The origins of time: a systematic review of the neural signatures of temporal prediction in infancy

Isabelle Rambosson[1,2], Damien Benis[1,2], Claire Kabdebon[3], Manuela Filippa[1,2,4*], Didier Grandjean[1,2*]

[1]Neuroscience of Emotion and Affective Dynamics Lab, Department of Psychology, University of Geneva, Geneva, Switzerland
[2]Swiss Center for Affective Sciences, University of Geneva, Geneva, Switzerland
[3]CRPN, UMR 7077, CNRS, Aix Marseille Université, France
[4]Division of Development and Growth, Child and Adolescent Department, University of Geneva, Geneva, Switzerland

Full postal address of each affiliation:
[1]Neuroscience of Emotion and Affective Dynamics Lab, Department of Psychology, University of Geneva, Geneva, Switzerland
[2]Swiss Center for Affective Sciences, University of Geneva, Geneva, Switzerland
University of Geneva
Rue du Général-Dufour, 24
CH - 1211 Geneva 4

[3]CRPN, UMR 7077, CNRS, Aix Marseille Université, France
Faculté des Sciences
3, Place Victor Hugo
13003 Marseille France

[4]Division of Development and Growth, Child and Adolescent Department, University of Geneva, Geneva, Switzerland
University of Geneva
Rue du Général-Dufour, 24
CH - 1211 Geneva 4

Email:
isabelle.rambosson@unige.ch
damien.benis@unige.ch
claire.kabdebon@univ-amu.fr
manuela.filippa@unige.ch
didier.grandjean@unige.ch

Correspondence:
Isabelle Rambosson
Neuroscience of Emotion and Affective Dynamics Lab, Department of Psychology, University of Geneva, Geneva, Switzerland
Swiss Center for Affective Sciences, University of Geneva, Geneva, Switzerland
University of Geneva
Rue du Général-Dufour, 24
CH - 1211 Geneva 4
Email: isabelle.rambosson@unige.ch

[*]The last two co-authors contributed equally to the manuscript.

Abstract

From birth, individuals' interpersonal dimension is underpinned by progressive learning of social interaction rules, their variations rooted in the temporal prediction of sensory events, and the inferences made about the organization of the social world. How this dimension is structured during infancy and articulated at the neural level is a critical question for cognitive and affective neurosciences. This systematic review aims to define the neural signatures of temporal prediction in newborns and infants and to discuss them in the context of the development of proximal cognitive and affective neural functions. Eight peer-reviewed studies were included, with 228 infants from birth to 9 months of age. Studies have evidenced that neural signatures of temporal prediction in infants present a broad cerebral localization, including the anterior and medial parts of the brain, especially in the frontal and central areas. Temporal prediction mechanisms emerge well before birth and evolve from early sensory-driven responses to complex top-down processing within the first year, shaped by both innate and experience-dependent factors, with influences like wakefulness and musical exposure that modulate neural integration across sensory and higher-order brain regions.

Keywords: newborns, infants, brain mechanisms, temporal prediction.

I. Introduction

In the first months of life, young infants undergo a period of intense brain maturation, during which they construct basic knowledge about the events and objects that dynamically change in their environment and about the effects of their actions on the world. This learning process, far from being guided only by bottom-up acquisitions, is based on a predictive processing framework (Emberson, 2017), which uses prediction at different levels as a strong apparatus to explain human brain functioning (Berger & Posner, 2023; Köster et al., 2020). In the predictive coding theory (Friston, 2005; Rao & Ballard, 1999), which is a unifying brain development neuro-computational conceptualization, based on Bayesian inference (Perfors et al., 2011), the organism builds probabilistic models, by acquiring statistical regularities from the environment (Clark, 2013) and constructing internal generative models of the world (Friston, 2010, 2012; Wolpert et al., 1995).

Especially in the early phases of development, the brain must improve inferences based on sensory inputs - by top-down or feedback neural signals - and minimize prediction errors - through bottom-up processes (Baek et al., 2020). Based on this prediction error related to imprecise or wrong predictions, the model from which predictions were generated is updated (Berger & Posner, 2023).

The above-mentioned mechanisms, linking past and future inputs, enable our cognitive and affective processes to engage with, react to, and adapt to a constantly changing environment (Baek et al., 2020; Berger & Posner, 2023).

1.1 Infants, like adults, have a predictive brain

There is ample evidence that the adult brain is highly predictive and follows the principles of the predictive coding theory (see Alexander & Brown, 2019; Berger & Posner, 2023 for a review; Carlsson et al., 2000; Kastner et al., 1999; Zhang et al., 2019). In adults, predictive coding, especially in the auditory domain, is supported by two main mechanisms (i.e., prediction error and repetition suppression; see Carbajal & Malmierca, 2018 for a review). Deviance detection, which is an automatic response to a divergence in a stimulation previously processed, allows in the predictive coding framework, the updating of the prior representational model and favors the integration of this novel information within the previously established framework (Winkler & Schröger, 2015). In the auditory domain, this mechanism is commonly studied using the auditory oddball paradigm, which consists of introducing a new sound after a series of repeated sounds. Such a sudden shift typically elicits an event-related potential (ERP) called the mismatch response (MMR) or mismatch negativity, characterized by a frontal positivity synchronized with a posterior negativity occurring 200-400 ms after the deviant stimulus (Basirat et al., 2014; Friederici et al., 2002). Subsequently, this early response is frequently followed 700 ms later by a late frontal Negative Slow Wave (Basirat et al., 2014; Dehaene-Lambertz & Dehaene, 1994). This ERP response has been hypothesized to originate from neuronal populations over a network comprised of the auditory midbrain and thalamus, displaying stimulus-specific adaptation (SSA, i.e., a modulation of firing rate in response to a deviant stimulus compared to a series of similar stimuli); triggering in this population a reduction over-time of the firing response (Carbajal & Malmierca, 2018). In adults, theta band activity has been shown to consistently decrease along the learning of a repeated sequence in line with SMA predictions (Crivelli-Decker et al., 2018). A theta synchrony increase has also been observed in a prefrontal subthalamic network in response to error monitoring and expectancy violation (Zavala et al.,

2018), and theta-gamma coupling has been linked to predictive-coding in a syllable representation paradigm (Hovsepyan et al., 2020) in adults.
Temporal prediction relies on temporal processing and timing prediction in adults. Research has shown that the cortex, the basal ganglia, and the cerebellum are all linked to temporal processing and timing operations (Harrington et al., 1998; Hinton et al., 1996; Hinton & Meck, 2004; Lejeune et al., 1997; Meck et al., 1998; Rao et al., 2001). More specifically, the basal ganglia and the cerebellum, as main neural bases of temporal processing, play a central role in timing tasks (e.g., interval production or timing tasks) and related (sensory) prediction errors conveyed by dopamine activity (Dreher & Grafman, 2002; Gardner et al., 2018; Ivry & Keele, 1989; Rao et al., 2014; Rao et al., 1997; Spencer et al., 2003). Indeed, the cerebellum is involved in the absolute (duration-based) timing of single sub second intervals or when the interval between two stimuli is known (Breska & Ivry, 2018; Grube, Cooper, et al., 2010; Grube, Lee, et al., 2010), whereas the basal ganglia are implicated in rhythmic events, rhythm discrimination, and beat prediction (Breska & Ivry, 2018; Grahn & Brett, 2009; Grahn & Rowe, 2013). Of course, other cortical regions are also involved in these processes including among others, the insula, the pre-supplementary motor area (SMA), and the SMA (e.g. Adams et al., 2013; Craig, 2009; Limongi et al., 2016; Limongi et al., 2013; Preuschoff et al., 2008) for emotion, and action predictions respectively. It should also be mentioned that the connectivity of these brain regions is modulated by mechanisms related to prediction, error prediction monitoring, and related updates of the internal models (Bastin et al., 2016; Iannaccone et al., 2015; Limongi et al., 2013).

Recent research suggests that a predictive-processing framework may also provide a unifying perspective for understanding young infants' cognitive processes (see Köster et al., 2020 for a review), covering an array of fundamental learning knowledge of their own social and physical environment, dynamically coordinating in time. Indeed, neural mechanisms involved in expectancy violation are already present in newborns (Alho et al., 1990; Bisiacchi et al., 2009; Cheour-Luhtanen et al., 1995; Cheour et al., 1998; Mahmoudzadeh et al., 2017; Mento et al., 2010), as demonstrated by the elicitation of mismatch negativity (MMN) through oddball paradigms, both in newborns (Cheour et al., 2002; Winkler et al., 2003) and during the fetal period (Draganova et al., 2005; Draganova et al., 2007). Findings by Köster et al. (2019, 2021) have shown that unexpected (in contrast to expected) events were linked to theta brain activity in 9-month-old infants, as a key element in the processing of prediction errors, over an extended time window (2 sec) and all the electrodes recorder on the scalp (based on 30 electrodes; Köster et al., 2021). Findings of theta modulation in infants, as well as accurate interval timing and beat processing within one week of birth in premature (32 weeks gestational age or wGA) and full-term babies (39 wGA) (Edalati et al., 2023; Háden et al., 2024) therefore suggest that adult-like processes are already in place early in human development.
In sum, decades of research show that newborns have neural mechanisms involved in temporal expectancy violations, with the auditory oddball paradigm used as an effective tool for studying these processes. Recent research has highlighted the importance of theta brain activity in processing prediction errors, emphasizing the complexity and persistence of infants' responses to unexpected events.

During development, infants systematically use statistical learning abilities, for example, to learn about auditory (i.e., linguistics; Saffran, 2020), visual, and proprioceptive inputs (Trainor, 2012). Infants can predict, using, e.g. EEG signals as measures, implying that predictions are inferred from implicit measures, not only the presentation of sequences of stimuli but also the consequences of their actions in the environment (i.e. behavioral

inferences). From the age of 2 months, infants consolidate an understanding of the causal link between one of their actions (a foot movement) and the movement of an object linked to it. At 9 months of age, the infant's brain can, therefore, predict the recurrence of this causal link (Kayhan et al., 2019). Moreover, if the prediction is disregarded (e.g., the object is detached from the foot and no longer moves), infants tend to increase their motor actions to reproduce the coupled event, thereby adapting the predictive model accordingly (Kayhan et al., 2019; Wen & Imamizu, 2022). Interestingly, infants predict an action better when they can perform it, reinforcing the link between action production and perception (Keysers & Perrett, 2004).

Predictive abilities have been investigated behaviorally in infancy by tracking anticipatory eye movements, demonstrating that from 3 months of age infants' brain can predict the position of a moving object (Canfield & Haith, 1991; Gredebäck & von Hofsten, 2004; Gredebäck et al., 2002) or the end state of a motor action (Ambrosini et al., 2013; Cannon & Woodward, 2012; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011). Developmental psychologists even capitalized on these precocious anticipatory abilities in associative learning tasks to address more general questions about infants' cognition and learning (Albareda-Castellot et al., 2011; Hochmann et al., 2011; Kovács & Mehler, 2009a, 2009b; McMurray & Aslin, 2004). In these experiments, infants are typically taught an association between the presentation of exemplars of a specific auditory or visual (or abstract) category and the subsequent appearance of a reinforcer on the left or right side of the screen. After a familiarization phase, infants are presented with novel exemplars of the same category, and their ability to correctly anticipate the appearance of the reinforcer on the left or right side of the screen is assessed as a marker for their categorization abilities. More recent work additionally demonstrated that when a situation is uncertain, the brain of 12-month-old infants can spontaneously anticipate the outcome of a scene, demonstrating untrained pro-active anticipatory behavior in young infants (Téglás & Bonatti, 2016).

