

Perceptual awareness in human infants: What is the evidence?

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Abstract

Perceptual awareness in infants during the first year of life is understudied, despite the philosophical, scientific and clinical importance of understanding how and when consciousness emerges during human brain development. Although parents are undoubtedly convinced that their infant is conscious, the lack of adequate experimental paradigms to address this question in preverbal infants has been a hindrance to research on this topic. However, recent behavioral and brain imaging studies have shown that infants are engaged in complex learning from an early age and that their brains are more structured than traditionally thought. I will present a rapid overview of these results which might provide indirect evidence of early perceptual awareness and then describe how a more systematic approach to this question could stand within the framework of global workspace theory, which identifies specific signatures of conscious perception in adults. Relying on these brain signatures as a benchmark for conscious perception, we can deduce that it exists in the second half of the first year, whereas the evidence before the age of five months is less solid, mainly due to the paucity of studies. The question of conscious perception before term remains open, with the possibility of short periods of conscious perception, which would facilitate early learning. Advances in brain imaging and growing interest in this subject should enable us to gain a better understanding of this important issue in the years to come.

The extended periods of sleep, limited vocalizations, and lack of clear voluntary actions in the weeks following birth have long been interpreted as indicators of a poor and empty mental life in infants, or a “blooming, buzzing confusion” (James, 1890). These interpretations reflect an enduring implicit bias to downplay infants’ abilities until there is overwhelming evidence to back them up. In addition, researchers often tend to challenge the parents’ belief that their infant is already competent, contrasting the emotional perspective of parents with objective scientific observation. These prejudices explain why certain questions, such as consciousness, have received little attention. However, since the 1980s, research into cognitive development has gradually proved parents right, revealing an astonishingly competent infant capable of rapid and complex learning and consciousness is beginning to be seen as a possible research question in infants. Before delving into the limited number of studies that directly address this question, and for readers less familiar with developmental issues, we offer a succinct overview of the cognitive and learning capacities of human infants and their cerebral basis. This lays the foundations for a more systematic approach to the study of consciousness from the earliest age.

Evidence of early learning in human infants

At birth, neonates are able to recognize their mother’s voice (DeCasper & Fifer, 1980), their native language (Mehler et al., 1988), a plausible biological movement (Simion et al., 2008). They imitate adult facial and manual movements

(Meltzoff & Moore, 1977), discriminate numbers (Izard et al., 2009) and geometrical shapes (Turati et al., 2003), and so forth. When placed on a crawler that compensates for their motor immaturity, they may even move towards a speaker playing their native language (Hym et al., 2023).

In addition to their remarkable ability to learn familiar features of the environment, as demonstrated by their preference for the mother’s voice and language, newborns exhibit an impressive capacity to learn even within the limitations of a time-limited experimental setting. For instance, full-term neonates are able to segment a speech stream based on the transition probabilities between syllables (Flo et al., 2019, 2022). They also detect an unusual repetition within an alternation pattern (Panzani et al., 2023), or a second-order regularity pattern (Moser et al., 2020, 2021). During the following months, infants continue to build on their success and long before the end of the first year of life, they have developed social skills (Hamlin et al., 2007), can interpret actions in relation to an actor’s goals (Southgate et al., 2014), represent hidden objects (Luo et al., 2003), perform syntactic computations (Marquis & Shi, 2012) and logical operations (Cesana-Arlotti et al., 2018; Ekramnia et al., 2021), have converged to the phonetics of their native language (Jusczyk, 2000) and learned a few words (Swingley, 2010), among many other acquisitions.

Is infant learning initially solely implicit and bottom-up?

