

EARLY SIGNATURE OF AUDITORY TEMPORAL PROCESSING IN PREMATURE NEONATES STUDIED THROUGH HIGH-RESOLUTION ELECTROENCEPHALOGRAPHY

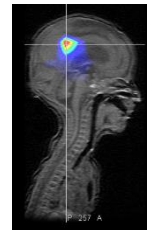
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GRAMFC

Groupe de Recherche sur l'Analyse Multimodale de la Fonction Cérébrale

INSERM U1105



Rhythm

The relative temporal relationship of auditory events

Temporal regularities are present at multiple hierarchical levels in both music and speech.

Temporal grouping of auditory events and perception of rhythmic patterns is central to how we recognize structure in sound sequences.

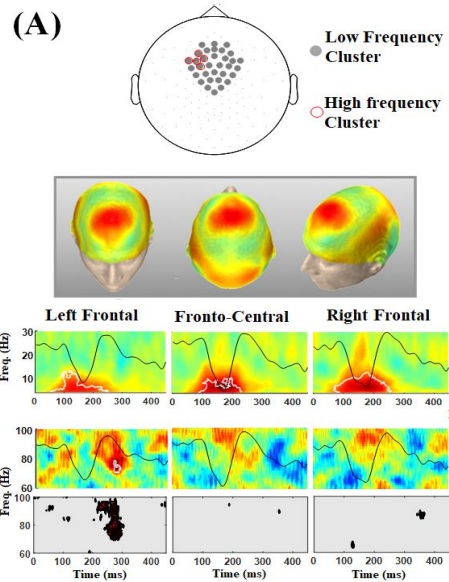
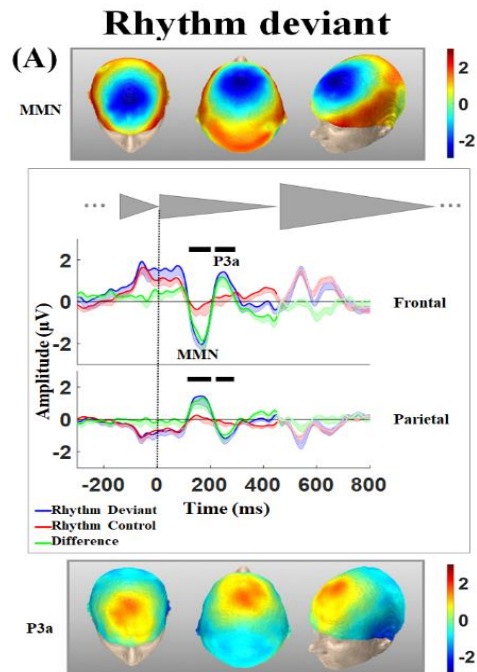
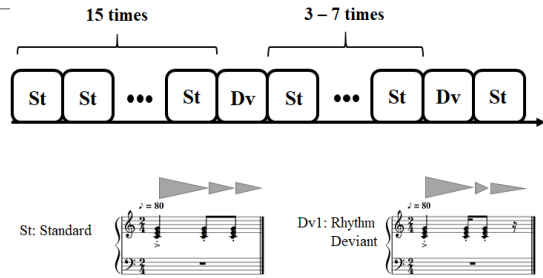
Rhythm tree over the first measure

The image shows a musical staff with a treble clef and a common time signature (C). The melody consists of 12 notes. A rhythm tree is drawn above the first measure, showing a hierarchical structure of groupings. Below the staff, a sequence of fractions and integers represents the relative durations of the notes. A green 'Count' line is positioned below the fractions, with numbers 1 through 12 aligned with each note.

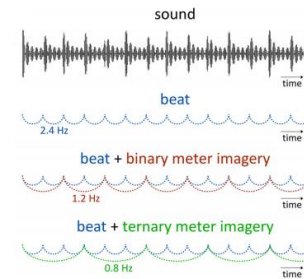
1 $\frac{1}{2}$ $\frac{1}{2}$ 1 $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ 2 $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{3}$ $\frac{3}{2}$ 1 $\frac{1}{2}$

Count 1 2 3 4 5 6 7 8 9 10 11 12

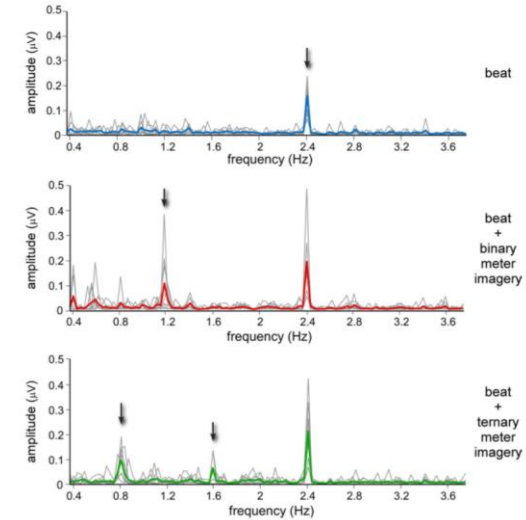
Rhythm Processing in the adult brain



(Edalati et al. 2020)