Over the past decade, some research has attempted to identify neural correlates of predictive processing in infancy using associative learning tasks. In 12-month-old infants, Kouider et al. (2015) showed that the arbitrary audio-visual associations acquisition could modulate visual brain responses, with enhanced EEG responses during early processing stages for expected events and neural activity in the late processing stages for unexpected visual events. Subsequent research using similar associative learning tasks also found correlates of increased neural processing in response to expected events (Kabdebon & Dehaene-Lambertz, 2019) and a late difference between expected and unexpected audio-visual associations in 5- to 6-month-old infants (Kabdebon & Dehaene-Lambertz, 2019; Rohlf et al., 2017). Neural signatures of audio-visual associations have also been investigated in later developmental stages in the context of early word learning using bimodal object-word priming designs. These studies report that consistent object-word priming typically elicits an increase in a frontally distributed N200-500 component and a decrease in the centroparietal N400 component, in 6- to 9-month-old infant ERPs to the word onset (Friedrich & Friederici, 2011; Friedrich et al., 2015, 2017), which could be interpreted as cross-modal/semantic prediction effects. Using functional near-infrared spectroscopy (fNIRS), Emberson et al. (2015) presented 6-month-old infants with a systematic audio-visual association, and they were able to record brain activations over the occipital cortex even when the image was unexpectedly omitted after the auditory cue, similar to the response to the actual image presentation. Notably, this occipital activation was not recorded when the auditory cue did not predict any visual event. These results are suggestive of expectation-based feedback signaling in infancy, although atypical in premature (< 33 wGA) babies (measurements have been realized before infants exhibited clinically identifiable developmental delays at 6 months of corrected age; Emberson, Boldin, et al., 2017), compatible with the predictive coding framework. Finally, a few additional studies from 4 months of age investigated

anticipatory pre-stimulus activity in similar audio-visual associative learning tasks in infants, reporting the build-up of a centrally distributed component during the delay between the predictive auditory cue and the onset of the visual stimulus (Kabdebon & Dehaene-Lambertz, 2019; Mento et al., 2022; Mento & Valenza, 2016) comparable to the Contingent Negative Variation (CNV), a neural signature of expectancy-based cortical activity, observed in adult participants.

1.2 Temporal predictions at the base of human synchrony and social interaction phenomena

The temporal structure of the stimuli in the environment plays a crucial role in the infant's predictive processes, and it constitutes the core element of the present review.

From birth, infants need to extrapolate regularities from the sensory world and coordinate their sensory and motor experience with the physical and human environment (Mento & Granziol, 2020). This coordination process is mainly based on the temporal dimension (Mento & Granziol, 2020). The development of an accurate temporal structure of the inputs/outcomes is critical for the formation of expectations (Mento & Granziol, 2020) during early dyadic and triadic exchanges.

Temporal violations can be extracted and updated from local – when the stimulus expectancy is induced by a narrow transitional probability - or global sequence's regularities - in the presence of non-adjacent, higher-level rules that supersede local transitions. As shown by Basirat et al. (2014), 3-month-old infants are already able to dissociate local and global violations in an auditory paradigm and to process these violations *via* two partially distinct brain systems (i.e. MRR/late frontal negative response for the local deviance condition *vs.* a shorter early mismatch response and a longer late response with cortical sources including the left inferior frontal region in the global deviance condition).

At a behavioral level, temporal predictions have been investigated in infants with interesting results. In one study, where 6- and 12-month-old infants' eye movements were recorded while observing rational and non-rational feeding actions, Gredebäck and Melinder (2010) reported a change in pupil size, signaling surprise, during violations of infants' expectations concerning rationality (i.e., in non-rational feeding actions). In another study, Gredebäck et al. (2018) demonstrated that the ability to predict actions in infants 6 months of age is associated with the inclination to react with surprise when social interactions deviate from what was expected. In the auditory modality, Werner et al. (2009) demonstrated using a fixed presentation rate of tone (i.e., fixed condition) and a mixed condition that infants (aged from 6 to 9 months) better detect a tone when it occurred either before or at an expected time following a cue; showing that infants demonstrate greater sensitivity to sounds that align with their temporal predictions.

At 4 months, in a stimulus omission paradigm where interstimulus length was manipulated, infants showed heart rate decelerative responses significantly related to the omitted rhythmical stimulus in a predictive sequence. Interestingly, authors concluded that not only can young infants estimate time intervals, but that this ability is linked to attentional processes (Colombo & Richman, 2002).

Synchrony, or the temporal coordination of micro-level social behaviors, is based on shared and repetitive-rhythmic sequences (Bernieri et al., 1988; Feldman, 2007b). Interindividual synchrony relies on anticipating each other's actions to coordinate in time

(Morganti et al., 2008; Sebanz & Knoblich, 2009). Mothers and their infants are involved in interpersonal synchronization from a very early age (Condon & Sander, 1974; Jaffe et al., 2001), and during their 3rd month of life, infants start to actively engage in face-to-face interactions, centered on the synchrony of vocalizations, non-verbal cues, gaze, and shared emotion expressions (Stern, 1985; Tronick, 1989). Interaction synchrony is fundamental to infants' cognitive, social, and emotional development (Feldman, 2007a; Jaffe et al., 2001) and relies on anticipatory abilities, which are crucial for the prediction of others' actions and for producing a coordinated response in time (Crown et al., 2002; Jaffe et al., 2001). A good example of these phenomena is the well-known "peek-a-boo" game: in this game, an adult and an infant engage in violating and confirming time expectations, underpinning infants' time prediction abilities (Baek et al., 2020).

1.3 Violations, predictions, expectations, and anticipations

If in newborns, dedicated neural mechanisms involved in expectancy violation are already in place (Mahmoudzadeh et al., 2017), it has been much less investigated whether and how early the ability to use this implicit information can be translated into specific, cortical anticipatory processes for future events. "Violation", "prediction", "expectation", and "anticipation" are four different constructs, with a gradient sophistication through a simple detection, to representation, and execution. Even if these four terms are often used synonymously or interchangeably in scientific articles, without really being defined, the idea of brain mechanisms dedicated to anticipation and prediction has been around for decades, as shown by Piaget's quotations below:

"*Anticipatory function [...] is to be found over and over again, at every level of the cognitive mechanisms and at the very heart of the most elementary habits, even of perception.*"
(Piaget, 1971, p. 191).
"*[...] The function of anticipation is common to cognitive mechanisms at all levels.*"
(Piaget, 1971, p. 193).

In the present review, we focus on the neural development of temporal predictive abilities in infancy. It is important to note that all studies on infant anticipation and prediction imply the temporal dimension; however, we aimed to focus only on studies where the temporal structure (or dynamic unfolding) of the stimuli is manipulated, and thus where the temporal dimension of the stimuli, rather than the stimuli characteristics, varied.

To date, comprehensive reviews addressing the neural correlates of temporal prediction in infants are lacking. The delineation of the defining characteristics and underlying neural substrates of temporal prediction phenomena holds promise for advancing our understanding of the genesis and maturation of core cognitive functions intricately linked to dynamic temporal processes. Consequently, the outcomes of our investigation stand to contribute significantly to (a) the timely identification of deviations in the developmental trajectory of these capacities and (b) the formulation of early intervention strategies grounded in this foundational comprehension.

II. Methods

The search and selection strategies have been conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines (Page et al., 2021).

2.1. Literature search strategy

A web-based search strategy was elaborated to identify articles relative to the neural signatures of temporal prediction in infancy, including infants from birth to 12 months. To conduct a thorough web-based article search, articles were searched in two electronic databases: CINAHL and Web of Science.
The search was conducted using the keywords mentioned below (Box 1). To find the most plausible possibilities regarding the investigated subject, the terms *Infant* and *Brain* remained fixed in all searches.

Box 1. Search terms

Anticipation, auditory anticipation, auditory violation, baby, brain, cortical, infant, neonate, neural, newborn, prediction, predictive coding, rhythmic violation, sensory prediction, and top-down.

2.2. Inclusion and exclusion criteria for the selection of eligible studies

Criteria for inclusion of studies were as follows: (a) published in English, (b) empirical peer-reviewed studies embracing a clear methodological stance, (c) on temporal prediction, (d) 0 to 12-month-old infants, and (e) with brain outcomes.
Multiple findings of the same article were treated as a single study. Books, book chapters, discussions and theoretical papers, reviews, theses, and dissertations were excluded.

2.2.1. Excluded studies on infants' prediction: which and why?

The present systematic review aimed to highlight the neural signatures of temporal prediction in infancy. Therefore, we excluded all the papers that did not contain an explicit violation of the temporal structure of a series of regular stimuli. Thus, we excluded the studies employing oddball paradigms that are not based on a rhythmical violation, in which the infant perceives a difference between what is currently presented and what was presented before (e.g., Ackles & Cook, 1998), which translates into terms of deviance or novelty effect during development (Kushnerenko et al., 2013).
In the same vein, we also excluded all the paradigms based on the violation of two paired stimuli (e.g., audio and visual stimuli; see Kersey & Emberson, 2017; Rohlf et al., 2017; Wang et al., 2022 for examples). We excluded studies simply changing the order of the elements in a sequence (e.g., Basirat et al., 2014), or the order of stimuli presentation (e.g., Baek et al., 2022), and studies with repetition suppression paradigms (Emberson et al., 2019; Emberson, Cannon, et al., 2017). In general, it follows that all the studies investigating associative learning paradigms, where the association between two or more stimuli was violated, were excluded.

2.3. Results of the search

4135 potentially relevant references were found in the primary literature search. 426 articles were excluded based solely on the title or abstract. We identified 124 articles for a relevant full-text review. Based on a critical review (using the criteria mentioned in the previous paragraph) of the full text, only 8 articles were identified as eligible for inclusion (cf. Figure 1).