This early learning is believed to be driven primarily by statistical processes (Clerkin & Smith, 2022; Isbilen & Christiansen, 2022; Maye et al., 2002; Saffran & Kirkham, 2018) modulated by species-specific biases (Dehaene-Lambertz et al., 2008; Spelke, 2022) and critical periods (Pena et al., 2012; Werker & Hensch, 2015). The acquisition of native language phonology is a notable example. The convergence toward the phonetic repertoire and phonotactic rules of the native language during the first year of life are classical examples of such learning (Maye et al., 2002). The gender and race effect in face perception are other examples: Infants are much better to discriminate faces corresponding to the features of those frequently encountered (Sangrigoli & De Schonen, 2004). But while statistical learning is indeed powerful, it may not fully account for human infant learning, even in the case of phonology: For English-speaking infants to retain the ability to discriminate a Mandarin Chinese contrast, it is not enough to expose them to the speech of a Mandarin speaker; there must be real conversational exchanges between the adult and the infant (Kuhl et al., 2003). Humans also benefit from the other's knowledge and from being explicitly directed toward the object/concept to learn. Explicit learning thus implies that the teacher and pupil are sharing a common communication space and shared attention toward the same object, in other words that the pupil has a perceptual awareness of the object (figure 1). Therefore, determining at what age infants become able to use such explicit teaching might provide indirect evidence of perceptual awareness.

From the earliest months, infants appear actively engaged in learning, seeking and using information rather than passively receiving it. For instance, infants rapidly learn to use communication cues and speech (Marno et al., 2015) to guide their attention to relevant aspects of an object or event. Three-month-olds infer that pictures accompanied by a sentence such as "Look at the toma" belong to the same category (i.e. dinosaurs) and are distinct from another category such as fishes (Ferry et al., 2013). They are sensitive to the fact that the utterance accompanying the images is a system of communication between people (Ferguson & Waxman, 2016). Indeed, they don't spontaneously care about a sequence of tones accompanying the images unless they have been exposed to a 2-minute video of adults communicating vividly

using these tones. While infants can form categories without the aid of speech/communication labels (Mareschal & Quinn, 2001; Quinn et al., 1993), a common label facilitates the categorization process by explicitly pointing to it (Kabdebon & Dehaene-Lambertz, 2019; Perszyk & Waxman, 2018). At a later age (9 months), they use the number of speech labels to deduce the number of objects hidden behind a screen (Xu, 2002), pointing and communicative cues vs grasping at 12 months to deduce the link between a word and a reference (Pomiechowska & Csibra, 2022), etc.. To use such cues effectively, infants are likely to maintain a stable and explicit representation of the task at hand: They must direct their attention to the signaled object and appropriately and accurately integrate the accompanying word.



Figure 1: *Explicit teaching requires both adult and child to be aware of the same object. This shared attention enables the mother to amplify the infant's perceptual awareness of the object and, eventually, to provide the infant with a symbol (a word) to represent the object. But at what age can infants have sufficient perceptual awareness to benefit from such teaching?*

A neural benchmark of perceptual awareness

Although infants may appear to be aware of their environment and control their attention to gain knowledge about it, they cannot report their perception. Therefore, researchers as caregivers rely on indirect clues to hypothesize conscious perception during the first year. To resolve this issue, one approach is to use neural signatures associated with perceptual awareness in adults

and study when they become observable in infants.

When stimuli are presented at perceptual threshold to adults, considerable differences are observed between trials in which the same stimulus is reported to have been perceived or not (Dehaene & Naccache, 2001; Del Cul et al., 2007; Sadaghiani et al., 2009). Initial perceptual processing is independent of the adult's report, indicating an early process of evidence accumulation in parallel and modular pathways whereas conscious access is marked by a radical change in neural activity (Mashour et al., 2020; Sergent et al., 2021; van Vugt et al., 2018). Notably, a wide network of fronto-parietal areas is activated for stimuli exceeding threshold, described as an ignition of a global neuronal workspace (figure 2A). The recurrent activation of long-distance connections enables the maintenance of perception and focused attention through top-down amplification of sensory input. Additionally, it allows for the broadcasting of information both internally to other cortical areas and for external reporting. This stable representation can be explicitly maintained and manipulated offering the possibility to combine it with past memories and values as also to drive future actions and learning (Dehaene et al., 1998). Thus, a radical difference between two types of trials can be captured by brain imaging, both in terms of the signal dynamics accessible by EEG (early responses being dependent on the stimulus features contrasting with late responses correlated with subjective perception) and the regions involved accessible by MRI. The clearly distinguishable neural pattern observed in these experiments between conscious and unconscious perception can be used as a benchmark: i.e. the observation of similar temporal and spatial patterns in young infants would provide positive evidence for conscious perception.

