from a study [122] that measured a reasonable approximation thereof, 'Φ autoregressive', implied that consciousness is in place near birth.

It is not entirely clear what GWT [123] predicts with respect to the emergence of consciousness. Recent evidence (see main text) suggests that some kind of parietal/prefrontal workspace is in place from birth, but whether this workspace qualifies as consciousness-supporting is uncertain, in part because the advocates of GWT have not supplied a precise specification of what constraints a workspace must meet in order to qualify as truly 'global'.

Although the four theories discussed here differ in significant respects, they converge on the importance of the thalamocortical system for sustaining consciousness, a structure that is widely, although not universally [124], regarded as a prerequisite for consciousness. If it is granted that a functioning thalamocortical system is necessary for consciousness, then an early (i.e., 'not before') limit can be set on the emergence of consciousness of around 24–26 weeks gestation.

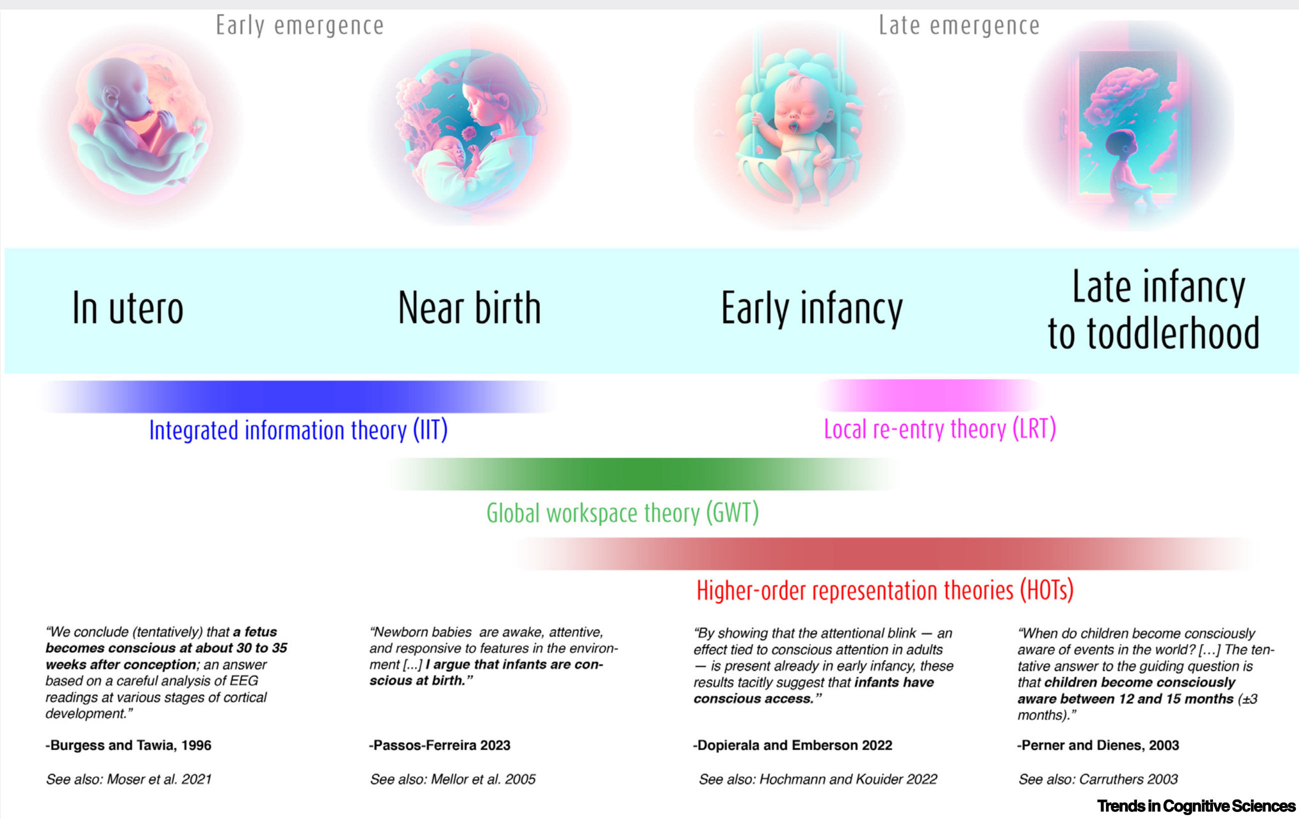

Figure I. Four perspectives on the emergence of consciousness. Although experts rarely make precise claims about when consciousness begins, here we connect several views [4,5,16,65,125–128] to different developmental periods and theories. The timeline gives the point at which one can make the claim that consciousness has emerged, with some uncertainty, based on a given theory. Abbreviation: EEG, electroencephalography.