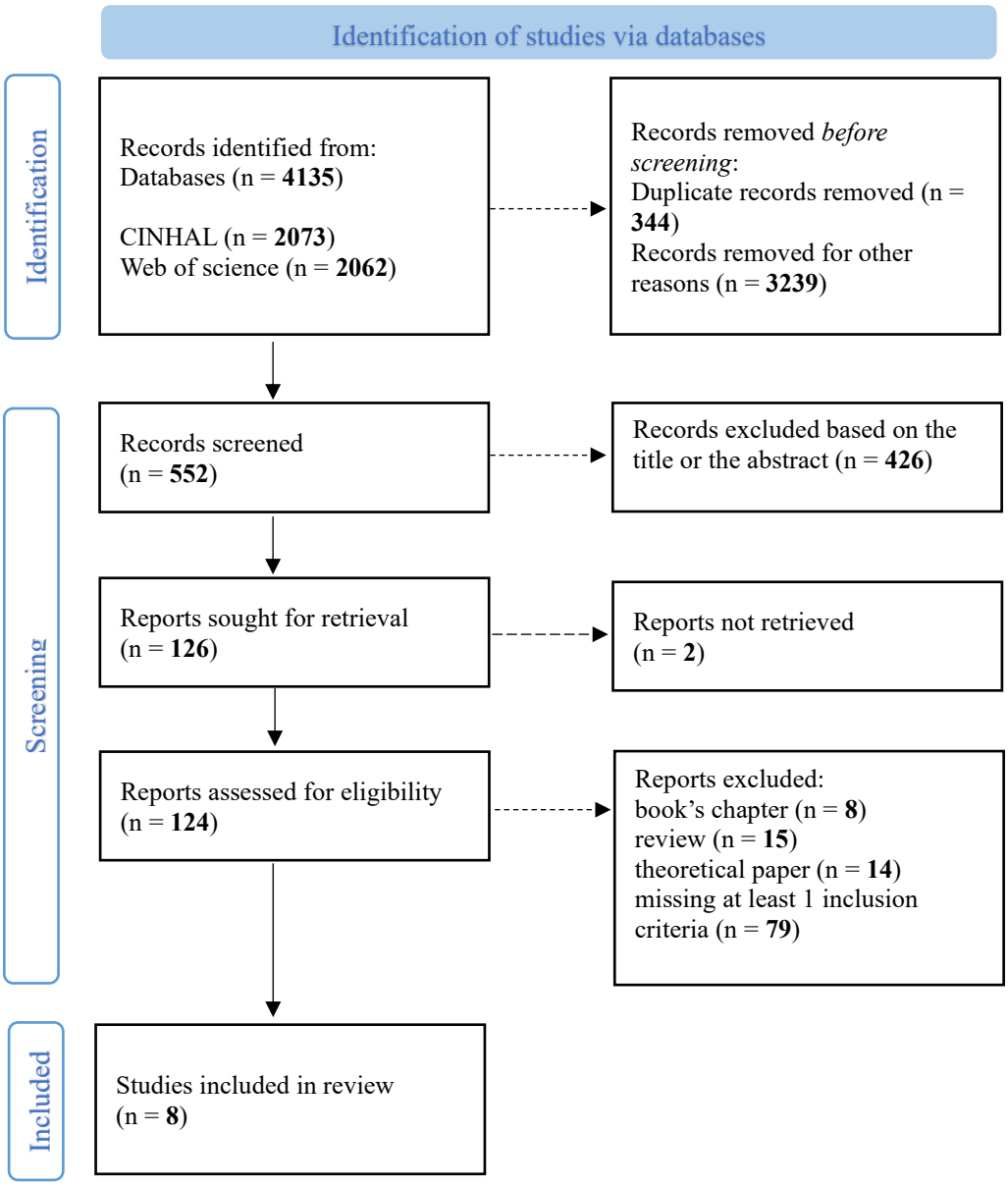

Figure 1. **Study selection flow diagram**

2.4. Data extraction

The principal data were extracted from selected studies and included the author and the year of publication. Studies featured an experimental design or were intervention studies with an experimental design. The experimental paradigm, the population characteristics, and the assessment and stimuli domains were extracted. We also extracted brain outcome

measures, regions of interest, significant results, the conclusion, and potential bias evaluation from the selected studies.

III. Results

3.1. Studies design and population characteristics

3.1.1. *Studies design*

All the selected studies had an experimental design, except for one intervention study with a control group (Zhao & Kuhl, 2016). The studies' main characteristics and a short description of the designs are presented in Table 1.

More specifically, four studies used auditory rhythmic regularities meter, temporal regularities, or observed goal-directed action structural violations paradigms (Edalati et al., 2022; Maffongelli et al., 2018; Otte et al., 2013; Winkler et al., 2009). Two studies used an auditory or audio-visual paradigm (Mento & Valenza, 2016; Zhao & Kuhl, 2016). The last two studies used a vibrotactile stimulation-omission paradigm (Dumont et al., 2022) and a temporal structure detection paradigm (Háden et al., 2015).

3.1.2. Population

The selected studies included a total population of 228 infants. Among these infants, 40 were preterm (32-33 wGA at birth and 33 wGA at test) neonates (Dumont et al., 2022; Edalati et al., 2022). Two studies were conducted on a total of 44 full-term (39-40 wGA at birth and 1-3 days at test) newborns (Háden et al., 2015; Winkler et al., 2009). One study was conducted on 76 2-month-old participants (Otte et al., 2013). Another study was conducted on 14 6- to 7-month-old infants (Maffongelli et al., 2018). The last two studies recruited 9-month-old infants, for a total of 54 infants (Mento & Valenza, 2016; Zhao & Kuhl, 2016).

In four studies, infants were asleep when tested (Dumont et al., 2022; Edalati et al., 2022; Háden et al., 2015; Winkler et al., 2009). In the study of Otte et al. (2013), 36 infants were awake, and 40 were asleep at the time of testing. Nothing has been mentioned about the infant's state at the moment of the test in the other studies.

One selected study (Mento & Valenza, 2016) has also been conducted on 14 adults (adults' results have not been included in this systematic review but are presented in the supplementary material; cf. Figures 4 and 5).

3.2. Stimuli domains

Five of eight experimental paradigms used auditory stimuli like auditory rhythm, trains of complex tones with different pitches, different types of tones, a two-measure rock drum, or a triple meter structure (Edalati et al., 2022; Háden et al., 2015; Otte et al., 2013; Winkler et al., 2009; Zhao & Kuhl, 2016).

In one study, audio and visual stimuli were paired, where Mento and Valenza (2016) used pictures of real female faces along with digitized samples of notes played by different musical instruments. One study used visual stimuli consisting of sequences of familiar goal-directed actions (Maffongelli et al., 2018). Finally, tactile stimuli have been used only in one study (Dumont et al., 2022).

A more detailed description of the stimuli used in each study is available in Table 1.

3.3. Aims

The declared aim of three studies was to assess infants' abilities to extract temporal regularities in a series of stimuli to form sensory predictions (Dumont et al., 2022; Edalati et al., 2022; Zhao & Kuhl, 2016). Two studies focused on the ability of infants to develop temporal expectations, with an interest in anticipatory neuronal mechanisms and their similarity with adult's spatiotemporal dynamics (Mento & Valenza, 2016; Winkler et al., 2009). The goal of the study by Otte et al. (2013) was to understand if infants could identify violations in temporal regularities. The last two studies aimed to evaluate infants' brain sensitivity to the manipulation of pitch steps at different repetition rates (Háden et al., 2015) and the impact of the manipulation of hierarchical organization on neurological processing (Maffongelli et al., 2018).

3.4. Brain outcome measures and regions of interest

3.4.1. *Brain outcome measures*

Of the eight selected studies, six used electroencephalography (EEG) as a brain measure. More information about the type of EEG used or the number of channels can be found in Table 2. The measured brain responses were ERPs (e.g., CNV, MMN/MMR; Edalati et al., 2022; Mento & Valenza, 2016; Otte et al., 2013; Winkler et al., 2009). The last two studies used Diffuse Correlation Spectroscopy (or DCS) (Dumont et al., 2022) and magnetoencephalography (or MEG) (Zhao & Kuhl, 2016) as brain measures.

3.4.2. Regions of interest

Three studies focused on one specific brain region (Dumont et al., 2022; Maffongelli et al., 2018; Winkler et al., 2009), whereas other studies investigated multiple brain regions. Most of the selected studies (5/8) concentrated on specific brain activations for temporal prediction in the frontal regions (Edalati et al., 2022; Háden et al., 2015; Maffongelli et al., 2018; Mento & Valenza, 2016; Otte et al., 2013) and three studies in central areas (Háden et al., 2015; Otte et al., 2013; Winkler et al., 2009).

Three studies focused on the involvement of parietal (Otte et al., 2013), temporal (Zhao & Kuhl, 2016), and temporoparietal regions (Mento & Valenza, 2016) in temporal prediction.

One study focused on specific brain activations for temporal prediction in frontocentral regions (Edalati et al., 2022), and another one in prefrontal areas (Zhao & Kuhl, 2016).

The last study involved the primary somatosensory cortex (Dumont et al., 2022).

It's important to note that six on eight studies (Edalati et al., 2022; Háden et al., 2015; Maffongelli et al., 2018; Mento & Valenza, 2016; Otte et al., 2013; Winkler et al., 2009) used surface EEG; while Zhao and Kuhl (2016) used source reconstruction in a MEG paradigm. Two studies (Edalati et al., 2022; Mento & Valenza, 2016) used surface EEG and brain source location or reconstruction. Indeed, in their studies, Edalati et al. (2022) used DCM analysis for brain source location, while Mento and Valenza (2016) extracted the regions of interest (i.e., inferior and middle frontal gyri and the right temporoparietal areas) from a reconstruction of brain sources.

More detailed information about brain regions of interest is summarized in Table 2.

Table 1. **Description of experimental design, population, stimuli domain, and aim**

Author, reference	**Experimental design**	**Population** Number, age (mean ± standard deviation; range; sex) Infants' state at test	**Stimuli domain** Type of stimuli and description	**Aim**
1. Dumont et al. (2022)	Vibrotactile stimulation-omission paradigm: fixed *vs*. jittered ISI (not predictable stimulus onset). Stimuli were interspersed with omission trials: 1 omission trial every 7-12 vibrations.	20 preterm neonates (m at birth = 32.1 ± 0.5 wGA, m at test = 33.3 ± 0.2 corrected wGA; age range at test: 33.0-33.4 corrected wGA; 11 females). Infants were asleep.	Tactile stimuli. Vibration with a palm vibrator, 3 sec. long vibrations interspersed with 5 sec. long intervals. 10 omissions among 84 stimuli. 13 min. total length.	To assess the ability of premature newborns to form a sensory prediction based on a tactile sequence.
2. Edalati et al. (2022)	Auditory rhythmic regularities violations paradigm: oddball paradigm with high-probability standard rhythm (p = 79%) and infrequent deviant rhythm trials (p = 21%). Two control sequences without any standard trial in between.	20 preterm neonates (m at birth = 31.48 ± 1.23 wGA; m at test = 33 ± 1.44 wGA; NA; 8 females). Infants were asleep.	Auditory stimuli. Auditory rhythm in 2/4 m, 60 beats/min. Intertone intervals: 1000, 500, 500 ms (standard rhythm), and 1000, 250, 750 ms (deviant rhythm).	To test if preterm newborns (30-34 wGA) detect temporal regularities in rhythmic patterns. To test the presence of top-down predictions (rhythmic deviations).
3. Háden et al. (2015)	Temporal structure detection paradigm: trains of complex tones varying in pitch (F0) across trains. A pitch was randomly selected for each train. Trains consisted of 8–24 tone repetitions ("slow" rate tones in the 1st part of the train and "fast" rate tones in the 2nd part), followed by a silent interval.	30 full-term neonates (m at birth = 39.7 ± 1 wGA; age range at test: 1-3 days; 14 females). Infants were asleep.	Auditory stimuli. Trains of complex tones with 8 different pitches taken from the C major scale: C3, D3, E3, F3, G3, A3, B3, and C4). Total duration: 22 min.	To evaluate if the newborn brain is sensitive to the overall probability of ascending *vs.* descending pitch steps in the stimulus block at different repetition rates.

4. Maffongelli et al. (2018)	Structural violations of observed goal-directed action sequences paradigm: control *vs.* violation condition (temporal inversion of two adjacent steps of an action sequence).	14 6-7 months old infants (m = 200 days ± NA; 179-235 days; 7 females). NA	Visual stimuli. Sequences of familiar goal-directed actions as a series of still pictures.	To investigate whether or not a manipulation of the hierarchical organization of an observed familiar action sequence results in differential neurophysiological processing already in infants at the age of 6 to 7 months.
5. Mento and Valenza (2016)	Audio-visual paradigm: oddball paradigm simulating a "Peekaboo" game. Standard (p = 0.77) *vs.* delayed (p = 0.23) conditions.	15 9 months old infants (m = 283 days ± 23.9; 252-333 days; 5 females). NA 14 adults (m = 25 years ± 3.2; 20-32 years; 9 females).	Visual and auditory stimuli. Visual stimuli: pictures of real female faces, which could be covered by hands or bare-faced and smiling. Auditory stimuli: digitized samples of the notes C_4, E_4, G_4, and C_5 played by different musical instruments - i.e., trumpet, oboe, saxophone, and piano.	To understand whether (1) anticipatory neural mechanisms instantiated by temporal expectancy are already operating early in life and (2) these rely on similar or different spatiotemporal dynamics as compared to adults.
6. Otte et al. (2013)	Auditory oddball paradigm: violation of temporal regularities. Regular 300 ms ISI between standard tones (p = 0.7). 3 deviants (p = 0.1 each): - 100 ms ISI. - 2 spectral deviants.	76 2 months old infants (m = 70.1 days ± 6.2 days; NA; 46 females). 36 waking (20 females) and 40 sleeping (26 females) infants.	Auditory stimuli. Four types of tones: one standard (300 ms ISI) and three deviants. One deviant, identical to the standard, preceded by a 100 ms ISI. Two spectral deviants (white noise sound and novel sound).	To shed light on whether infants can identify violations of temporal regularities (detection ISI shortenings). To examine the effects of the state of alertness on the MMR.