Is the infant brain sufficiently mature to support conscious computations?

Thanks to advances in brain imaging, it is now possible to obtain MRI and EEG-MEG data in infants, even premature neonates and fetuses, to study when the infant's brain would be mature enough to support such high-level computations. The human brain matures over two decades, at different speeds in different regions (figure 2B). During the last trimester of gestation, neurons

finish migrating to their final location but a stream of migrating inhibitory interneurons is still visible heading for frontal areas during the first six months post-term birth (Paredes et al., 2016). Neuron maturation, dendritic tree expansion, synaptogenesis and pruning, axon myelination continue throughout childhood, notably in frontal and parietal high-level areas. However, immature does not mean non-functional and all brain imaging studies highlight a complex organization of the human brain, much earlier than previously thought, suggesting a continuity of cognitive operations across the ages.

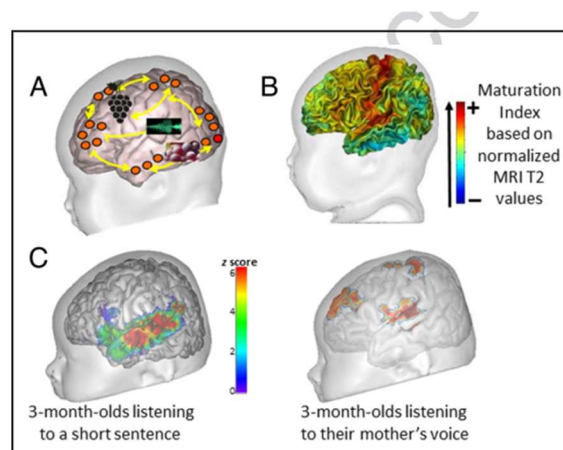


Figure 2. (A) Model of perceptual awareness based on the ignition of a global workspace (B) Maturation index and (C) activations in response to speech in 3-month-olds (after Leroy et al., 2011; Dehaene-Lambertz et al., 2006, 2010). Frontal areas are immature. Nevertheless, fMRI activations are observed with specificities relative to the task suggesting that the cerebral architecture observed in adults is in place and functioning early.

Contradicting the conventional view of an initially poorly structured human brain, fMRI studies of resting state have highlighted the early parcellation of the cortical organization, similar to what is described at older ages (Fransson et al., 2007; Doria et al., 2010; Smyser et al., 2010; Sylvester et al., 2023), with precursors observed in fetuses from 20 weeks of gestation (wGA) onwards (Turk et al., 2019). Specialized networks for language (Dehaene-Lambertz et al., 2010), voice (Blasi et al., 2011) and face (Adibpour et al., 2017; Deen et al., 2017; Kosakowski et al., 2022) perception are present, with functional asymmetries similar to those described in adults: At six months of gestation (29 wGA), the perception and discrimination of syllables already involve a set of superior temporal and inferior frontal regions that share many features with the linguistic network described later on (Dehaene-Lambertz et al., 2002; Mahmoudzadeh et al., 2013). This is all the more remarkable as neuronal migration is far from being complete at this age

(see Kostović et al., 2021 for a review of events occurring during the last trimester of gestation and correspondence with MRI images).

The adult's organization of the ventral visual areas, where specific areas respond to different image categories such as faces, bodies, and places is observed in 2-9 month-olds (Kosakowski et al., 2022). This functional organization of the ventral areas is accompanied by a specific pattern of functional connectivity with distant regions (Barttfeld et al., 2018; Kamps et al., 2020; Li et al., 2020). Moreover, the brain processes various features of a stimulus, such as the speaker's voice and the linguistic value of a syllable (Bristow et al., 2008; Dehaene-Lambertz et al., 2010; Mahmoudzadeh et al., 2016), or the number and identity of objects (Gennari et al., 2023; Hyde et al., 2010; Izard et al., 2008), in different brain regions in parallel. All these results reveal that brain circuits are functionally specified early on, and that the massively parallel implicit processing of the environment observed in adults already operates from the earliest ages.