The cluster-based approach

Rather than adopt a theory-first approach, we suggest that the study of infant consciousness would be better served by adopting a cluster-based approach, in which claims about the **ontogenesis** of consciousness are addressed by looking at when the various markers of consciousness in adults (and children) first emerge. The cluster-based approach has been applied to questions of consciousness in non-human animals [24] and humans who have sustained severe brain damage [25,26] and there is every reason to think that it might be fruitfully applied to the question of infant consciousness. Although no single marker is likely to provide definitive proof of consciousness (or its absence), we might be justified in moving from a position of agnosticism to one of warranted belief if there is convergence across a variety of markers.

Within the set of markers of consciousness, we can distinguish two-way markers (i.e., those which have high sensitivity and high specificity) from one-way markers (those which have high specificity but low or unknown sensitivity). A marker qualifies as two-way if its presence/absence corresponds with the presence/absence of consciousness and it qualifies as merely one-way if its presence corresponds with the presence of consciousness, but (as far as we know) its absence does not correspond with the absence of consciousness. Because our focus here is on one-way markers, our main conclusions will concern an upper bound on the emergence of consciousness. That said, we view the development of thalamocortical connectivity, generally regarded as necessary for consciousness, as providing a lower bound of 24–26 weeks gestation [2,27] on the emergence of consciousness.

Although many types of markers of consciousness could be considered, we will emphasize neural markers (Box 3). The interrogation of behavior is certainly relevant to the ascription of consciousness in infancy [28], but designing behavioral tasks to probe infant cognition is difficult and the results often allow for diverse interpretations. Historically, estimates of the age of onset of various cognitive processes have reduced considerably as more sensitive tasks have been invented. More fundamentally, motor control is extremely rudimentary in the first few months of infancy [29] and it is entirely possible that consciousness comes on-line before it can be expressed in behavior. An exclusive focus on behavioral markers might therefore provide a misleadingly late picture of when consciousness first emerges.

The case for early emergence

Here, we present four lines of evidence supporting an early emergence view (Figure 1). The first line of evidence appeals to data indicating that intrinsic connectivity networks that are correlated with the capacity of consciousness [30–32] are present and active early in development. One of the most prominent of these networks is the default mode network (DMN), so named because the brain defaults to this mode of activity, which includes mind-wandering and self-referential processes [33], in task-free resting states. Although DMN activity is probably not required for consciousness [34,35], studies looking at the recovery of consciousness following anesthesia and severe brain damage in adults suggest that consciousness is associated with reciprocal modulation between the activity of the DMN and frontoparietal networks, in particular, the dorsal attention network (DAN) and the executive control network (ECN) [36,37]. Previous research had failed to find evidence of anything more than a rudimentary DMN in infants [38,39], but a more recent study [40] using a large fMRI dataset of newborn infants (n = 428) found not only that the default mode, dorsal attention, and executive control networks were present as distinct networks shortly after full-term birth (or by term-equivalent age), but that a reciprocal relationship between the DMN and the DAN was also present. This is a striking finding, for it suggests that key features of the neural circuitry associated with consciousness are present at birth (or term-equivalent age for infants born prematurely).

Box 3. Neural measures for investigating the emergence of consciousness

Given the unique concerns of infant research, experimenters often choose neural measurement tools that have fast set-up and are robust to motion artifacts. Using electroencephalography (EEG) [129], neural data can be recorded while the infant rests in the caregiver's arms and a flexible, geodesic 'net' of electrodes can be quickly fitted to an infant's head [130] (Figure IA). An even faster set-up time can be achieved using magnetoencephalography (MEG) [75], which simply requires the infant to be positioned toward the sensor array, without the additional set-up time demanded by EEG to adjust channel impedances. Furthermore, MEG, unlike EEG, is not distorted by the skull, which, in infants, contains fontanels, leading to uneven smearing of the EEG signal [131]. Some MEG systems can also record fetal brain activity (Figure IB), which is currently not possible using non-invasive EEG. Only a few infant and fetal MEG systems are operational [75], but optically pumped magnetometers (next-generation MEG devices that can be applied in an *ad hoc* manner to different head shapes using a 3D-printed helmet [105]) will likely make infant data more accessible in coming years.