7. Winkler et al. (2009)	Meter violation paradigm. Standard patterns: base pattern and 3 standard deviants with omission on the lowest metrical level (p = 22.5 % each). 1 deviant pattern (p = 10%) with metrically salient omissions in the base pattern. 1 control pattern repeating the deviant pattern 100% of the time.	14 newborn infants (NA; age range at birth: 37-40 wGA, age range at test: 2-3 days; 3 females). Infants were asleep.	Auditory stimuli. Two-measure rock drum accompaniment pattern composed of snare, bass, and hi-hat spanning 8 equally spaced positions.	To investigate if newborns can extract the beat of the rhythmical sequence (stronger expectation).
8. Zhao and Kuhl (2016)	Intervention study with experimental design. Auditory oddball paradigm (standard, p = 85%; deviant, p = 15%). Effects of a laboratory-controlled music intervention on infants' neural processing of temporal structure in music and speech: music (intervention group) *vs.* play (control group) activities for 12 sessions.	39 9-months old infants (NA; NA; NA). Intervention group (n = 20) and control group (n = 19). Inclusion in the analysis of the MEG recordings of 36 participants in the music condition (18 from intervention, 6 females; 18 from control, 9 females) and 35 participants in the speech condition (16 from intervention, 4 females; 19 from control, 10 females). NA	Intervention phase: multimodal, social, and repetitive stimuli (synchronization of the infants' movements to the musical beats in the intervention group *vs.* play without music in the control group). Testing phase: auditory stimuli. Music condition: triple meter structure (strong complex tone combined with two weak complex tones with sound-onset-asynchrony of 300 ms). Speech condition: disyllabic nonword speech (combination of synthesized syllables with silent gaps in between).	To test whether the intervention enhanced infants' general ability to extract temporal structure and generate more robust predictions about future stimuli in complex auditory sounds.

Table 2. **Description of brain outcome measures, region of interest, significant results, conclusion, and limitations**

Author, reference	Brain outcome measures	Region of interest (ROI)	Significant results	Conclusion	Limitations
1. Dumont et al. (2022)	Diffuse Correlation Spectroscopy (DCS).	Primary somatosensory cortex.	Jittered ISI: blood flow ↗ during omissions ($t(8) = 2.622$, $p = 0.031$; Cohen's d = 0.874). Likely but not certain stimulus onset expectation → ✚ somatosensory cortex. Fixed ISI: blood flow ↘ during omissions ($t(10) = -4.023$, $p = 0.002$, Cohen's d = -1.213). Stimulus onset expectation → − somatosensory cortex.	Sensory prediction is already presented 4 weeks before term. Sensory prediction: opposite somatosensory cortex activity regulation depending on the stimulus onset probability.	High attrition rate (low signal-to-noise ratio of DCS).
2. Edalati et al. (2022)	EEG (124-channel HydroCel Geodesic Sensor Net). - ERPs (MMR).	Frontal and frontocentral regions. Surface EEG and source location	Deviant rhythm condition: enhanced early (~150-350 ms) frontal and frontocentral mismatch response ($p < 0.05$), subsequent negative deflection (400-500 ms). Rhythm violations processing not limited to primary auditory areas (source location in the DCM analysis): - ⇄ connections between the bilateral A1 and the bilateral STG, the right STG and the right IFG (highest model exceedance probability, $p = 0.52$). Feedback loop within the auditory cortex. The effect size is missing.	Premature neonates detect rhythmic regularities and deviations. Processing of rhythm deviation: primary auditory areas but higher level temporo-frontal cortical structures in a bottom-up and top-down stream, as in adults. Following deviance detection, an error signal travels forward toward higher-order regions. Then, a feedback loop allows comparison of	Small population size. The model parameters were those defined by default in DCM in adults.

				predicted and sensed stimuli. Onset of the thalamocortical and cortico-cortical circuits: sophisticated structure underlying predictive rhythm processing.	
3. Háden et al. (2015)	EEG (Ag/AgCl electrodes) - ERPs	Frontal and central regions (electrodes placed at scalp locations F3, Fz, F4, C3, Cz, and C4). Surface EEG	≠ ERP responses for train onsets, presentation rate changes, and expected tone (train offsets). - Train onset: early negative (0-200 ms, N1) followed by a late positive component (250-400 ms, P2) with a frontocentral maximum. - Presentation-rate changes: early frontocentral negative response (~50-120 ms) with an apparent central (Cz) maximum. - Expected tone: early distributed positive response (0-150 ms) followed by a negative one (250-350 ms). The effect size is missing.	Newborn's brain is sensitive to the onset and offset of sound trains as well as changes in the presentation rate. N1 and P2, coding detection and processing of sound are present in infants during sound-train presentation. At birth, infants are sensitive to temporal aspects of segregating sound sources, speech, and music perception.	NA
4. Maffongelli et al. (2018)	EEG (128-channel Geodesic Sensor Net). - ERPs	Frontal regions Surface EEG	Action sequence structural violation: bilateral anterior positivity in early (200-350 ms) and late (500-650 ms) time windows. Early time window (200-350 ms): ✚ positive amplitude for the violation condition in the right frontal hemisphere ($t(13) = -2.28$, $p = .01$).	The ability to perceive the temporal structure of familiar actions starts early on in development. Bilateral ERP differences between	NA

			Late time window (500-650 ms): ✚ positive amplitude for the violation condition in the left frontal hemisphere ($t(13) = -1.92$, $p = .03$). The effect size is missing.	control and violation conditions in infants (with a significant early response in the right-frontal region).	
5. Mento and Valenza (2016)	EEG (geodesic EEG system; high-density 128-channel HydroCel Geodesic Sensor Net) - ERPs (CNV).	Inferior and middle frontal gyri, right temporoparietal areas (inferior and superior parietal cortex, inferior, middle, and superior temporal gyri). Surface EEG and source reconstruction	Central-positive/posterior-negative CNV in infants *vs.* anterior-positive/posterior-negative CNV in adults soon after the ISI onset to the presentation of the second stimulus (corrected $p < 0.05$). Dynamic changes in anticipatory ERP activity across the task ($p < 0.05$): posterior cluster ✚ negative and anterior/central cluster ✚ positive. - Posterior cluster: ≠ latency ranges. Time-on-task effect 400 ms after the ISI onset in infants *vs.* 170 ms in adults. Brain sources reconstruction. Adults and infants: right prefrontal cortex and in particular, the inferior and the middle frontal gyrus. Infants: temporoparietal areas, with a larger activity in the right hemisphere. Adults: strong activation of the SMA. The effect size is missing.	The human brain's capacity to translate temporal predictions into anticipatory neural activity emerges early in life with an adult-like CNV present in infants and adults and common frontal sources in the two populations. The underlying spatiotemporal cortical dynamics change across development, with a temporoparietal shift toward SMA during development.	A small number of artifact-free trials in the delayed condition didn't allow splitting data into more blocks to test an implicit learning effect.
6. Otte et al. (2013)	EEG (64-electrode locations cap) - ERPs (MMN)	Central, frontal, and parietal regions. Surface EEG	Frontocentral electrode sites: ✚ amplitude response for all deviants. - ISI-deviant → negative peak (~200 ms) followed by a smaller late positive wave (starting ~300 ms). - Novel sounds and white-noise deviant → strong positive wave (peak ~300 ms). Positive and negative MMRs elicited by ISI-deviant, only in waking infants ($t_{awake_ISI\text{-}deviant}(35) = -3.236$, $p < .01$). Amplitudes attenuated in sleeping infants (NA) for white-noise deviant and abolished for ISI-deviant.	Ability to extract temporal and spectral regularities from a sound sequence is already functional in the first months of life. Infant's state of alertness → scalp distribution of all deviant-stimulus responses. The ISI-	NA

			The state of alertness influences MMR responses: ✚ effect of the state of alertness on ISI-deviant response for the negative MMR. The effect size is missing.	deviant response observed during wakefulness is abolished during sleep.	
7. Winkler et al. (2009)	EEG (Ag/Cl-electrodes) - ERPs (MMN).	Central regions (electrodes placed at scalp locations C3, Cz, and C4). Surface EEG	Brain responses to deviant stimulus ≠ responses to standard and deviant-control patterns (NA). Difference between deviant and deviant-control conditions: negative waves at 200 ms and 316 ms followed by a positive wave at 428 ms (NA). Difference between deviant and standard/deviant-control conditions: significant in 40-ms-long latency ranges centered on the early negative and the late positive difference peaks (NA). Type of stimulus: effect on both peaks (early negative waveform: $F[2,26] = 3.77$, $p < 0.05$, $\varepsilon = 0.85$, and $\boldsymbol{\eta}^2 = 0.22$; positive waveform: $F[2,26] = 8.26$, $p < 0.01$, $\varepsilon = 0.97$, $\boldsymbol{\eta}^2 = 0.39$). Differences between: - deviant and deviant-control responses in both latency ranges (df = 26, $p < 0.05$ and 0.01 for the early negative and the late positive waveforms, respectively). - deviant and standard responses for the positive waveform (df = 26, $p < 0.01$).	Beat violation in a rhythmic sound sequence is detected by newborns and is already functional at birth. Newborns detect regular features in a highly variable acoustic environment. Different responses to deviant stimulus associated with the violation of sensory expectations.	NA
8. Zhao and Kuhl (2016)	MEG (306-channel Elekta Neuromag) - MMR	Temporal and prefrontal areas. Source reconstruction	Intervention group: - ✚ MMR responses to temporal structure violations around 200 ms in the music condition in both temporal auditory and prefrontal cortical regions (NA). - identical results for temporal structure violations in speech (NA).	Music intervention: enhanced neural processing of temporal structure in music and speech, thus enhancing infants' ability to extract temporal	NA

			The effect size is missing.	structure information and to predict future events in time.	

Abbreviations list of Tables 1 and 2

- CNV (contingent negative variation)
- DCM (dynamic causal modeling)
- EEG (electroencephalography)
- ERPs (event-related potentials)
- DCS (diffuse correlation spectroscopy)
- IFG (inferior frontal gyri)
- ISI (interstimulus interval)
- MMR (mismatch response)
- MMN (mismatch negativity)
- SMA (supplementary motor area)
- STG (superior temporal gyri)
- wGA (weeks gestational age)

3.5. Results and conclusions of the included studies

Results summarizing the main finding of the included studies will be presented in a longitudinal perspective, with the infant's age increasing as presented in Figure 2, as well as results extracted from source location and reconstruction in Figure 3.

In preterm neonates aged 33 (corrected) weeks of gestational age, one study showed that in a vibrotactile paradigm, omissions in the jittered interstimulus interval (or ISI) condition (i.e., in likely but not certain stimulus onset expectation) induce an activation of the somatosensory cortex, whereas a deactivation is observed in this region during omission when the stimulus onset was expected (in the fixed interstimulus interval condition) (Dumont et al., 2022). In preterm babies, another study (Edalati et al., 2022) has shown that in an auditory rhythmic regularities violation paradigm, a deviant condition elicited an early (~150–350 ms) frontal and frontocentral mismatch response (MMR), followed by a negative deflection (400-500 ms). More specifically, using Dynamic Causal Modeling (or DCM) for source location, authors showed that MMR is not limited to the primary auditory cortex but consists of a feedback loop within the auditory cortex, associated with bidirectional connections between the bilateral primary auditory cortex and the bilateral superior temporal gyrus, the right superior temporal gyrus and the right inferior frontal gyrus (Edalati et al., 2022).
In infants born prematurely, sensory prediction following a vibrotactile stimulation is already present and implies the primary somatosensory cortex with an opposite activity regulation depending on the stimulus onset probability (Dumont et al., 2022). Likewise, the infant's brain extracts rhythmic regularities and detects deviations from them. This operation, as with adults, also relies on higher-level temporofrontal brain structures in a bottom-up and top-down fashion (Edalati et al., 2022). Indeed, after deviance detection, an error signal is sent toward higher-order regions, followed by a feedback loop that enables the comparison between predicted and sensed stimuli (Edalati et al., 2022).