Entrainment to rhythm

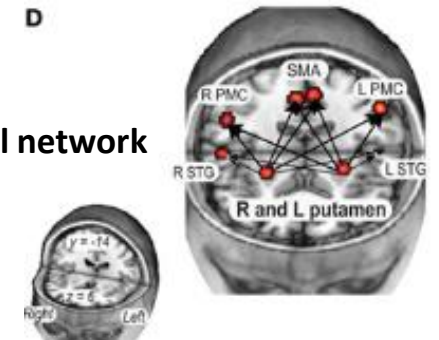


(Nozardan et al. 2011)

Detection of rhythm deviant and the underlying oscillatory activity

Underlying functional network

(Grahn et al. 2009)



Rhythm and Temporal Regularities

Rhythm is particularly an important feature of acoustic events because its temporal regularity enables predictions about upcoming sounds.



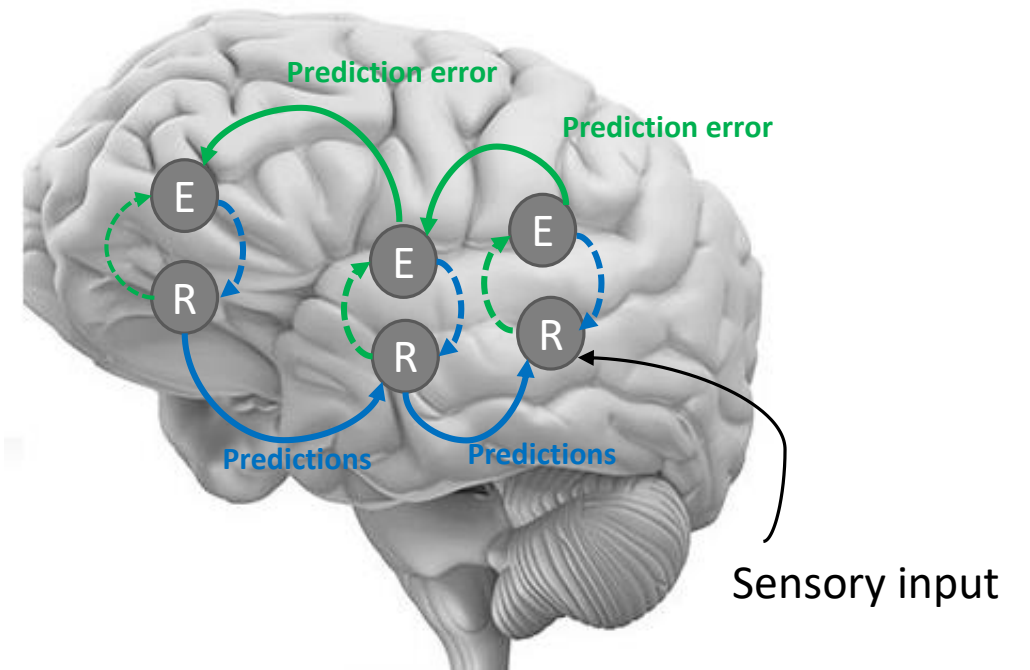
Rhythmic stream →

Dynamic prediction of **when** →

Rhythm and Temporal Regularities

higher level systems provide a prediction of the inputs to lower level regions and lower regions respond to failures to predict with an error term, which is propagated to higher areas.

Auditory acoustic regularities are transformed into predictions about current sensory signals via the interaction of E and R populations.

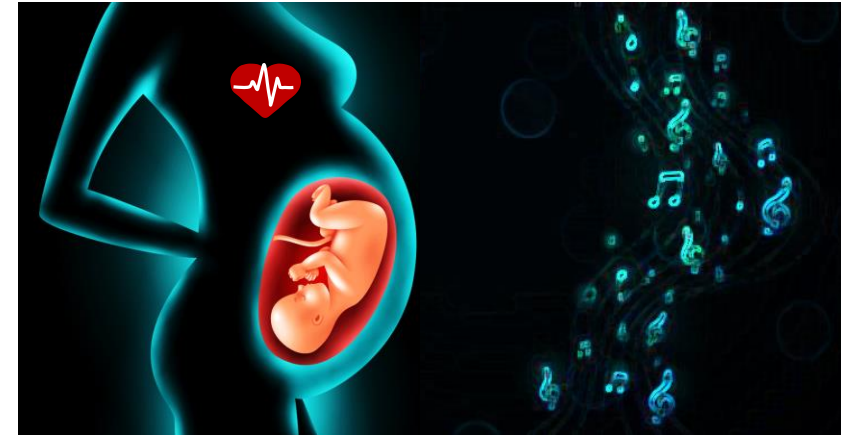


Rhythm processing, an early developing process

As early as twenty-five weeks gestational age (wGA), hearing is operational.