A third tool is functional near infrared spectroscopy (fNIRS) [132,133], which records hemodynamic activity reflecting oxygen usage by the infant brain (Figure IC). Due to the hemodynamic response function, fNIRS data lack the very high temporal resolution of MEG/EEG data, but the minimal preparation time of fNIRS makes it attractive for infant research, and high-density, fiberless, portable fNIRS systems are now available for infant research [134]. Like fNIRS, functional magnetic resonance imaging (fMRI) measures hemodynamic activity as a proxy for neural activity, but unlike fNIRS, it is capable of imaging infant brain activity with high (<1 cm) spatial resolution (Figure ID). Although infant fMRI experiments are challenged by motion sensitivity and a loud scanner environment, these obstacles are generally overcome by waiting until the infant is sleeping and then recording spontaneous data during sleep, although protocols for recording awake infant fMRI have recently been introduced as well [79,80,135,136]. Such protocols are a useful expansion of the infant researcher's toolkit, as a scientific consensus regarding infant consciousness will likely require a confluence of evidence from not one but many of the aforementioned tools, as well as infant behavioral data.

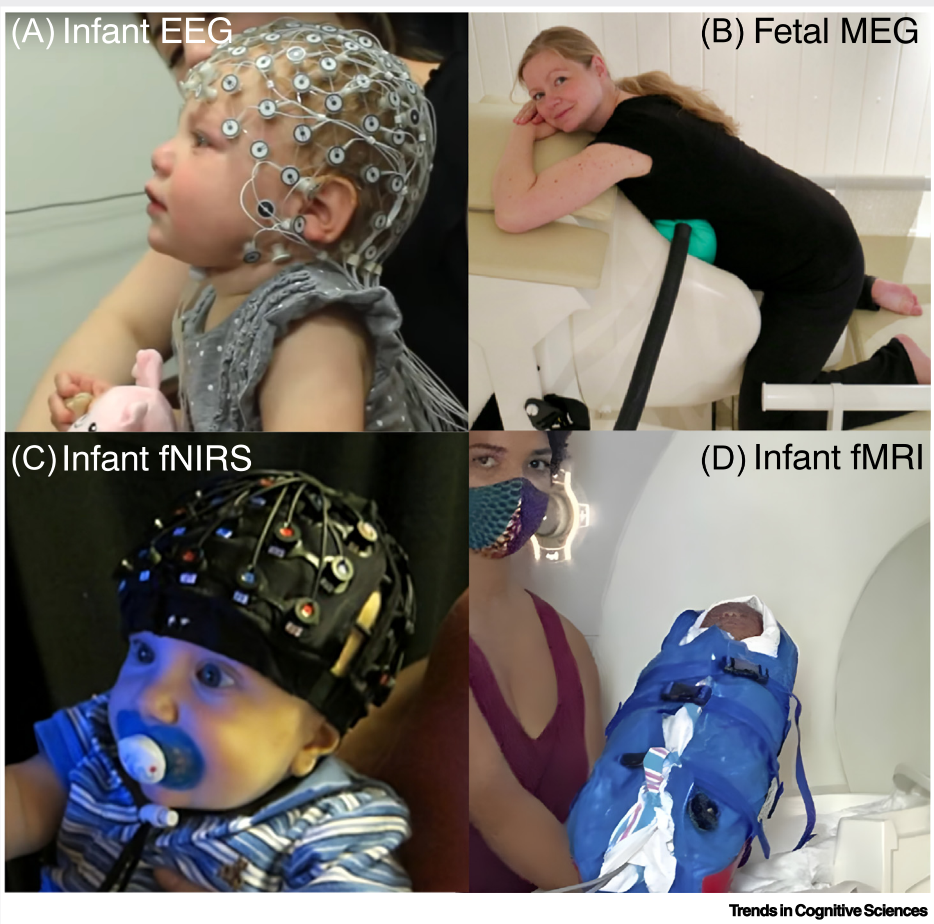

Figure I. Examples of techniques for recording brain activity and/or neuroimaging in infants and fetuses. (A) Infant electroencephalography (EEG) with a geodesic electrode net (laboratory of Shafali Jeste, video still from https://www.youtube.com/watch?v=x6sTJP0dFgg). (B) Fetal magnetoencephalography (MEG) recorded from a pregnant woman (University Hospital Tübingen). (C) Infant functional near infrared spectroscopy (fNIRS) recording with multichannel optode cap (AI upscaled from [133]). (D) An infant is prepared for functional magnetic resonance imaging (fMRI) (AI upscaled from [137]). Abbreviation: AI, artificial intelligence.

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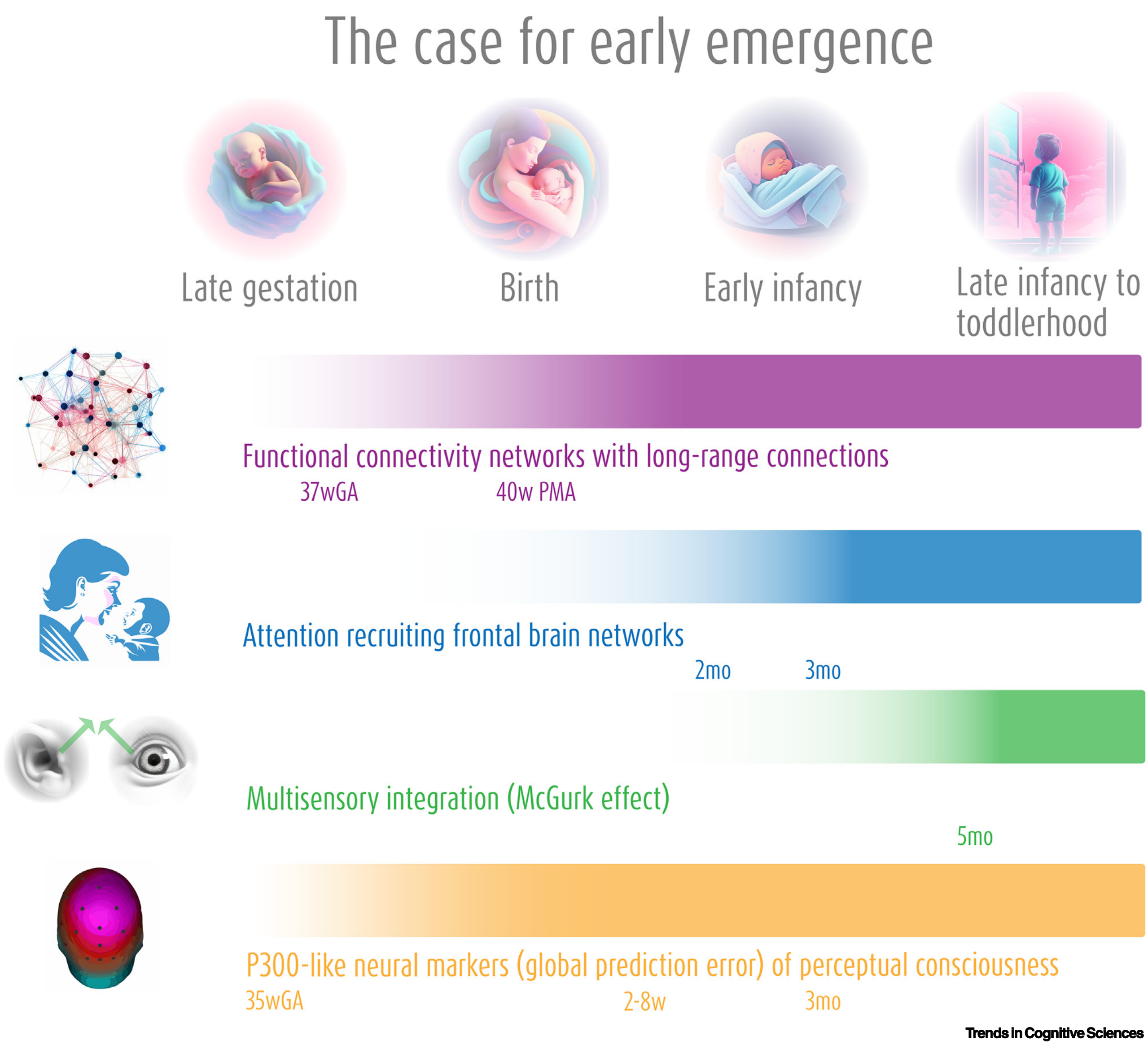