At birth, full-term infant's brain is already sensitive to changes in the rate at which sounds occur, as shown by the elicited early frontocentral negative response (~50-120 ms) (Háden et al., 2015) and present a different response to a deviant stimulus (Winkler et al., 2009). Indeed, Winkler et al. (2009) have observed two negative waves (peaking at 200 ms and 316 ms) followed by a positive wave (peaking at 428 ms) in central regions for the difference between the deviant and the deviant control conditions; further post hoc analysis also revealed significant differences between the deviant and the standard response for the positive waveform in the same brain region.
As shown by these studies implying frontal and central regions, at birth the infants' brain is already sensitive to the temporal aspect of sounds and their segregation, and detect regularities in highly a variable acoustic environment, as well as beat violations in a rhythmic sequence that violate infants' sensory expectations (Háden et al., 2015; Winkler et al., 2009).

In 2-month-old infants, an ISI-deviant elicited a negative peak (~200 ms) followed by a smaller late positive wave (~300 ms) in the frontal, central, and parietal regions; whereas novel sounds and white-noise deviants elicited a strong positive wave in the same brain regions (Otte et al., 2013). However, the highest amplitude response has been observed on frontocentral sites for all deviants, although these amplitudes attenuate for white-noise deviants and abolish for ISI-deviants in sleeping infants (Otte et al., 2013). Interestingly, Otte et al. (2013) reported that ISI-deviant elicited positive and negative MMRs only in waking infants; showing an effect of the infant's state of alertness (awake *vs.* asleep) on the scalp

distributions of the MMR responses, with a larger effect of the state of alertness on ISI-deviant response for the negative-going MMR.
Early in life, the infant's brain can extract temporal regularities from a sound sequence. As shown by the authors, the infant's state of alertness impacts the frontocentroparietal response distribution to deviant conditions (i.e., the response to ISI-deviant observed in waking infants is abolished during sleep) (Otte et al., 2013).

At 6 to 7 months of age, a structural violation in an action sequence elicited a bilateral anterior positivity in early (200-350 ms) and late (500-650 ms) time windows, with a more positive amplitude for the violation condition in the right and left frontal hemispheres, respectively (Maffongelli et al., 2018).
As shown by this study, the temporal structure of familiar goal-directed actions and their violation can be detected in 6-7-month-old infant's brain, resulting in bilateral ERPs modifications in the frontal regions (Maffongelli et al., 2018).

At 9 months old, Mento and Valenza (2016) reported anticipatory brain activity, with dynamic changes in anticipatory ERP activity along the task (i.e., the posterior cluster at the surface of the scalp became more negative and the anterior/central cluster more positive indicating, using brain sources reconstruction, a larger neural activity in the inferior and middle frontal gyri, and the right temporoparietal areas as the temporal contingency between the two stimuli was implicitly processed by infants' brain in the delayed condition) in an oddball paradigm simulating a "Peekaboo" game. A laboratory-controlled music intervention (Zhao & Kuhl, 2016) revealed in both temporal auditory and prefrontal cortical regions (using source reconstruction) larger MMR responses (~200 ms) to temporal structure violations in music and speech in infants of the same age.
These results show that the infant's brain is already able to translate predictions of temporal time sequences into prefrontal and temporoparietal anticipatory brain activities at 9 months of age, which translates into an adult-like CNV (Mento & Valenza, 2016). This neural processing could be enhanced by a music intervention, as shown by Zhao and Kuhl (2016), for a better prediction of upcoming events.

More detailed information on the studies' results is summarized in Table 2.

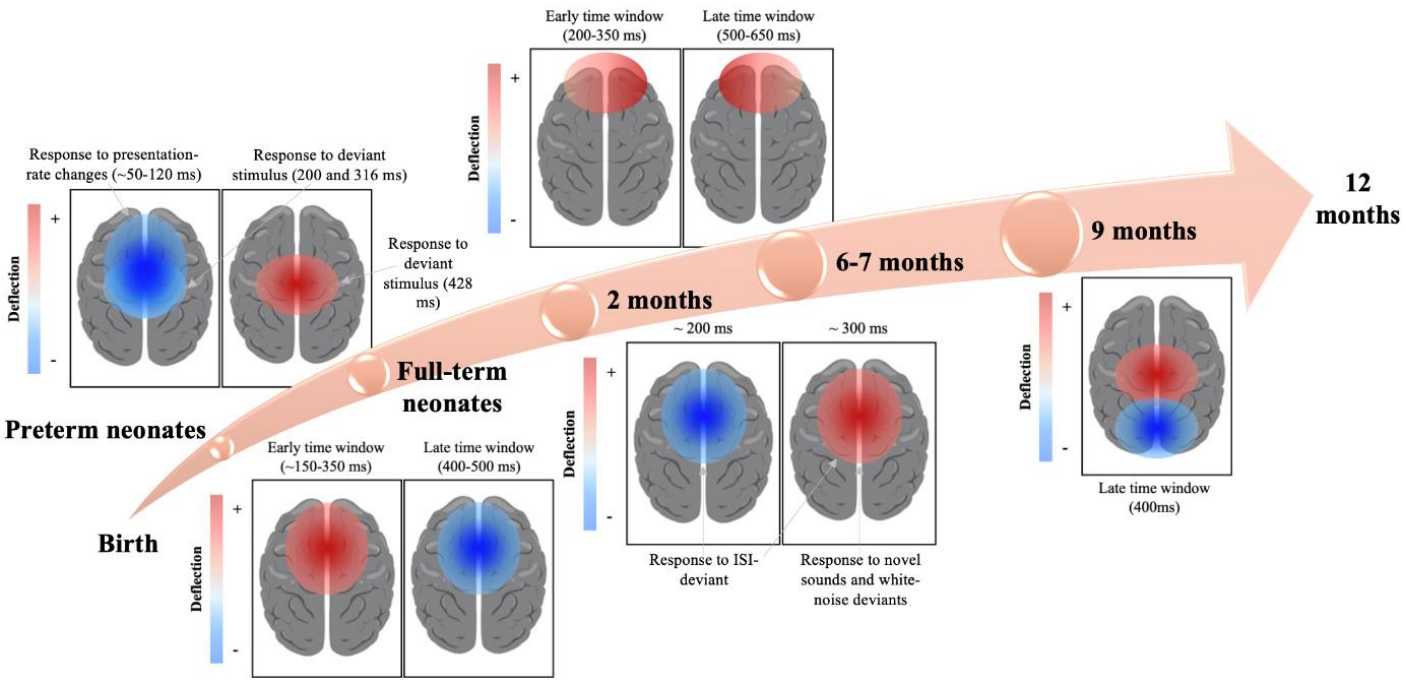

***Figure 2*. A longitudinal perspective of the neural signatures of temporal prediction in infancy at the scalp surface (extract from Edalati et al., 2022; Háden et al., 2015; Maffongelli et al., 2018; Mento & Valenza, 2016; Otte et al., 2013; Winkler et al., 2009).**

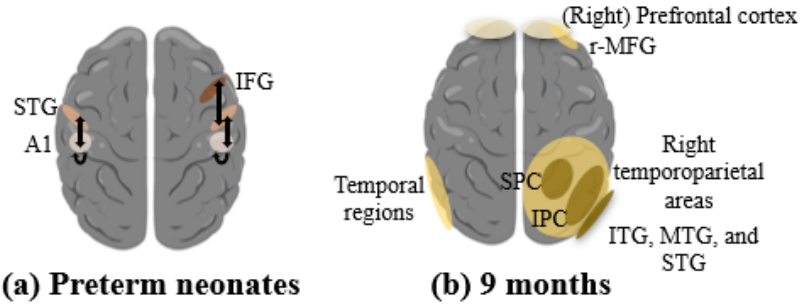

***Figure 3*. Source location and reconstruction of temporal prediction in (a) preterm neonates and (b) 9-month-old infants (extract respectively from Edalati et al., 2022; Mento & Valenza, 2016; Zhao & Kuhl, 2016).** (a) In preterm neonates, DCM analysis identified bidirectional connections between the bilateral auditory cortex (A1) and the bilateral superior temporal gyri (STG), the right STG and the right inferior frontal gyrus (IFG), and a feedback loop within the auditory cortex. (b) In 9-month-old infants, source reconstruction identified a cortical activity in the right prefrontal cortex, including the inferior and the middle frontal gyrus (r-MFG) and in the right temporoparietal areas (with an extending activity over the inferior (IPC) and the superior (SPC) parietal cortices, the inferior (ITG), the middle (MTG), and the superior (STG) temporal gyri). Moreover, in 9-month-old infants, a MEG study identified brain activity in the temporal (auditory) and prefrontal cortices.

3.6. Bias evaluation

3.6.1. By the authors on their paradigm

Five studies did not report any bias evaluation. Dumont et al. (2022) reported a high attrition rate. Edalati et al. (2022) reported a small population size (with 20 preterm neonates in total) and used model parameters based on adults. Mento and Valenza (2016) couldn't test an implicit learning effect due to a small number of artifact-free trials.

IV. Discussion

The primary objective of this systematic review was to identify the neural signatures of temporal prediction in infancy and to point out the brain signatures of prediction mechanisms, examining their consistency and evolution over time, from birth to 12 months of age.

Over a third of the recruited infants were newborns, demonstrating that early investigations enable the exploration of the initial development of temporal predictive abilities. Within the chosen studies, both premature and full-term infants underwent testing at birth, 2 months, 6-7 months, and 9 months old. Notably, there is a testing gap between the ages of 2 and 6-7 months and after 9 months, as no studies have been conducted on infants at

the age of 12 months. The consistency in measurements allows us to adopt a longitudinal perspective in our discussion, spanning from birth to 9 months of age.

Regarding the methods of investigation, electroencephalography (EEG) has been largely used in the reported studies, thereby establishing EEG as the gold standard for assessing the brain's temporal signature of prediction early in infancy. EEG use as a brain measure proves particularly suitable for evaluating temporal and rhythmic brain mechanisms in infants, rather than other brain measurement techniques (i.e., current studies on auditory processing in infancy use EEG as a brain measure; see Edalati et al., 2023, for an example).

Within the chosen studies, two deviations from using EEG have been noted, with DCS (Dumont et al., 2022) in preterm neonates and magnetoencephalography employed in the assessment of older infants, as indicated by the research conducted by Zhao and Kuhl (2016).

The current systematic review allowed us to draw some conclusions about the localization, temporality, and polarity (at the surface of the scalp) of the neural signatures of temporal prediction in infants aged 0 to 9 months, as well as their longitudinal development over time.

Infants' temporal predictions, based on surface location, appear to primarily focus on the brain's centro-anterior regions, including the frontal and central areas.