The fetus hears the isochronous rhythm of the maternal heartbeat, and respiration

Despite the attenuation of sound and distortion of its frequency content by the maternal tissue, the rhythmic information is preserved.



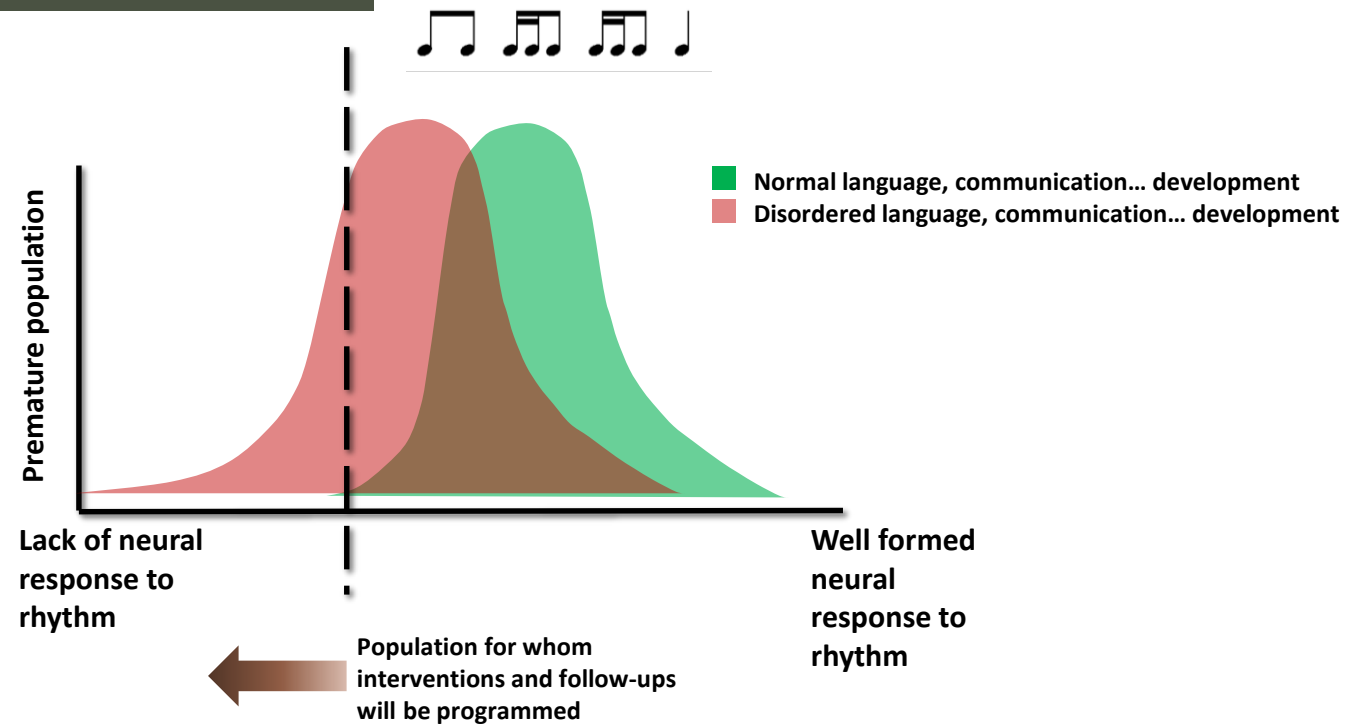
Deprivation of patterned sound experience and exposure to the extra-uterine environment could cause suboptimal auditory development.



Why rhythm

Rhythm processing in premature neonates, a developmental neurobiomarker of auditory temporal processing?

The first step characterization of the neural response...



Rhythm Perception in early development

- Can the premature neonate entrain to a rhythm? At what level? What are the underlying mechanisms?
- Can the premature neonate detect the violations from regular rhythmic structures? What are the underlying mechanisms?

Rhythm Perception, entrainment to an ambiguous rhythm

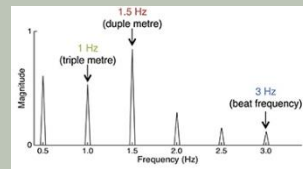
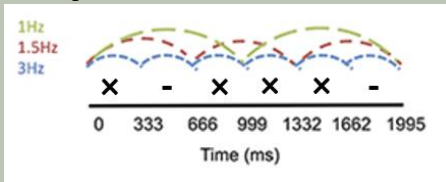
Can the premature brain group the auditory events as does the adult brain?