Figure 1. The case for early emergence. The most compelling evidence for early emergence comes from studies of: (i) functional connectivity networks in fetuses [143] and newborns [40,41]; (ii) attention in young infants [53,144]; (iii) multisensory integration in young infants (namely, the McGurk effect) [59,60]; and (iv) global neural prediction errors in fetuses [65], newborns [64], and young infants [63]. The P300 scalp topography shown to the left of the bottom row is adapted from [145] (CC BY 4.0), and the cartoon images of developing brains are adapted from [3] (CC BY-NC 4.0). All other images are generative artificial intelligence (Midjourney). Abbreviations: GA, gestational age; PMA, post-menstrual age.

Of course, even if the networks required for consciousness are in place from birth (or soon after) [41–43], it might be argued that they do not play a significant role in cognitive processing. However, a study of infants in a neonatal intensive care unit with suspected neurological injury found that disruption to the ECN at term-equivalent age was predictive of the emergence of motor impairments at 4 and 8 months of age [44], suggesting a causal link between the ECN and behavior even at this young age.

A second line of evidence for the early emergence of consciousness involves attention. Although the mechanisms of consciousness are widely taken to be distinct from those of attention [45,46], there are close links between the two phenomena, and it is plausible to suppose that the emergence of consciousness broadly tracks that of attention. This is particularly the case with respect to top-down (endogenous, voluntary) attention, which emerges at about 3–6 months of age [47,48]. If bottom-up (exogenous, involuntary) attention is also sufficient for consciousness, as has sometimes been suggested [49,50], then we have grounds for locating the emergence of consciousness significantly earlier, for bottom-up attention is evident from eye movements in newborns [51]. However, caution must be exercised here, as subcortical (and thus, presumably, unconscious) pathways may be driving the earliest forms of bottom-up attention [52]. That said, a recent study [53] found that stimulus-driven attention in infants recruits the same frontoparietal and cingulo-opercular networks that are recruited in adults, thus suggesting that a link between bottom-up attention and consciousness might be in place as early as 3 months.

A third line of evidence for early-onset accounts of consciousness comes from research on multisensory integration. Certain forms of multisensory integration, such as the detection of temporal synchrony between auditory and visual streams, can occur outside of consciousness [54–56] and their presence in early infancy provides little evidence for infant consciousness. However, other forms of multisensory integration do appear to occur only when the integrated stimuli are consciously perceived [57]. For example, the **McGurk effect** disappears when flash suppression is used to prevent the visual stimulus from reaching awareness [58]. This is directly relevant to the question of infant consciousness, for consistent McGurk-type effects can be found at 5 months of age [59,60] and even sometimes from 4 months, albeit intermittently [61].

A fourth line of evidence for the early emergence of consciousness exploits an **auditory oddball paradigm** (the 'local-global' paradigm). First developed in connection with disorders of consciousness [62], the local-global paradigm exploits a **P300** (or 'P3b') response, a late cortical response often associated with surprise and the reorientation of attention. Although P300 responses to first-order ('local' or within-trial) auditory oddballs do not appear to be predictive of consciousness (e.g., they can be found in UWS patients), P300 responses to second-order ('global' or between-trial) auditory oddballs (the 'global effect') exhibit greater specificity to consciousness [e.g., these responses can be found in minimally conscious state (MCS) patients but not UWS patients] [62]. For this reason, the global effect is widely taken to be suggestive of perceptual consciousness. Strikingly, an early ERP event-related potential (ERP) study found evidence of a P300-like 'negative slow wave' responses to global oddballs in 3-month-old infants [63], while more recent studies using magnetoencephalography (MEG) have found evidence of a P300-like response to global oddballs in newborns [64] and fetuses past 35 weeks gestational age [65].