In preterm, full-term, and 2-month-old infants, bilateral ERP modifications at a similar timing have been observed at the surface of the scalp in fronto-central areas in response to rhythm violation or deviance (Edalati et al., 2022; Háden et al., 2015; Otte et al., 2013; Winkler et al., 2009). These ERP modifications are characterized by an early negative deflection followed by a late positive wave in full-term neonates and 2-month-old infants (Háden et al., 2015; Otte et al., 2013; Winkler et al., 2009); whereas an opposite polarity change is observed in preterm neonates (Edalati et al., 2022). Regarding the temporality of these ERPs in full-term and 2-month-old infants, a common 200 ms negative wave is present in both paradigms (Otte et al., 2013; Winkler et al., 2009); however, the late positive deflection appears earlier in a 2-month-old infant’s brain (Otte et al., 2013). This earlier response to deviance might indicate, if similar brain processes are involved, a differentiation of deviance detection mechanisms only a few months after birth. The observed polarity and temporality differences between preterm, full-term, and 2-month-old infants (Edalati et al., 2022; Háden et al., 2015; Otte et al., 2013; Winkler et al., 2009) might be explained by the use of different experimental paradigms in each study, as well as different brain mechanisms and/or network implications, and their neural sources or desynchronization/synchronization. Potentially similar brain processes to prediction and their differentiation through the infant’s first year of life would be interesting to investigate in further studies using a unique temporal deviance detection experimental paradigm in different age groups.

At 6 to 7 months old, a bilateral frontal positivity both in early and late time windows is observed in response to a structural violation in action sequences (Maffongelli et al., 2018). The difference in observed ERP polarity (in comparison to the abovementioned studies) could be explained by the nature of the task, which involves action sequences.

Moreover, throughout infants' development, a noticeable shift in activated areas might be observed (measured at the surface of the scalp): central and frontal activity remains highly specific to this early cognitive ability, as observed in studies conducted in 6-7-month- and 9-month-old infants (Maffongelli et al., 2018; Mento & Valenza, 2016), but may extend to posterior areas as they develop (Mento & Valenza, 2016).

Some exceptions in the reported pool of activated brain areas have been noticed (Dumont et al., 2022). This variation can be attributed to the specific paradigm in this DCS study, involving vibrotactile stimulation that elicited distinct somatosensory responses. It is worth noting that we do not posit the primary somatosensory cortex as exclusively dedicated

to predictions. Despite the divergence in paradigm design from other studies, this form of stimulation is particularly intriguing and judicious, given that newborns' sensory perception is fundamentally intermodal.

The inquiry into the potential lateralization of prediction mechanisms in infants' brain signatures is interesting. However, the selected studies lack sufficient information to address this question comprehensively, with only two studies providing specificity on lateralization, based on source location and reconstruction, particularly focusing on the right prefrontal cortex and the right temporoparietal regions (Mento & Valenza, 2016), as well as the right STG and right IFG during rhythm violations processing in an auditory paradigm (Edalati et al., 2022).

In one included study (Mento & Valenza, 2016) adults were also tested using the same paradigm as in infants; based on this article, figures presenting the neural signatures at the scalp surface and the source reconstruction of temporal prediction in adults can be found in the supplementary material (cf. Figures 4 and 5).

Some limitations of the included studies emerged, though they did not diminish the significance of their findings. In our view, a term-born control population was missing in Dumont et al. (2022) and Edalati et al. (2022) as a follow-up measure in the first study. Additional data with a typically developing population could allow for a more comprehensive comparison and interpretation of the observed effects, providing valuable insights into the developmental trajectory of the studied phenomena and enhancing the generalizability of the findings. Maffongelli et al. (2018) had a limited sample size. In Dumont et al. (2022), brain measurements were limited to the specified region of interest, and we were unable to encompass the chosen brain regions to gain a better understanding of whole-brain signatures of prediction. Edalati et al. (2022) employed dynamic causal modeling with adults' model parameters to draw inferences regarding the neuronal architecture underlying the observed mismatch responses in preterm infants.

Moreover, in numerous studies, the infants' state during testing was not specified, posing a limitation to the corpus and, consequently, our conclusions. Studying very young infants is inherently challenging due to their limited moments of wakefulness; however, as they age, the frequency of wakeful periods increases, providing more data on alert infants. The absence of consistent reporting on infants' states during testing or the variability in infants' alertness levels during testing can pose challenges. As noted by Otte et al. (2013), the state of alertness in infants significantly influences brain responses, with sleeping infants exhibiting attenuated amplitudes and only waking infants displaying a response to an ISI-deviant. In future research, it is recommended to meticulously assess and ensure uniformity in infants' states during testing to enhance the reliability of findings.

Finally, there is a terminological limitation in the studies included. Indeed, the terms "anticipation", "expectation", "prediction", or "violation" are often used without being clearly defined, leading to terminological and, therefore, theoretical confusion.

V. Conclusion

Emerging even before birth, newborns demonstrate temporal predictive abilities within a structured temporal framework, with EEG serving as the gold standard for studying these early cognitive processes. While earlier research based solely on behavioral observations suggested that predictive abilities develop later, neurophysiological investigations have now confirmed that these capabilities are present from the earliest stages of life. Although these abilities have a broad cerebral localization, the majority of studies show that they are

concentrated in the anterior and medial parts of the brain, particularly in the frontal and central areas, with consistency across developmental stages. Temporal prediction mechanisms appear to transition from early sensory-driven responses to more complex, top-down predictive processing over the first year of life. The development of these mechanisms relies on both innate and experience-dependent factors, with external influences such as wakefulness and musical exposure modulating neural responses. This underscores the dynamic nature of temporal prediction development and highlights the integration of sensory and higher-order brain regions as infants mature.

Funding sources

This work was supported by the *Swiss National Science Foundation* [fund number UN11724].

References

Ackles, P. K., & Cook, K. G. (1998). Stimulus probability and event-related potentials of the brain in 6-month-old human infants: A parametric study. *International Journal of Psychophysiology*, *29*(2), 115-143. https://doi.org/10.1016/S0167-8760(98)00013-0

Adams, R. A., Shipp, S., & Friston, K. J. (2013). Predictions not commands: active inference in the motor system. *Brain Structure and Function*, *218*, 611-643. https://doi.org/10.1007/s00429-012-0475-5

Albareda-Castellot, B., Pons, F., & Sebastián-Gallés, N. (2011). The acquisition of phonetic categories in bilingual infants: New data from an anticipatory eye movement paradigm. *Developmental Science*, *14*(2), 395-401. https://doi.org/10.1111/j.1467-7687.2010.00989.x

Alexander, W. H., & Brown, J. W. (2019). The role of the anterior cingulate cortex in prediction error and signaling surprise. *Topics in Cognitive Science*, *11*(1), 119-135. https://doi.org/10.1111/tops.12307

Alho, K., Sainio, K., Sajaniemi, N., Reinikainen, K., & Näätänen, R. (1990). Event-related brain potential of human newborns to pitch change of an acoustic stimulus. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *77*(2), 151-155. https://doi.org/10.1016/0168-5597(90)90031-8

Ambrosini, E., Reddy, V., De Looper, A., Costantini, M., Lopez, B., & Sinigaglia, C. (2013). Looking ahead: Anticipatory gaze and motor ability in infancy. *PLoS One*, *8*(7), e67916. https://doi.org/10.1371/journal.pone.0067916

Baek, S., Jaffe-Dax, S., Bejjanki, V. R., & Emberson, L. (2022). Temporal Predictability Modulates Cortical Activity and Functional Connectivity in the Frontoparietal Network in 6-Month-Old Infants. *Journal of Cognitive Neuroscience*, *34*(5), 766-775. https://doi.org/10.1162/jocn_a_01828

Baek, S., Jaffe-Dax, S., & Emberson, L. L. (2020). How an infant's active response to structured experience supports perceptual-cognitive development. *Progress in Brain Research*, *254*, 167-186. https://doi.org/10.1016/bs.pbr.2020.05.015

Basirat, A., Dehaene, S., & Dehaene-Lambertz, G. (2014). A hierarchy of cortical responses to sequence violations in three-month-old infants. *Cognition*, *132*(2), 137-150. https://doi.org/10.1016/j.cognition.2014.03.013

Bastin, J., Deman, P., David, O., Gueguen, M., Benis, D., Minotti, L., Hoffman, D., Combrisson, E., Kujala, J., & Perrone-Bertolotti, M. (2016). Direct recordings from human anterior insula reveal its leading role within the error-monitoring network. *Cerebral Cortex*, bhv352. https://doi.org/10.1093/cercor/bhv352

Berger, A., & Posner, M. I. (2023). Beyond Infant's Looking: The Neural Basis for Infant Prediction Errors. *Perspectives on Psychological Science*, *18*(3), 664-674. https://doi.org/10.1177/17456916221112918

Bernieri, F. J., Reznick, J. S., & Rosenthal, R. (1988). Synchrony, pseudosynchrony, and dissynchrony: measuring the entrainment process in mother-infant interactions. *Journal of personality and social psychology*, *54*(2), 243. https://doi.org/10.1037/0022-3514.54.2.243

Bisiacchi, P. S., Mento, G., & Suppiej, A. (2009). Cortical auditory processing in preterm newborns: an ERP study. *Biological Psychology*, *82*(2), 176-185. https://doi.org/10.1016/j.biopsycho.2009.07.005

Breska, A., & Ivry, R. B. (2018). Double dissociation of single-interval and rhythmic temporal prediction in cerebellar degeneration and Parkinson's disease. *Proceedings of the National Academy of Sciences*, *115*(48), 12283-12288. https://doi.org/10.1073/pnas.1810596115

Canfield, R. L., & Haith, M. M. (1991). Young infants' visual expectations for symmetric and asymmetric stimulus sequences. *Developmental psychology*, *27*(2), 198. https://doi.org/10.1037/0012-1649.27.2.198

Cannon, E. N., & Woodward, A. L. (2012). Infants generate goal-based action predictions. *Developmental Science*, *15*(2), 292-298. https://doi.org/10.1111/j.1467-7687.2011.01127.x

Carbajal, G. V., & Malmierca, M. S. (2018). The neuronal basis of predictive coding along the auditory pathway: from the subcortical roots to cortical deviance detection. *Trends in Hearing*, *22*, 2331216518784822. https://doi.org/10.1177/2331216518784822

Carlsson, K., Petrovic, P., Skare, S., Petersson, K. M., & Ingvar, M. (2000). Tickling expectations: neural processing in anticipation of a sensory stimulus. *Journal of Cognitive Neuroscience*, *12*(4), 691-703. https://doi.org/10.1162/089892900562318

Cheour-Luhtanen, M., Alho, K., Kujala, T., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (1995). Mismatch negativity indicates vowel discrimination in newborns. *Hearing Research*, *82*(1), 53-58. https://doi.org/10.1016/0378-5955(94)00164-L

Cheour, M., Alho, K., Čeponiené, R., Reinikainen, K., Sainio, K., Pohjavuori, M., Aaltonen, O., & Näätänen, R. (1998). Maturation of mismatch negativity in infants. *International Journal of Psychophysiology*, *29*(2), 217-226. https://doi.org/10.1016/S0167-8760(98)00017-8

Cheour, M., Martynova, O., Näätänen, R., Erkkola, R., Sillanpää, M., Kero, P., Raz, A., Kaipio, M.-L., Hiltunen, J., & Aaltonen, O. (2002). Speech sounds learned by sleeping newborns. *Nature*, *415*(6872), 599-600. https://doi.org/10.1038/415599b

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*(3), 181-204. https://doi.org/10.1017/S0140525X12000477