A combination of sounds and silence

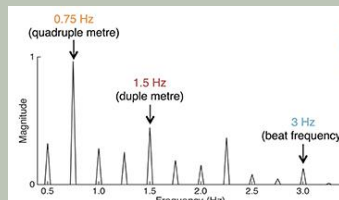
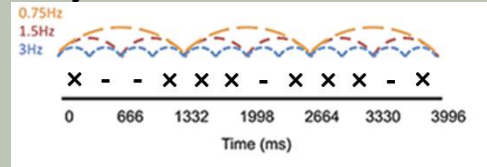
Each sound a combination of drum sounds

Beat inter-onset-interval 333 ms

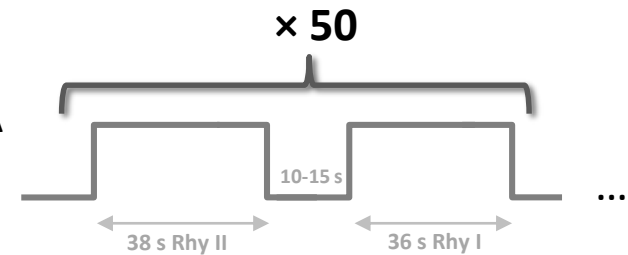
Rhythm I



Rhythm II

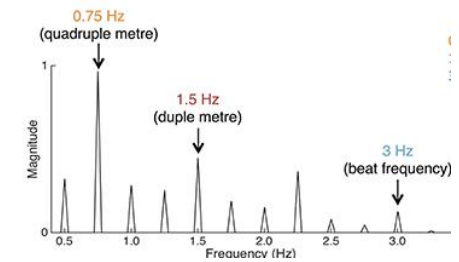
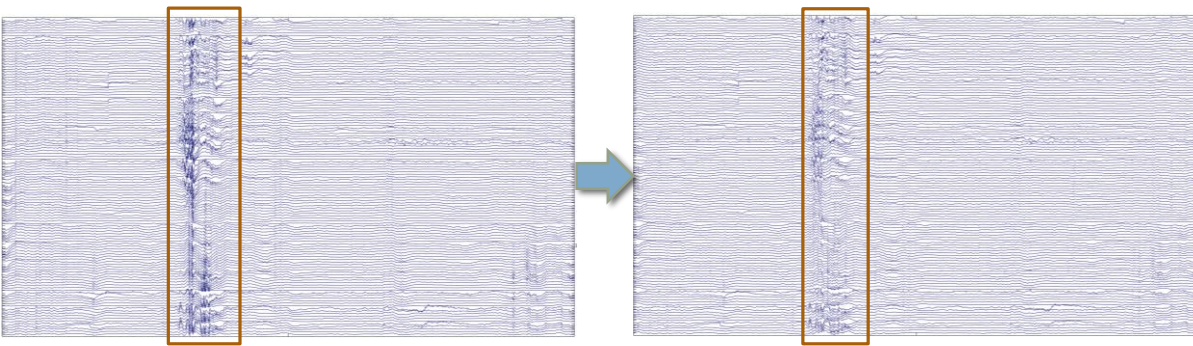


15 premature healthy neonates 29-34 wGA
50 blocks of 20 repetition for each rhythm
128 EEG recordings



In collaboration with Laurel Trainor, McMaster Institute for Music and the Mind, McMaster University, Canada

Rhythm Perception, entrainment to an ambiguous rhythm



$$Y_{ij} = \begin{cases} X_{ij} & |X_{ij}| < \theta \\ 0, & \text{otherwise} \end{cases} \text{ for } i=1, \dots, n, \quad j=1, \dots, T.$$

$$\hat{\mathbf{B}} = \arg \min_{\mathbf{B}} \sum_{t=1}^T \|\mathbf{B}\mathbf{x}_t - \mathbf{y}_t\|_2$$

Entrainment response to beat and meter frequencies

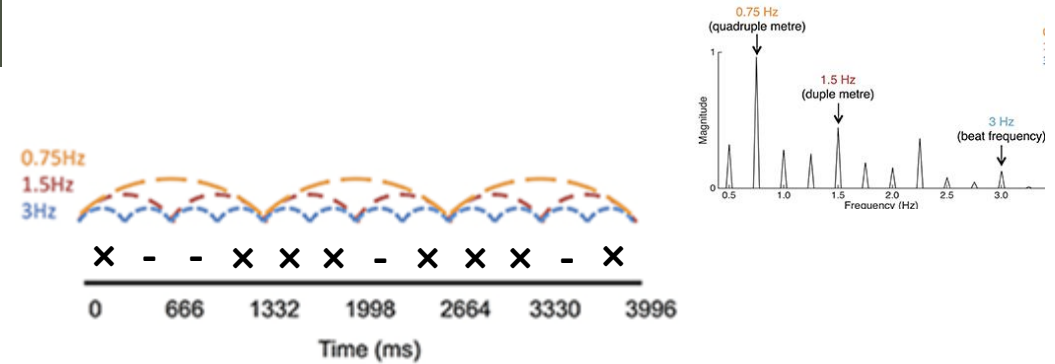
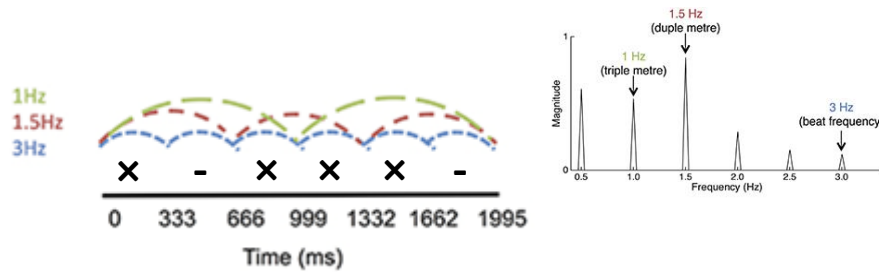
HR- EEG