Even when we consider the strongest evidence from local-global paradigms, however, the corresponding findings [63–65] must be qualified in two ways. Firstly, the parameters (mainly, the latency) of the infant response differ from those of the adult P300 response, as axonal conduction velocities are slower in the immature brain [66], resulting in delayed cortical components as compared with adults. And yet, despite different latencies, a plausible case can be made for thinking that the infant's P300-like response plays the same functional role as the adult's P300 response. Second, the specificity of the global effect as an indicator of consciousness has been questioned, for there is some evidence that the global effect can be obtained in the absence of consciousness [67]. These findings are important, but they do not undermine our case for the early emergence of consciousness, because our claim is only that late cortical responses to global oddballs are widely regarded as having better than chance accuracy for detecting consciousness, and, as such, should inform our 'best guess' regarding the presence of consciousness in the developing human.

Because P300-like responses to global oddballs indicate that higher-order networks are online and are able to communicate with auditory networks, evidence of the global effect in early infancy converges with other findings in infants (reviewed above) indicating that attentional and higher-order regions mature earlier than had been thought. These findings are also of a piece with predictive processing approaches to perceptual consciousness [68].

It is important to recognize that at least some (and perhaps all) of these markers are experience-dependent and their emergence can be delayed/altered by a variety of factors. For example, premature birth has been associated with disruption to the DMN and frontoparietal networks [40,69] and with an absence of the neural response to surprising sensory omissions that is usually seen at 6 months [70]. The fact that some of the markers of consciousness can be delayed/altered by adverse environmental conditions does not imply that consciousness itself is delayed (recall that we are treating these markers as one-way rather than two-way markers), but we should certainly take seriously the possibility that consciousness emerges at different times in different individuals. Care must be taken in making comparisons between infants based on age alone

Finally, we note the possibility of applying a perturbational approach to the question of infant consciousness. The most sophisticated perturbational approach to the detection of consciousness thus far is the **perturbational complexity index (PCI)**, in which the cortex is perturbed by the application of transcranial magnetic stimulation (TMS) pulses and the complexity of the cortical response is then measured by electroencephalography (EEG) [71]. Data from studies involving the loss and recovery of consciousness in the context of general anesthesia, non-rapid eye movement sleep, and disorders of consciousness suggest that an individual's PCI response can inform ascriptions of consciousness [71–74]. Because the risk profile of TMS in early development is unknown, its use in infants and fetuses is regarded as unethical when not medically justified. However, a sensory version of the PCI approach might be viable, in which the infant (or fetal) cortex would be perturbed not by TMS, but by the presentation of a visual, auditory, or even olfactory stimulus [75]. Although this 'sensory PCI' approach has yet to be rigorously implemented, it may prove to be an important tool in the quest to detect the earliest forms of consciousness [76].

What is it like to be a baby?

Thus far we have focused on the 'when' of infant consciousness, but the 'what' of infant consciousness raises equally important – and, in certain ways, more tractable – issues. Here, we bracket questions about whether infants of a certain age are conscious and focus instead on the question of what the character of their experience is like (assuming that they are conscious).

The content of infant experience is, of course, constrained by the immature state of various perceptual systems. In vision, acuity is low at birth. Color detection is also limited at birth and mature trichromatic processing does not emerge until about 3 months of age [77,78]. However, category-specific responses to faces, scenes, and bodies have been seen using fMRI in the ventral visual pathway from as early as 2 months [79] (see also [80]). Intriguingly, differences in the long-range neural connectivity of different category-specific regions are present about 1 week after birth, suggesting that some of the broader associations may already be evoked [81].

Given that the auditory system matures before the visual system, there is reason to suspect that the infant's auditory experience might be richer and more complex than their visual experience. From birth, infants show behavioral sensitivity to their mother's voice [19] and the prosody of their native language [82,83], although research into neural responses to speech (as opposed to comparable auditory stimuli) has produced mixed results. Selective responses to music in nonprimary auditory cortex have been reported in 1-month-olds [84] and sensitivity to violations of musical beat has been reported in newborns [85]. An ERP study of preterm infants (Box 4) suggests that by 30 weeks gestational age, the Perisylvian region is able to support the detection of both phonetic (/da/ versus /ga/) and voice (male versus female) change [86] and there is even evidence that the fetus recognizes its mother's voice [87].