More importantly for our question, the second notable result revealed by brain imaging is that prefrontal regions involved in high-level cognition are already active in infancy. Frontal areas, which were previously assumed to be too immature to be functional at this age, are repeatedly observed in fMRI studies (figure 2C). The use of large cohorts of participants, advances in data acquisition and improved data processing algorithms have confirmed the presence of long-range anteroposterior functional correlations underlying the frontoparietal, dorsal attention and default mode networks since the neonatal period (Sylvester et al., 2023). Stimulation studies have also reported robust prefrontal activations (Dehaene-Lambertz et al., 2002, 2006, 2010; Ellis et al., 2021; Mahmoudzadeh et al., 2013), with distinct areas being recruited depending on the task at hand. For example, verbal working memory tasks activates the inferior frontal regions (Dehaene-Lambertz et al., 2002), whereas the longer-term memory of the prosodic contours of the native language engages the dorso-lateral prefrontal cortex and inferior parietal region, corresponding to the phonological store in adults (Dehaene-Lambertz et al., 2006). Distinct responses to familiar and unfamiliar stimuli, such as the mother's voice and an unknown female's voice, are observed in the median prefrontal and orbitofrontal areas (Dehaene-Lambertz et al.,

2010), mirroring activations seen in adults (Roy et al., 2012).

These findings suggest that information travels through the entire bottom-up functional hierarchy and reaches high-level integrative regions early in brain development (i.e. already during the last trimester of gestation). Since these regions are crucial for directing attention and selecting stimuli according to the subject's goals through their particularly dense top-down connectivity, we may wonder whether they might have comparable functions in infants and potentially contribute to the conscious selection of external stimuli.

Is there any evidence supporting the ignition of a global workspace in infants?

Most behavioral experiments in infants rely on a surprise reaction after a change, or on a preferential response to one of two stimuli measured by reaching or gaze orientation towards one of the presented stimuli. However, such responses could arise automatically by solely relying on a bottom-up accumulation of evidence or a habituation/dishabituation response. Are infants limited to such shallow bottom-up processing, or do they also exhibit longer-scale, sustained mental states capable of exerting a top-down influence on subsequent stimuli? To this day, very few paradigms have convincingly studied to what extent infants' behavior and brain responses correspond to an internal drive, such as expectation, awareness or curiosity, and mainly during the second semester post-term birth.

One of these paradigms is based on attentional blink, which tests the competition between successive stimuli to enter the global workspace. Five- and eight-month-olds seem not to see a second stimulus when it follows too closely a first one (Hochmann & Kouider, 2022; Tsurumi et al., 2021). Interestingly, the attentional blink duration is particularly long at 5 months (i.e. 1200 ms), accelerates slowly at 8 months (800 ms), reaching 200 ms in 3-year-olds and adults tested with the same paradigm (Hochmann & Kouider, 2022). We observed similar results using EEG in 4-month-olds, the SOA between the two stimuli had to be longer than 800 ms to generate attentional movement towards a second lateralized stimulus (i.e. a face) after a first attractive central stimulus, a teddy bear (Leroy et al., in preparation). Furthermore, we observed that even at visible SOA (1200 ms), the engagement on the first

central stimulus conditioned the attentional orientation to the second one. In other words, if infants were deeply engaged in processing the teddy bear picture as revealed by an evoked N290 component, they did not perceive the following lateralized female face in contrast to trials in which they were minimally engaged (no N290 evoked by the central teddy bear). The N290 amplitude is known to be modulated by attention to faces in infants (Guy et al., 2016). Awareness of the lateralized face was assessed by a correct saccade to the face in trials with overt orientation, but also in trials without saccade (covert orientation) by the modulation of the EEG power at the frequency of the flickering background on which the lateralized face was presented. This study clearly reveals a bottleneck in the serial processing of the two successive images to elicit an attentional movement in 4-month-old infants.