Preprocessing
Block averaging

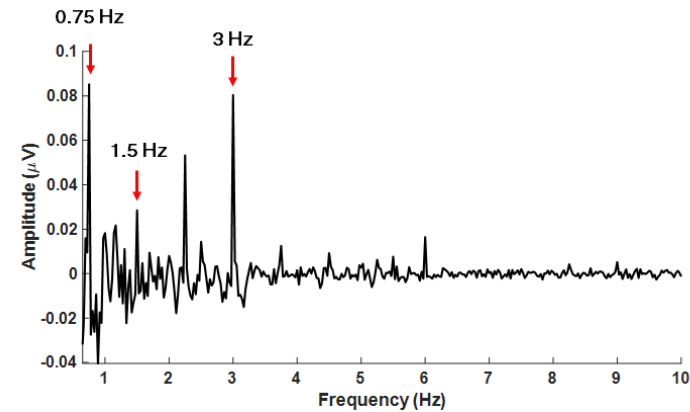
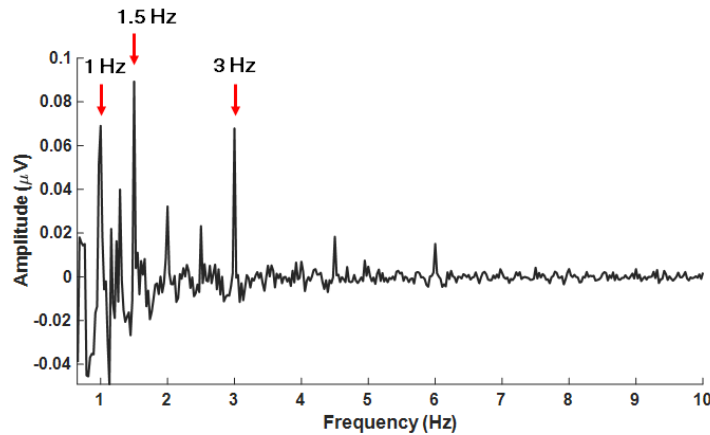
Fourier transform
Normalization

Rhythm Perception, entrainment to an ambiguous rhythm

Both stimuli elicited clear EEG responses frequency-locked to the rhythms, at frequencies corresponding to both beat and meter.



Frequency
Tagging
Analysis



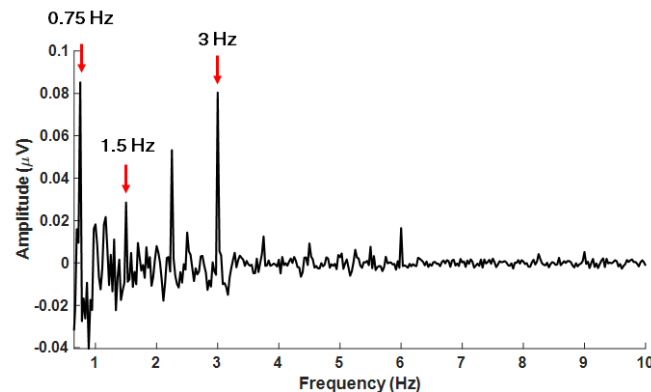
Grand average

Premature neonate entrains to both beat and meter frequencies, and hence groups the auditory events