A particularly challenging question concerns the development of the infant's awareness of its own body and its capacities for action. Although some work has been done in this area [88–91], bodily and agentive experience in the infant has received significantly less attention than perceptual experience. It is plausible that bodily experiences reach conscious awareness earlier than other aspects of sensory experience, possibly even before birth. Consider the loose analogy of a sensory isolation float tank, which is sometimes compared with the womb (e.g., [92]). Adults who float in isolation tanks experience enhanced interoception despite (or perhaps because of) minimization of all external sensory afferents [93]. On this basis, it might be suggested that interoceptive experience emerges before exteroceptive experience.

For the most part, the development of consciousness is a story of perceptual expansion, in which the infant becomes perceptually sensitive to a wider range of environmental features as it ages. However, perceptual narrowing, in which infants lose the capacity to discriminate between features that they had previously been sensitive to, also occurs. For example, 6- to 10-month-olds raised in English-speaking households are able to discriminates between consonants used in Hindi (but not English) that monolingual English-speaking adults cannot discriminate [94] (for a review see [95]), but that ability is lost by 10 months of age. Perceptual narrowing also occurs in vowel discrimination, in which 4-month-olds have the capacity to discriminate between non-

Box 4. Preterm infants as a model of age-equivalent fetuses

Globally, 11% of all live births are preterm (occurring before 37 weeks gestation) and 1.7% are extremely or very preterm (occurring before 32 weeks gestation) [138]. Preterm infants [129] and age-equivalent fetuses [139] share some common patterns of cortical activity and both have remarkable capacities for learning (e.g., [65,86]). Given the difficulties of imaging *in utero* and the relative ease with which preterm infants can be studied, preterm infants are often used as a model of age-equivalent fetuses. Although much can be learned about the fetal brain in this way, caution should be exercised when generalizing from preterm infants to age-equivalent fetuses, for there are multiple points of contrast between these two populations.

For one, preterm infants are characterized by more risk factors (e.g., fetal infection, maternal stress) [140] than age-equivalent fetuses. While not every preterm birth is clearly associated with a risk factor, it is likely that the fetus only leaves the protection of the womb when a threat to its health arises, one which has most likely already affected its development and may continue to affect its development after birth.

A second contrast concerns the environments to which preterm infants and their age-equivalent counterparts have been exposed. The uterine environment is characterized by rhythmic auditory stimulation produced by the maternal heart, internal organs, and maternal voice. The fetus is also exposed to sedating neuromodulators such as adenosine, pregnenolone, and prostaglandin D2 [5], which, together with low oxygen levels (referred to as 'Mount Everest *in utero*'), suppress fetal activity [27]. (Given this sedation, it is possible that the capacity for consciousness is never realized in the fetus, even if the requisite neural circuity is already in place.) By contrast, the infant's environment is irregular and noisy [141] (particularly so in the case of preterm infants whose first weeks are typically spent in a neonatal intensive care unit), and neural activity in infants is no longer suppressed by neuromodulators or low levels of oxygen. Birth itself marks an important state transition, as the neurohormones (such as catecholamines) that are released during the process of birth promote wakefulness [142]. Indeed, it is possible that the transition from the quiet, low-variance *in utero* environment to a noisy, high variance, *ex utero* environment is itself partially responsible for triggering consciousness.

In short, accounts of consciousness that have been developed with reference to preterm infants may apply only in part, if at all, to age equivalent fetuses.

native vowel sounds (that is, vowel sounds that do not feature in the language to which they have been exposed), which they lose by 10 months of age [96], and in lexical tone discrimination, in which young infants (who have not been exposed to tonal languages) have the capacity to discriminate between lexically significant tones, which they too lose by 10 months of age [97]. Perceptual narrowing is not restricted to speech comprehension, but also occurs in the domain of face perception. For example, 3-month-old infants are as good at discriminating between other-race faces as they are at discriminating between same-race faces, but by 9 months of age they have lost that capacity (whilst showing improvements in same-race discriminability) [98].

The character of perceptual experience is determined not just by the features that are encoded but also by its spatial and temporal structure. Here, there is evidence that the structure of infant consciousness differs in fundamental ways from that of adult consciousness [99]. Using a crowding-based paradigm, Farzin et al. [100] showed that the effective spatial resolution of visual perception increases from 6 months to 15 months, but that even at 15 months of age it is only half that of adults. Objects that can be recognized when they are presented by themselves in the periphery are not recognized when presented with flankers (i.e., 'crowded') until they are only 3° from fixation, implying that infants may have limited awareness of individual parts in a crowded scene as compared with adults.