Another usable paradigm is to present masked visual stimuli of different durations to separate responses above and under perceptual threshold. Faces or scrambled faces were thus presented to 5, 12 and 15 mo-olds in a behavioral experiment (Gelskov & Kouider, 2010) then using EEG (Kouider et al., 2013). The early visual responses for faces (e.g. the visual P400) were linearly modulated by the duration of the image presentation, whereas a late component (after 750 ms) exhibited an all-or-none ignition response in correspondence with the behaviorally determined age-matched visual threshold (Gelskov & Kouider, 2010). Thus, ERPs revealed the same stages and neural signature of perceptual awareness as in adults despite a longer

presentation threshold (100 ms in 5 mo-olds and 50 ms in older infants) and a delayed sustained response, the latency of which accelerates with age (figure 3).

The late component is part of a family of late responses (around one second) described in young infants that have been associated with directing attention to a new event, memory, familiarity, etc.. (Csibra et al., 2008; Dehaene-Lambertz & Dehaene, 1994; Richards, 2001, 2003) These slow responses are considered equivalent to the P300/P600 in adults (Csibra et al., 2008) , without it being possible to prove directly that they really correspond to an active and sustained process capable of redirecting subsequent attention, or only to a late bottom-up access to frontal areas. However, the modulation of the late component by the conditions of the masking and attentional blink paradigms follows the same pattern as in adults, the only difference residing in its latency. The slow access to the global workspace in the masking experiment explains the long duration of the attentional blink, in both cases around the second. This slowness reflects the protracted maturation of the parietal-frontal associative regions (Lebenberg et al., 2019), notably the frontal regions in term of neuronal migration (Paredes et al., 2016), neuronal maturation (Faux et al., 2012; Gascoigne et al., 2021), synaptogenesis and pruning (Huttenlocher & Dabholkar, 1997) and connectivity (Dubois et al., 2006). The protracted maturation of high-level areas contrasts with the faster maturation of the

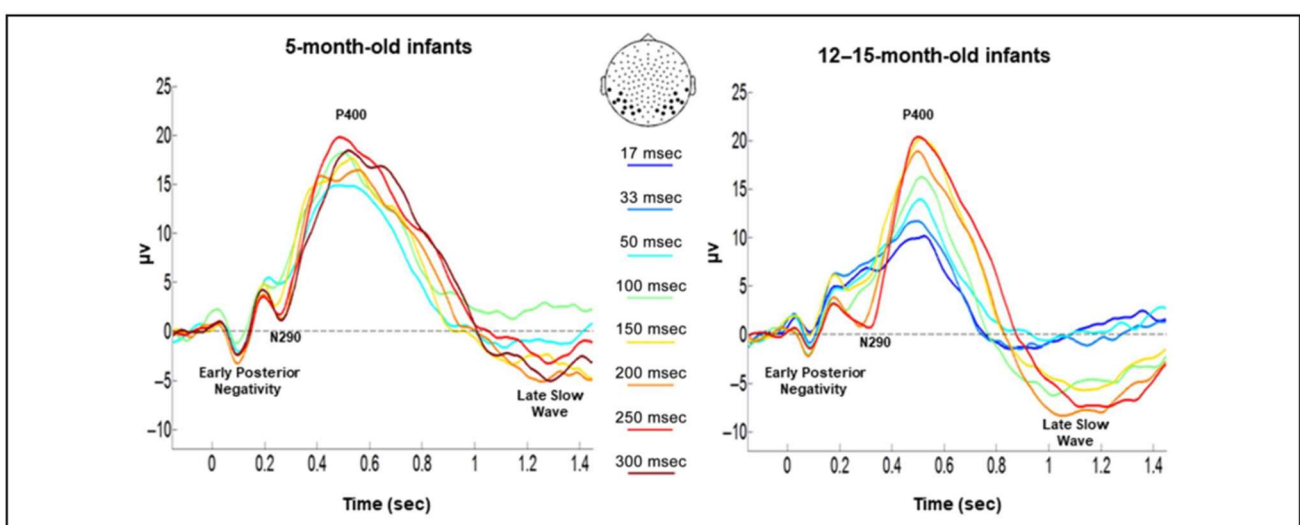


Figure 3: Grand-average ERP to faces above and below the visible threshold (100 ms at 5-months, 50 ms after one year) in 5 and 12-15 month-old infants (after Kouider et al, 2013). The amplitude and duration of the P400 are in line with the face presentation duration whereas the late slow wave has an all-or-none response consistent with the age-matched visual threshold suggesting conscious access. Note the long latency, around the second, of this late response.

primary cortices. For example, the visual P1 reaches adult latency at 12 weeks whereas the P300 latency is still around 500-600 ms at 4 years of age contrasting with 300-350 ms in adults in the same paradigm (Polich et al., 1990).