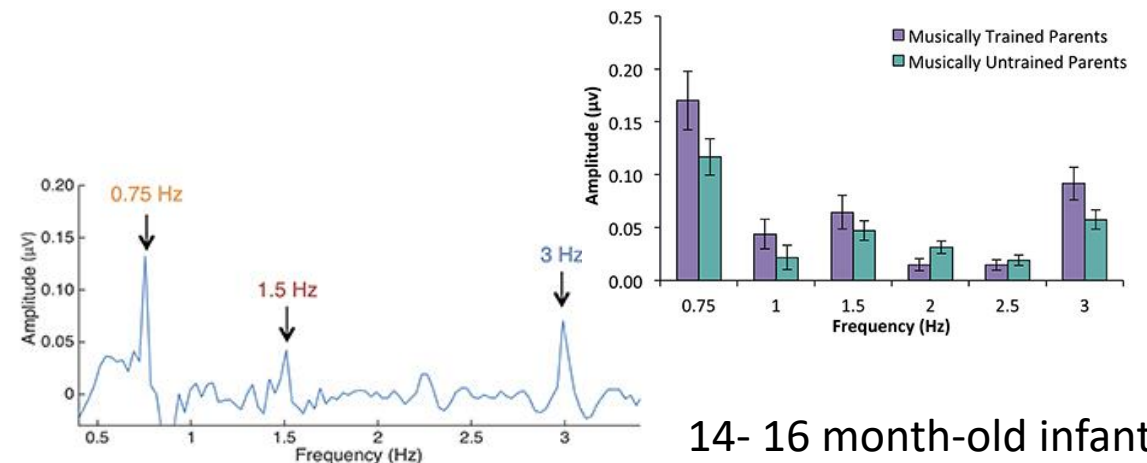
Rhythm Perception, entrainment to an ambiguous rhythm

Extracting the beat information and grouping these beats into metrical hierarchies

- The role of premature birth on this process
- Its evolution in the course of development
- The underlying functional networks



29- 34 wGA premature neonates



14- 16 month-old infants

Cirelli et al. 2016

What is the functional neural networks underlying this process?

Rhythm Perception in early development

- Can the premature neonate entrain to a rhythm? At what level?
- Can the premature neonate detect the violations from regular rhythmic structures? What are the underlying mechanisms?

Rhythm Perception, violation detection

How violation of rhythmic structures is processed in the premature brain? What are the underlying mechanisms?

A simple rhythm in 2:4 meter with pure tones of 990 Hz.
A 25% accent on the first beat to reinforce the meter

Rhythm tree



Standard



Rhythm deviant

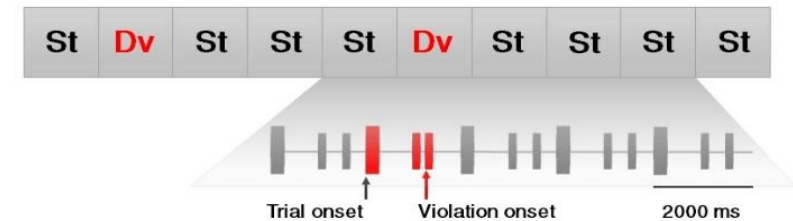
- 19 healthy premature neonates born at **30-34 wGA**, tested during the first week of life

- Paradigm: **oddball**

- **128-electrode EEG recording**



(A)



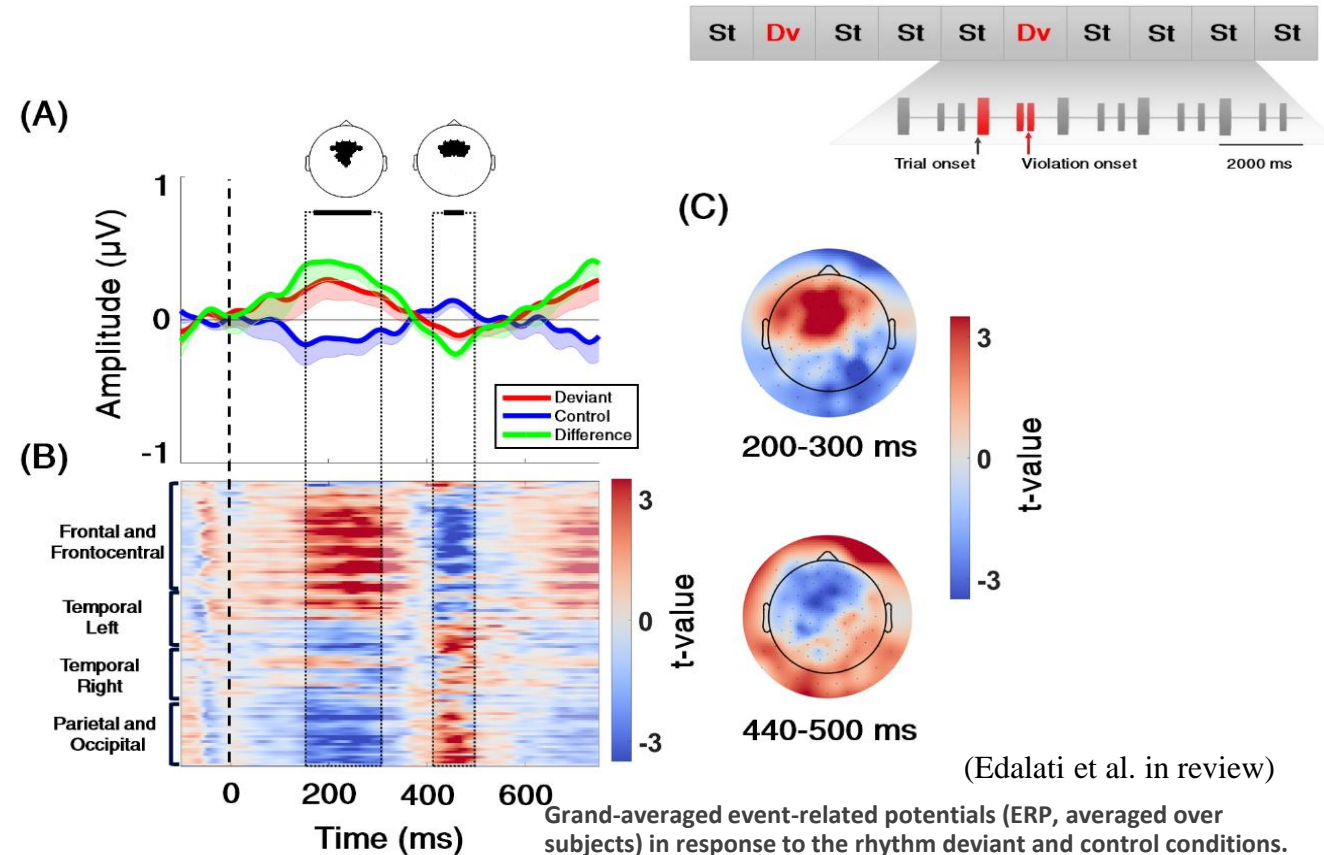
(B)