An even more striking contrast between infant and adult experience concerns the temporal structure of visual awareness. This can be probed using the attentional blink, a phenomenon in which the second of two visual targets goes undetected due to the subject's attention being captured by the first target. A recent study found that the attentional blink was 6 six times longer in 5-month-old infants than it is in adults, and that although its duration shortened as infants aged (by 8 months of age it had halved), it does not reach adult levels of length until the age of 3 years [101]. Further evidence that the capacity of consciousness is significantly restricted in infants comes from the finding that 3–12 month-old infants parse animated movies into fewer events (i.e., events of longer duration) than adults do [102] and, correspondingly, integrate sensory information over longer temporal windows [103].

Taken as a whole, these findings suggest that the infant's stream of consciousness is characterized by a reduction of perceptual content at any one point in time, but that the range of perceptual features to which young infants are experientially sensitive may be wider, in certain domains, at least, than that to which older infants are experientially sensitive.

Concluding remarks

Although the problem of identifying when and in what form consciousness begins is very far from being solved, the developments reviewed here suggest that the study of infant consciousness is now a legitimate field within the science of consciousness. Just as recent methodological advances are beginning to provide tentative (albeit limited) answers to questions about consciousness in non-human animals [24] and severely brain-injured individuals [104], they are also beginning to provide tentative (albeit limited) answers to questions about the first stirrings of human experience. In particular, some newer strands of evidence seem to point towards consciousness having an early onset, rather than a late onset (as has often been assumed). Although 'early' in this context potentially encompasses the prenatal period, we emphasize that this evidence is still from late (third trimester) pregnancy, generally after 35 weeks of gestation [65].

Of course, there is much we do not know (see Outstanding questions). A better understanding of infant consciousness will require improved techniques for collecting data about the developing brain. In particular, new innovations in MEG, such as optically pumped magnetometers, may

Outstanding questions

Is the transition from unconsciousness to consciousness sharp? Although the transition from unconsciousness to consciousness is often assumed to be sharp, biology is full of 'intermediate' and 'fuzzy' cases, instances in which the concept in question neither determinately applies nor determinately fails to apply (e.g., are viruses living organisms?). Could the boundary between unconsciousness and consciousness allow for 'intermediate' and 'fuzzy' cases? If so, might there be periods during which the developing organism is neither determinately conscious nor determinately unconscious?

How can we generalize from adults to infants? The cluster-based approach that we have employed here uses markers of adult consciousness to probe for consciousness in infants/fetuses, but given the neuroanatomical and functional differences between adults and infants/fetuses, questions can be raised about the legitimacy of such inferences.

Do infants or fetuses dream and, if so, of what? Although infants (and fetuses) spend an abundant amount of each day in rapid eye movement sleep, it is unclear if they dream. If we consider dreams to be simulations of reality, we might ask what prior model of the world the infant, with its highly limited experience, could draw upon to generate dream content; this consideration becomes even more relevant when we pose the question of newborns or fetuses. To reword Philip K. Dick, 'Do infants dream of prior sheep?'

Does consciousness emerge piecemeal? Might different aspects of consciousness come online at different times? For instance, it might be suggested that interoceptive experiences emerge prenatally, but exteroceptive experiences emerge later, perhaps only postnatally.

pave the way for high density multichannel MEG recordings tailored toward the head size of infants using 3D-printed helmets [105]. Besides the recording technologies themselves, innovative new experiments and analyses will also be needed. The development of techniques for using fMRI to study awake infants is already yielding dividends and the prospect of making PCI approaches infant-friendly by substituting sensory stimulation for TMS may deliver even richer rewards [75].

Although progress in understanding the origins of consciousness will likely be advanced by a better understanding of brain development, understanding the implications of developmental data for accounts of the emergence of consciousness will also require a better understanding of the neural and functional basis of consciousness. This review has taken a theory-neutral approach to infant consciousness, but it is likely that a full understanding of the emergence of experience will require the development of a complete and widely accepted theory of consciousness.

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Declaration of interests

The authors have no interests to declare.

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