Another slow response, which may also indicate an explicit expectation of an event, is the contingent negative variation (CNV) that slowly builds up over central electrodes when infants are waiting for a second stimulus in a pair (Mento et al., 2022; Mento & Valenza, 2016). This response is also observed when trials in which infants are expecting a specific stimulus vs an unknown stimulus are compared (Kabdebon & Dehaene-Lambertz, 2019). This CNV has been reported from 4-months of age (Mento et al., 2022) and would need to be studied at an earlier age.

Is there any evidence supporting top-down amplification following perceptual awareness?

If the results presented above are compatible with a slow ignition of a global workspace, is there any evidence in favor of the second characteristic linked to perceptual awareness in adults: the top-down amplification of sensory input? The first study showing an indisputable top-down effect in infants is a near infra-red spectroscopy (NIRS) experiment performed by Emberson et al. in 6-month-olds (Emberson et al., 2015; Jaffe-Dax et al., 2020). A sound announced the appearance of a smiley face 750 ms later. In the few trials where the smiley was not presented, the infants still showed occipital activations, which could therefore only be induced in a top-down manner. In a second study, the authors confirmed the occipital activation to the missing stimulus and recorded activity under frontal sensors, suggesting that frontal regions may be responsible for this visual expectation. A more direct test of attentional control was performed by Ellis et al. (2021) in 3 to 12 mo-olds using MRI and a visual spatial cueing task in which the cue was invalid or neutral in 25% of trials to predict the location of an interesting target. More activation to invalid than valid trials was observed in the anterior cingulate cortex (ACC) and in anterior portions of the frontoparietal network. Once again structurally immature areas are shown functional and thus might be expected to support the same type of computations than at later ages. However, the age range was large, the sample of participants was small and the main reported difference concerned invalid vs valid trials in which the saccadic movement had to be replanned in a

short time frame. In a previous EEG study, frontal sources were reported for planned saccades (valid trials) whereas invalid trials generated subcortical reflexive responses (Richards, 2001). It is thus difficult to assert whether the frontal and anterior cingulate cortex (ACC) activations were really related to an attentional movement rather than to a bottom-up visual surprise when there was an unexpected change in location.

EEG studies investigated whether anticipation might correspond to a specific item rather than a general readiness to receive a second stimulus and looked at a modulation of the ERPs in correct vs incorrect pairs of stimuli after infants have learned that an auditory event predicted a specific image. A two-stage pattern was again recorded comprising a priming effect for the expected stimulus on the early visual components, followed by a late slow wave around the second. This pattern was observed by Kabdebon et Dehaene-Lambertz (2019) in 5-mo-olds and Kouider et al (2015) in 12-mo-olds. Congruent and incongruent pairs were compared with a third condition (a non-predictive cue in Kabdebon et al and an absence of cue in Kouider et al) to assess the effect of the infant's explicit expectations on the identity of the second item in the pair. These ERP results are coherent with the NIRS results presented above (Emberson et al., 2015; Jaffe-Dax et al., 2020) favoring a top-down sensory amplification when a stimulus is explicitly expected. This interpretation is all the more likely as the SOA between the two elements of the pair was long (1.720 s) in Kabdebon et Dehaene-Lambertz (2019) allowing to observe a CNV preceding the image when infants knew which one they had to predict. However, it remains possible that low-level associations might underlie such priming and late surprise responses.

The difficulty of drawing firm conclusions is a recurring problem in infant studies, as it is difficult to have all the conditions in the same experiment due to the short attention span of infants, and studies of conscious perception have not been systematic enough to successively address the points useful for a demonstration. However, we have described a set of results consistent with the hypothesis of the ignition of a global workspace associated with top-down amplification in infants suggesting perceptual awareness from the second semester post-term onward. Is it possible to obtain evidence at an earlier age?