Rhythm Perception, violation detection

Rhythm deviant elicited an MMR that was followed by a subsequent negative deflection.

Soon after the onset of the establishment of thalamocortical circuits for auditory perception, the premature brain detect the violation from a rhythmic structure



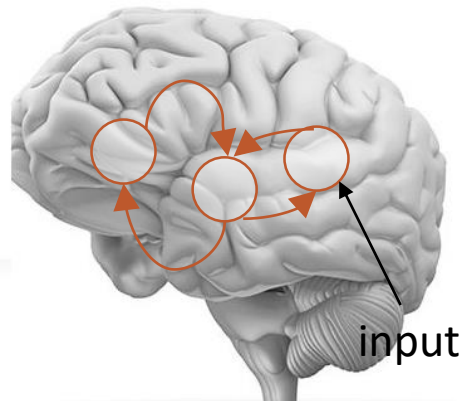
Premature brain creates a mismatch response to deviation from a regular rhythmic structure

Rhythm Perception in early development

- Can the premature neonate entrain to a rhythm? At what level?
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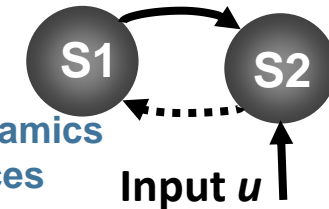
Dynamic Causal Modeling

To make inferences about the effective connectivity between predefined sources and the modulation of the connection by the task



Dynamic Causal Modelling

Assume that ERPs are generated by temporal dynamics of a network of a few sources



Describe temporal dynamics Within and between sources by differential equations $\dot{x} = f(x, u, \theta)$

Each source projects to the sensors, following forward modeling



Solve for the model parameters using Bayesian model inversion

$$p(\theta | y, m)$$
$$p(y | m)$$

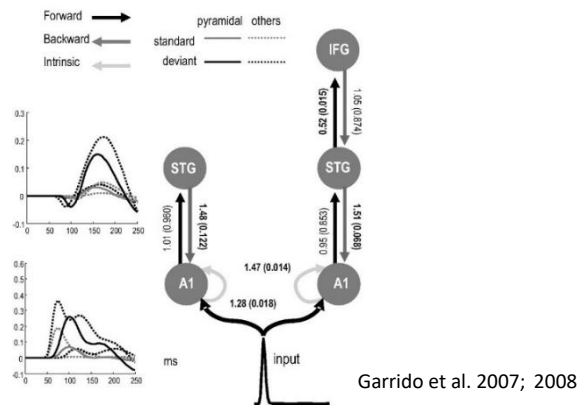
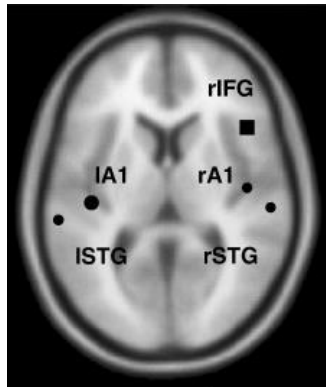
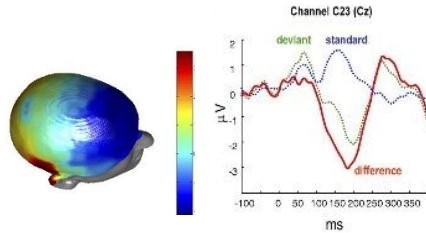
David et al. 2006
Garrido et al. 2007

Rhythm Perception, an immature mechanism?