Colombo, J., & Richman, W. A. (2002). Infant timekeeping: Attention and temporal estimation in 4-month-olds. *Psychological science*, *13*(5), 475-479. https://www.jstor.org/stable/40063883

https://journals.sagepub.com/doi/pdf/10.1111/1467-9280.00484?download=true
Condon, W. S., & Sander, L. W. (1974). Synchrony demonstrated between movements of the neonate and adult speech. *Child development*, 456-462. https://doi.org/10.2307/1127968
Craig, A. (2009). Emotional moments across time: a possible neural basis for time perception in the anterior insula. *Philosophical transactions of the Royal Society B: Biological sciences*, *364*(1525), 1933-1942. https://doi.org/10.1098/rstb.2009.0008
Crivelli-Decker, J., Hsieh, L.-T., Clarke, A., & Ranganath, C. (2018). Theta oscillations promote temporal sequence learning. *Neurobiology of Learning and Memory*, *153*, 92-103. https://doi.org/10.1016/j.nlm.2018.05.001
Crown, C. L., Feldstein, S., Jasnow, M. D., Beebe, B., & Jaffe, J. (2002). The cross-modal coordination of interpersonal timing: Six-week-olds infants' gaze with adults' vocal behavior. *Journal of psycholinguistic research*, *31*, 1-23. https://doi.org/10.1023/A:1014301303616
Dehaene-Lambertz, G., & Dehaene, S. (1994). Speed and cerebral correlates of syllable discrimination in infants. *Nature*, *370*(6487), 292-295. https://doi.org/10.1038/370292a0
Draganova, R., Eswaran, H., Murphy, P., Huotilainen, M., Lowery, C., & Preissl, H. (2005). Sound frequency change detection in fetuses and newborns, a magnetoencephalographic study. *NeuroImage*, *28*(2), 354-361. https://doi.org/10.1016/j.neuroimage.2005.06.011
Draganova, R., Eswaran, H., Murphy, P., Lowery, C., & Preissl, H. (2007). Serial magnetoencephalographic study of fetal and newborn auditory discriminative evoked responses. *Early human development*, *83*(3), 199-207. https://doi.org/10.1016/j.earlhumdev.2006.05.018
Dreher, J. C., & Grafman, J. (2002). The roles of the cerebellum and basal ganglia in timing and error prediction. *European Journal of Neuroscience*, *16*(8), 1609-1619. https://doi.org/doi.org/10.1046/j.1460-9568.2002.02212.x
Dumont, V., Giovannella, M., Zuba, D., Clouard, R., Durduran, T., Guillois, B., & Roche-Labarbe, N. (2022). Somatosensory prediction in the premature neonate brain. *Developmental Cognitive Neuroscience*, *57*, 101148. https://doi.org/10.1016/j.dcn.2022.101148
Edalati, M., Mahmoudzadeh, M., Ghostine, G., Kongolo, G., Safaie, J., Wallois, F., & Moghimi, S. (2022). Preterm neonates distinguish rhythm violation through a hierarchy of cortical processing. *Developmental Cognitive Neuroscience*, *58*, 101168. https://doi.org/10.1016/j.dcn.2022.101168
Edalati, M., Wallois, F., Safaie, J., Ghostine, G., Kongolo, G., Trainor, L. J., & Moghimi, S. (2023). Rhythm in the premature neonate brain: Very early processing of auditory beat and meter. *Journal of Neuroscience*, *43*(15), 2794-2802. https://doi.org/10.1523/JNEUROSCI.1100-22.2023
Emberson, L. (2017). How does experience shape early development? Considering the role of top-down mechanisms. *Advances in child development and behavior*, *52*, 1-41. https://doi.org/10.1016/bs.acdb.2016.10.001
Emberson, L. L., Boldin, A. M., Riccio, J. E., Guillet, R., & Aslin, R. N. (2017). Deficits in top-down sensory prediction in infants at risk due to premature birth. *Current Biology*, *27*(3), 431-436. https://doi.org/10.1016/j.cub.2016.12.028
Emberson, L. L., Boldin, A. M., Robertson, C. E., Cannon, G., & Aslin, R. N. (2019). Expectation affects neural repetition suppression in infancy. *Developmental Cognitive Neuroscience*, *37*, 100597. https://doi.org/10.1016/j.dcn.2018.11.001

Emberson, L. L., Cannon, G., Palmeri, H., Richards, J. E., & Aslin, R. N. (2017). Using fNIRS to examine occipital and temporal responses to stimulus repetition in young infants: Evidence of selective frontal cortex involvement. *Developmental Cognitive Neuroscience*, *23*, 26-38. https://doi.org/10.1016/j.dcn.2016.11.002

Emberson, L. L., Richards, J. E., & Aslin, R. N. (2015). Top-down modulation in the infant brain: Learning-induced expectations rapidly affect the sensory cortex at 6 months. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(31), 9585-9590. https://doi.org/10.1073/pnas.1510343112

Falck-Ytter, T., Gredebäck, G., & Von Hofsten, C. (2006). Infants predict other people's action goals. *Nature neuroscience*, *9*(7), 878-879. https://doi.org/10.1038/nn1729

Feldman, R. (2007a). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry*, *48*(3-4), 329-354. https://doi.org/10.1111/j.1469-7610.2006.01701.x

Feldman, R. (2007b). Parent–infant synchrony: Biological foundations and developmental outcomes. *Current Directions in Psychological Science*, *16*(6), 340-345. https://doi.org/10.1111/j.1467-8721.2007.00532.x

Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *Neuroreport*, *13*(10), 1251-1254. https://journals.lww.com/neuroreport/fulltext/2002/07190/neural_manifestation_of_cognitive_and_precognitive.6.aspx

Friedrich, M., & Friederici, A. D. (2011). Word learning in 6-month-olds: fast encoding–weak retention. *Journal of Cognitive Neuroscience*, *23*(11), 3228-3240. https://doi.org/10.1162/jocn_a_00002

Friedrich, M., Wilhelm, I., Born, J., & Friederici, A. D. (2015). Generalization of word meanings during infant sleep. *Nature communications*, *6*(1), 6004. https://doi.org/10.1038/ncomms7004

Friedrich, M., Wilhelm, I., Mölle, M., Born, J., & Friederici, A. D. (2017). The sleeping infant brain anticipates development. *Current Biology*, *27*(15), 2374-2380. e2373. https://doi.org/10.1016/j.cub.2017.06.070

Friston, K. (2005). A theory of cortical responses. *Philosophical transactions of the Royal Society B: Biological sciences*, *360*(1456), 815-836. https://doi.org/10.1098/rstb.2005.1622

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nature Reviews Neuroscience*, *11*(2), 127-138. https://doi.org/10.1038/nrn2787

Friston, K. (2012). The history of the future of the Bayesian brain. *NeuroImage*, *62*(2), 1230-1233. https://doi.org/10.1016/j.neuroimage.2011.10.004

Gardner, M. P., Schoenbaum, G., & Gershman, S. J. (2018). Rethinking dopamine as generalized prediction error. *Proceedings of the Royal Society B*, *285*(1891), 20181645. https://doi.org/10.1098/rspb.2018.1645

Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45*(1), 54-61. https://doi.org/10.1016/j.cortex.2008.01.005

Grahn, J. A., & Rowe, J. B. (2013). Finding and feeling the musical beat: striatal dissociations between detection and prediction of regularity. *Cerebral Cortex*, *23*(4), 913-921. https://doi.org/10.1093/cercor/bhs083

Gredebäck, G., Lindskog, M., Juvrud, J. C., Green, D., & Marciszko, C. (2018). Action prediction allows hypothesis testing via internal forward models at 6 months of age. *Frontiers in psychology*, *9*, 290. https://doi.org/10.3389/fpsyg.2018.00290

Gredebäck, G., & Melinder, A. (2010). Infants' understanding of everyday social interactions: A dual process account. *Cognition*, *114*(2), 197-206. https://doi.org/10.1016/j.cognition.2009.09.004

Gredebäck, G., & von Hofsten, C. (2004). Infants' evolving representations of object motion during occlusion: A longitudinal study of 6-to 12-month-old infants. *Infancy*, *6*(2), 165-184. https://doi.org/10.1207/s15327078in0602_2

Gredebäck, G., von Hofsten, C., & Boudreau, J. P. (2002). Infants' visual tracking of continuous circular motion under conditions of occlusion and non-occlusion. *Infant Behavior and Development*, *25*(2), 161-182. https://doi.org/10.1016/S0163-6383(02)00119-4

Grube, M., Cooper, F. E., Chinnery, P. F., & Griffiths, T. D. (2010). Dissociation of duration-based and beat-based auditory timing in cerebellar degeneration. *Proceedings of the National Academy of Sciences*, *107*(25), 11597-11601. https://doi.org/10.1073/pnas.0910473107

Grube, M., Lee, K.-H., Griffiths, T. D., Barker, A. T., & Woodruff, P. W. (2010). Transcranial magnetic theta-burst stimulation of the human cerebellum distinguishes absolute, duration-based from relative, beat-based perception of subsecond time intervals. *Frontiers in psychology*, *1*, 1946. https://doi.org/10.3389/fpsyg.2010.00171

Háden, G. P., Bouwer, F. L., Honing, H., & Winkler, I. (2024). Beat processing in newborn infants cannot be explained by statistical learning based on transition probabilities. *Cognition*, *243*, 105670. https://doi.org/10.1016/j.cognition.2023.105670

Háden, G. P., Honing, H., Török, M., & Winkler, I. (2015). Detecting the temporal structure of sound sequences in newborn infants. *International Journal of Psychophysiology*, *96*(1), 23-28. https://doi.org/10.1016/j.ijpsycho.2015.02.024

Harrington, D. L., Haaland, K. Y., & Hermanowitz, N. (1998). Temporal processing in the basal ganglia. *Neuropsychology*, *12*(1), 3. https://doi.org/doi.org/10.1037/0894-4105.12.1.3

Hinton, S., Meck, W., & MacFall, J. (1996). Peak-interval timing in humans activates frontal-striatal loops. *NeuroImage*, *3*(3), S224. https://doi.org/10.1016/S1053-8119(96)80226-6

Hinton, S. C., & Meck, W. H. (2004). Frontal–striatal circuitry activated by human peak-interval timing in the supra-seconds range. *Cognitive Brain Research*, *21*(2), 171-182. https://doi.org/10.1016/j.cogbrainres.2004.08.005

Hochmann, J. R., Benavides-Varela, S., Nespor, M., & Mehler, J. (2011). Consonants and vowels: Different roles in early language acquisition. *Developmental Science*, *14*(6), 1445-1458. https://doi.org/10.1111/j.1467-7687.2011.01089.x

Hovsepyan, S., Olasagasti, I., & Giraud, A.-L. (2020). Combining predictive coding and neural oscillations enables online syllable recognition in natural speech. *Nature communications*, *11*(1), 3117. https://doi.org/10.1038/s41467-020-16956-5

Iannaccone, R., Hauser, T. U., Staempfli, P., Walitza, S., Brandeis, D., & Brem, S. (2015). Conflict monitoring and error processing: new insights from simultaneous EEG–fMRI. *NeuroImage*, *105*, 395-407. https://doi.org/10.1016/j.neuroimage.2014.10.028

Ivry, R. B., & Keele, S. W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience*, *1*(2), 136-152. https://doi.org/doi.org/10.1162/jocn.1989.1.2.136

Jaffe, J., Beebe, B., Feldstein, S., Crown, C. L., Jasnow, M. D., Rochat, P., & Stern, D. N. (2001). Rhythms of dialogue in infancy: Coordinated timing in development. *Monographs of the Society for Research in Child Development*, i-149. https://www.jstor.org/stable/pdf/3181589.pdf

Kabdebon, C., & Dehaene-Lambertz, G. (2019). Symbolic labeling in 5-month-old human infants. *Proceedings of the National Academy of Sciences*, *116*(12), 5805-5810. https://doi.org/10.1073/pnas.1809144116

Kanakogi, Y., & Itakura, S. (2011). Developmental correspondence between action prediction and motor ability in early infancy. *Nature communications*, *2*(1), 341. https://doi.org/10.1038/ncomms1342

Kastner, S., Pinsk, M. A., De Weerd, P., Desimone, R., & Ungerleider, L. G. (1999). Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron*, *22*(4), 751-761. https://doi.org/10.1016/S0896-6273(00)80734-5