Perceptual awareness before 5 months of age

The even shorter attention span of infants at an earlier age, combined with the immaturity of the peripheral visual system, leaves little opportunity for testing perceptual awareness in the first trimester after term, let alone in the pre-term period. This explains the small number of studies exploring this question at this age. Regarding resting state studies, Sylvester et al (2023) observed a weaker anterior-posterior connectivity in neonates than at later ages. However, neonates were asleep during the scans whereas older participants were awake. Regarding fMRI activation studies, they reveal a modulation of frontal activation depending on vigilance state and stimulus repetition suggesting that these activations are not simply the result of the propagation of a bottom-up flow of activity but might reflect focused attention. Listening to sentences in the native language vs their backward-played version activated the right dorso-lateral frontal gyrus in awake but not sleeping 2-3 month-olds, contrasting with persistent activity in the superior temporal regions in sleeping infants (Dehaene-Lambertz et al., 2002). Activity in the left inferior frontal gyrus was increased by repetition of a sentence (Dehaene-Lambertz et al., 2006) or of a cross-modal vowel (Bristow et al., 2008) contrasting with the decrease of activity seen in auditory areas (Bristow et al., 2008; Dehaene-Lambertz et al., 2010). This specific pattern of increased activity in frontal areas suggests an intended and conscious effort to maintain a complex stimulus in working memory.

A more direct paradigm proposed to test consciousness in adults is based on the presentation of auditory sequences with first and second-order regularities (Bekinschtein et al., 2009). In this paradigm, sequences of five sounds (consisting of repeated sounds such as XXXXX, or four repeated and one different: XXXXY depending on the block) are presented. These sequences are themselves repeated with rare deviant sequences. Thus, deviance can be studied at the local level (is the latest sound of the sequence different from the previous ones?) and at the global level (is the current sequence of five sounds similar, or not, to the general pattern of sequences in the block? e.g. XXXXX in the middle of XXXXY sequences is a deviant sequence). Whereas the amplitude of the early and automatic mismatch response is dependent on the transition probabilities

between the two sounds in the block (Basirat et al., 2014; King et al., 2013), the violation of the second-order regularity elicits a late P300 response, but only in attentive adults. It was not observed in sleeping adults (Strauss et al., 2015) and comatose patients (Bekinschtein et al., 2009; Engemann et al., 2018) suggesting that this paradigm can be used as a tool to test the level of consciousness in unresponsive populations (Bekinschtein et al., 2009).

The same two levels of responses, manifested as an early mismatch response (270-370 ms) sensitive to the statistical transitions between syllables within blocks and a late slow wave (900-1200 ms) only observed for sequences deviating from the pattern in the block, have been reported in awake, attentive three-month-old infants, using an adapted but similar EEG paradigm. The cerebral sources of the two deviant responses were consistent, with superior temporal sources supporting local deviance detection and inferior frontal sources underlying global deviance detection (Basirat et al., 2014). This clear two-stage pattern result is in line with the pattern of responses observed in the studies described above in older infants, notably involving a global workspace with top-down amplification as expected from adults' reports.

Using MEG in sleeping neonates, Moser et al (2020) also observed responses in two successive time-windows: an early mismatch response for local deviant (200-400 ms) and a late response around 700 ms sensitive to the global deviance, but only during periods of high heart rate variability. It may seem paradoxical to obtain such results in sleeping neonates but not sleeping adults (Strauss et al., 2015). However, awakening and sleep are progressively organized during childhood, with sleep comprising only two clear stages at birth: quiet sleep and active sleep plus indeterminate periods, frequent transitions between sleep stages and numerous awakenings. It is therefore possible that the period of high heart rate variability mixes periods of active sleep and wakefulness, which might enable infants to compute second order regularities at least for some trials and continue learning during the following rapid eye-movement (REM) sleep period. Such a possibility has been described in adults (Andrillon et al., 2017). On the other hand, statistical learning is also more efficient in sleeping neonates than in sleeping adults (Flo et al., 2022). It is therefore possible for second-order

regularities to be calculated using long-range associations integrated over periods of several seconds (Benjamin et al., in press), without being conscious of this regularity.

Remarkably, the same paradigm was tested in fetuses using fetal MEG (Moser et al., 2021). The authors only recorded a mismatch response to local deviants in fetuses under 35 weeks of gestation with no response to global deviance. By contrast over 35 weeks of gestation, there was a response at 350-650 ms to global deviants but no mismatch response to local deviants. This response was only observed during periods of high heart rate variability. The latter findings are reminiscent of those obtained in fMRI in propofol-anesthetized macaques in whom also no response to local deviants was observed in contrast to global deviants (Uhrig et al., 2014). These paradoxical results were interpreted by the authors as a fusion of the five sounds in a single event due to temporal sluggishness leaving only two events (XXXXX and XXXXY). Thus, the recorded response would correspond to a mismatch response to a new event and not to second-order learning. This interpretation would be compatible with the relatively “early latency” of the global deviant response in fetuses relative to full-term neonates. Remember that at this premature age, although the general plan and specific circuits similar to those described at later ages are already observed, many peculiarities are present, the effects of which on cognition are little known. For example, a double circuitry involving the first born neurons in the sub-plate is present during late gestation to compensate for the weak excitation of pyramidal neurons and their reduced connectivity (Kostović, 2020). GABA_A acts as an excitatory transmitter in the immature brain before switching to its common inhibitory role around birth (Ben-Ari, 1997). Moreover, fetuses are maintained in a state of sleep compared to preterm neonates of the same term-age by the many sedative substances secreted by the maternal placenta and the fetus itself (Deidda et al., 2014; Gascoigne et al., 2021; Lagercrantz & Changeux, 2009a). The similarity between the responses of human fetuses and those of monkeys anesthetized with propofol, a GABA_A agonist that causes a functional disconnection between frontal and parietal components of the global workspace, may be a fruitful direction to pursue in understanding the fetal state.

Given the diversity of results obtained with the same “local-global” paradigm depending on age (3 months, neonates and fetuses at different gestational ages), it is difficult to get a clear picture of the development of consciousness during the weeks surrounding the term without further studies. We need to compare different paradigms and investigate how brain maturation (i.e. term age) but also the *in-utero* vs *ex-utero* environment (preterm neonates vs fetuses) affects the cortical responses. Clear markers of awakening, notably at the single-trial level, should also be developed to track vigilance which might be less continuous but nevertheless present in neonates. We can nevertheless speculate on the importance of two events for consciousness to emerge: 1) the maturation of cortico-cortical connectivity and thalamo-cortical connectivity, resulting in the progressive disappearance of the *tracé alternant* in EEG around 32-35 wGA (more efficient connectivity would provide a greater possibility of ignition and reverberation of activity) and 2) birth, which exposes the neonate to a variety of stimulating events combined with the loss of the *in-utero* sedative environment plus a change in the inhibitory-excitation balance due to the GABA_A switch (Lagercrantz & Changeux, 2009). We lack too much information on brain development at the end of the human gestational period, and studies on rodents are certainly instructive, but this period differs too much between rodents and primates to allow easy equivalences.

Conclusion

We have considered here a specific aspect of consciousness, which is the possibility for the infant to explicitly represent an element of his environment to learn about it and build expectation on what should follow. Although it is quite evident for parents that their infant is conscious, the experimental evidence is scarce due to the difficulties to test infants. Functional studies combined with what we know on brain maturation of the fronto-parietal connectivity suggest that, from term birth, infants might be aware of their environment, but only for relatively short periods of awakening during the first weeks. The pre-term period remains an open question and needs to be studied in greater depth in terms of brain maturation and functional activity both in preterm neonates and fetuses. Thanks to advances in brain imaging and experimental paradigms, this question becomes accessible. Emergence of consciousness is not just a scientific

quest, as this issue has important implications for infant care, particularly in balancing pain perception and side effects of anesthetics on brain maturation (Mellor et al., 2005), but also for learning and providing the infant with a suitable, stimulating environment.

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