Kayhan, E., Meyer, M., O'Reilly, J. X., Hunnius, S., & Bekkering, H. (2019). Nine-month-old infants update their predictive models of a changing environment. *Developmental Cognitive Neuroscience*, *38*, 100680. https://doi.org/10.1016/j.dcn.2019.100680

Kersey, A. J., & Emberson, L. L. (2017). Tracing trajectories of audio-visual learning in the infant brain. *Developmental Science*, *20*(6), e12480. https://doi.org/10.1111/desc.12480

Keysers, C., & Perrett, D. I. (2004). Demystifying social cognition: a Hebbian perspective. *Trends in Cognitive Sciences*, *8*(11), 501-507. https://doi.org/10.1016/j.tics.2004.09.005

Köster, M., Kayhan, E., Langeloh, M., & Hoehl, S. (2020). Making sense of the world: infant learning from a predictive processing perspective. *Perspectives on Psychological Science*, *15*(3), 562-571. https://doi.org/10.1177/1745691619895071

Köster, M., Langeloh, M., & Hoehl, S. (2019). Visually Entrained Theta Oscillations Increase for Unexpected Events in the Infant Brain. *Psychological science*, *30*(11), 1656-1663, Article 0956797619876260. https://doi.org/10.1177/0956797619876260

Köster, M., Langeloh, M., Michel, C., & Hoehl, S. (2021). Young infants process prediction errors at the theta rhythm. *NeuroImage*, *236*, 118074. https://doi.org/10.1016/j.neuroimage.2021.118074

Kouider, S., Long, B., Le Stanc, L., Charron, S., Fievet, A. C., Barbosa, L. S., & Gelskov, S. V. (2015). Neural dynamics of prediction and surprise in infants. *Nature communications*, *6*, Article 8537. https://doi.org/10.1038/ncomms9537

Kovács, Á. M., & Mehler, J. (2009a). Cognitive gains in 7-month-old bilingual infants. *Proceedings of the National Academy of Sciences*, *106*(16), 6556-6560. https://doi.org/10.1073/pnas.0811323106

Kovács, Á. M., & Mehler, J. (2009b). Flexible learning of multiple speech structures in bilingual infants. *Science*, *325*(5940), 611-612. https://doi.org/10.1126/science.1173947

Kushnerenko, E. V., Van den Bergh, B. R., & Winkler, I. (2013). Separating acoustic deviance from novelty during the first year of life: a review of event-related potential evidence. *Frontiers in psychology*, *4*, 595. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3763200/pdf/fpsyg-04-00595.pdf

Lejeune, H., Maquet, P., Bonnet, M., Casini, L., Ferrara, A., Macar, F., Pouthas, V., Timsit-Berthier, M., & Vidal, F. (1997). The basic pattern of activation in motor and sensory temporal tasks: positron emission tomography data. *Neuroscience letters*, *235*(1-2), 21-24. https://doi.org/10.1016/S0304-3940(97)00698-8

Limongi, R., Pérez, F. J., Modroño, C., & González-Mora, J. L. (2016). Temporal uncertainty and temporal estimation errors affect insular activity and the frontostriatal indirect pathway during action update: A predictive coding study. *Frontiers in human neuroscience*, *10*, 276. https://doi.org/10.3389/fnhum.2016.00276

Limongi, R., Sutherland, S. C., Zhu, J., Young, M. E., & Habib, R. (2013). Temporal prediction errors modulate cingulate–insular coupling. *NeuroImage*, *71*, 147-157. https://doi.org/10.1016/j.neuroimage.2012.12.078

Maffongelli, L., Antognini, K., & Daum, M. M. (2018). Syntactical regularities of action sequences in the infant brain: When structure matters. *Developmental Science*, *21*(6), e12682. https://doi.org/10.1111/desc.12682

Mahmoudzadeh, M., Wallois, F., Kongolo, G., Goudjil, S., & Dehaene-Lambertz, G. (2017). Functional maps at the onset of auditory inputs in very early preterm human neonates. *Cerebral Cortex*, *27*(4), 2500-2512. https://doi.org/10.1093/cercor/bhw103

McMurray, B., & Aslin, R. N. (2004). Anticipatory eye movements reveal infants' auditory and visual categories. *Infancy*, *6*(2), 203-229. https://doi.org/10.1207/s15327078in0602_4

Meck, W., Hinton, S., & Matell, M. (1998). Coincidence-detection models of interval timing: Evidence from fMRI studies of cortico-striatal circuits. *NeuroImage*, *7*(4), S281. https://doi.org/10.1016/S1053-8119(18)31114-5

Mento, G., Duma, G. M., Valenza, E., & Farroni, T. (2022). Face specific neural anticipatory activity in infants 4 and 9 months old. *Scientific Reports*, *12*(1), 12938. https://doi.org/10.1038/s41598-022-17273-1

Mento, G., & Granziol, U. (2020). The developing predictive brain: How implicit temporal expectancy induced by local and global prediction shapes action preparation across development. *Developmental Science*, *23*(6), e12954. https://doi.org/10.1111/desc.12954

Mento, G., Suppiej, A., Altoè, G., & Bisiacchi, P. S. (2010). Functional hemispheric asymmetries in humans: electrophysiological evidence from preterm infants. *European Journal of Neuroscience*, *31*(3), 565-574. https://doi.org/10.1111/j.1460-9568.2010.07076.x

Mento, G., & Valenza, E. (2016). Spatiotemporal neurodynamics of automatic temporal expectancy in 9-month old infants. *Scientific Reports*, *6*, 36525. https://doi.org/10.1038/srep36525

Morganti, F., Carassa, A., & Riva, G. (2008). *Enacting intersubjectivity: A cognitive and social perspective on the study of interactions* (Vol. 10). Ios Press.

Otte, R., Winkler, I., Braeken, M., Stekelenburg, J., Van der Stelt, O., & Van den Bergh, B. (2013). Detecting violations of temporal regularities in waking and sleeping two-month-old infants. *Biological Psychology*, *92*(2), 315-322. https://doi.org/10.1016/j.biopsycho.2012.09.009

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *International journal of surgery*, *88*, 105906. https://doi.org/10.1016/j.ijsu.2021.105906

Perfors, A., Tenenbaum, J. B., Griffiths, T. L., & Xu, F. (2011). A tutorial introduction to Bayesian models of cognitive development. *Cognition*, *120*(3), 302-321. https://doi.org/10.1016/j.cognition.2010.11.015

Piaget, J. (1971). *Biology and knowledge: An essay on the relations between organic regulations and cognitive processes.* University of Chicago Press.

Preuschoff, K., Quartz, S. R., & Bossaerts, P. (2008). Human insula activation reflects risk prediction errors as well as risk. *Journal of Neuroscience*, *28*(11), 2745-2752. https://doi.org/10.1523/JNEUROSCI.4286-07.2008

Rao, A. K., Marder, K. S., Uddin, J., & Rakitin, B. C. (2014). Variability in interval production is due to timing-dependent deficits in Huntington's disease. *Movement Disorders*, *29*(12), 1516-1522. https://doi.org/10.1002/mds.25998

Rao, R. P., & Ballard, D. H. (1999). Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nature neuroscience*, *2*(1), 79-87. https://doi.org/10.1038/4580

Rao, S. M., Harrington, D. L., Haaland, K. Y., Bobholz, J. A., Cox, R. W., & Binder, J. R. (1997). Distributed neural systems underlying the timing of movements. *Journal of Neuroscience*, *17*(14), 5528-5535. https://doi.org/10.1523/JNEUROSCI.17-14-05528.1997

Rao, S. M., Mayer, A. R., & Harrington, D. L. (2001). The evolution of brain activation during temporal processing. *Nature neuroscience*, *4*(3), 317-323. https://doi.org/10.1038/85191

Rohlf, S., Habets, B., von Frieling, M., & Röder, B. (2017). Infants are superior in implicit crossmodal learning and use other learning mechanisms than adults. *ELife*, *6*, e28166. https://doi.org/10.7554/eLife.28166

Saffran, J. R. (2020). Statistical language learning in infancy. *Child Development Perspectives*, *14*(1), 49-54. https://doi.org/10.1111/cdep.12355

Sebanz, N., & Knoblich, G. (2009). Prediction in joint action: What, when, and where. *Topics in Cognitive Science*, *1*(2), 353-367. https://doi.org/10.1111/j.1756-8765.2009.01024.x

Spencer, R. M., Zelaznik, H. N., Diedrichsen, J., & Ivry, R. B. (2003). Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science*, *300*(5624), 1437-1439. https://doi.org/10.1126/science.1083661

Stern, D. (1985). *The psychological world of the infant*. Basic Books.

Téglás, E., & Bonatti, L. L. (2016). Infants anticipate probabilistic but not deterministic outcomes. *Cognition*, *157*, 227-236. https://doi.org/10.1016/j.cognition.2016.09.003

Trainor, L. J. (2012). Predictive information processing is a fundamental learning mechanism present in early development: Evidence from infants. *International Journal of Psychophysiology*, *83*(2), 256-258. https://doi.org/10.1016/j.ijpsycho.2011.12.008

Tronick, E. Z. (1989). Emotions and emotional communication in infants. *American psychologist*, *44*(2), 112. https://doi.org/10.1037/0003-066X.44.2.112

Wang, S., Tzeng, O. J., & Aslin, R. N. (2022). Predictive brain signals mediate association between shared reading and expressive vocabulary in infants. *PLoS One*, *17*(8), e0272438. https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0272438&type=printable

Wen, W., & Imamizu, H. (2022). The sense of agency in perception, behaviour and human–machine interactions. *Nature Reviews Psychology*, *1*(4), 211-222. https://doi.org/10.1038/s44159-022-00030-6

Werner, L. A., Parrish, H. K., & Holmer, N. M. (2009). Effects of temporal uncertainty and temporal expectancy on infants' auditory sensitivity. *The Journal of the Acoustical Society of America*, *125*(2), 1040-1049. https://doi.org/10.1121/1.3050254

Winkler, I., Háden, G. P., Ladinig, O., Sziller, I., & Honing, H. (2009). Newborn infants detect the beat in music. *Proceedings of the National Academy of Sciences*, *106*(7), 2468-2471. https://doi.org/10.1073/pnas.0809035106

Winkler, I., Kushnerenko, E., Horváth, J., Čeponienė, R., Fellman, V., Huotilainen, M., Näätänen, R., & Sussman, E. (2003). Newborn infants can organize the auditory world. *Proceedings of the National Academy of Sciences*, *100*(20), 11812-11815. https://doi.org/10.1073/pnas.2031891100

Winkler, I., & Schröger, E. (2015). Auditory perceptual objects as generative models: Setting the stage for communication by sound. *Brain and Language*, *148*, 1-22. https://doi.org/10.1016/j.bandl.2015.05.003

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, *269*(5232), 1880-1882. https://www.jstor.org/stable/2889276

Zavala, B., Jang, A., Trotta, M., Lungu, C. I., Brown, P., & Zaghloul, K. A. (2018). Cognitive control involves theta power within trials and beta power across trials in the prefrontal-subthalamic network. *Brain*, *141*(12), 3361-3376. https://doi.org/10.1093/brain/awy266

Zhang, F., Jaffe-Dax, S., Wilson, R. C., & Emberson, L. L. (2019). Prediction in infants and adults: A pupillometry study. *Developmental Science*, *22*(4), e12780. https://doi.org/10.1111/desc.12780

Zhao, T. C., & Kuhl, P. K. (2016). Musical intervention enhances infants' neural processing of temporal structure in music and speech. *Proceedings of the National Academy of Sciences*, *113*(19), 5212-5217. https://doi.org/10.1073/pnas.1603984113