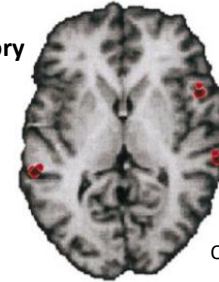
In adults

Neural effective connectivity underlying the mismatch negativity

Mismatch response to frequency deviation

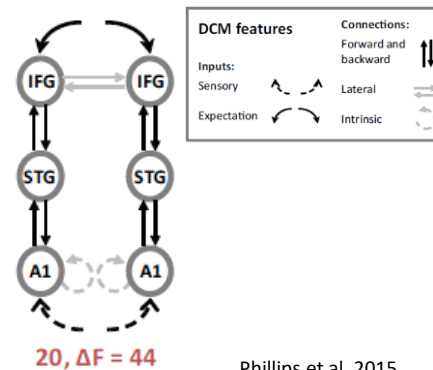


Activated regions in response to auditory change detection

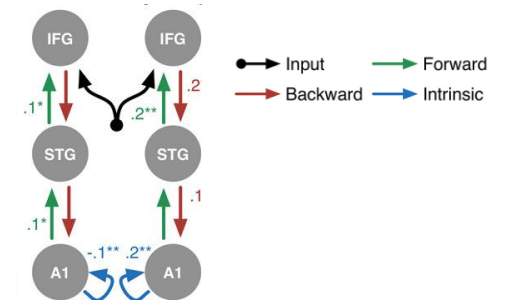


Opitz et al. 2002

Mismatch response to duration deviation

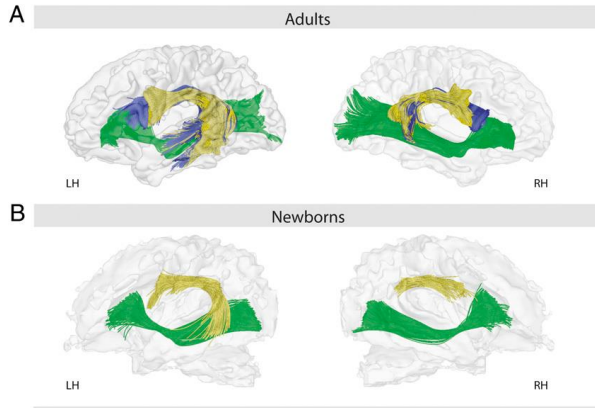


Mismatch response to omission

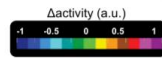
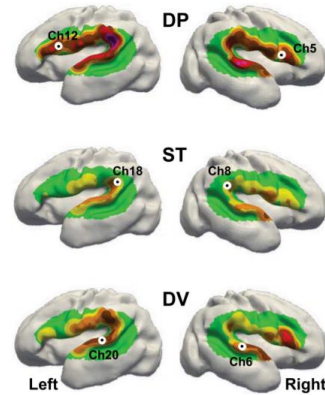


Chennu et al. 2016

Rhythm Perception, an immature mechanism?



- Dorsal pathway: Part of the AF/SLF connecting to Broca's area
 - Dorsal pathway: Part of the AF/SLF connecting to precentral gyrus premotor cortex
 - Ventral pathway connecting the ventral portion of the inferior frontal gyrus to the temporal cortex via the extreme fiber capsule system
- Perani et al. 2011

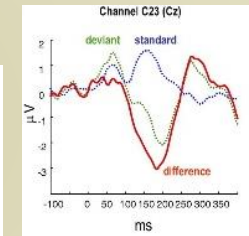
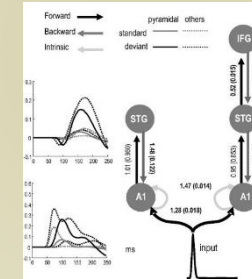
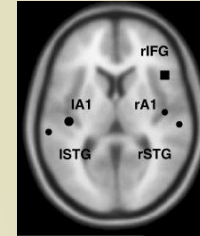


Mahmoudzadeh et al. 2013

Activation of the frontal cortex during mismatch response in premature neonates

In adults

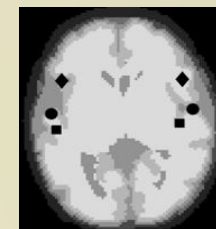
Neural effective connectivity underlying the mismatch negativity



Garrido et al. 2008

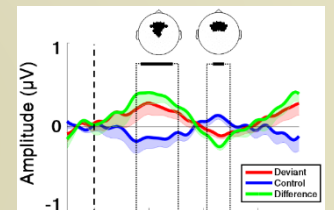
In premature neonates

Neural effective connectivity underlying the mismatch response



- ◆ IFG
- STG
- A1

?

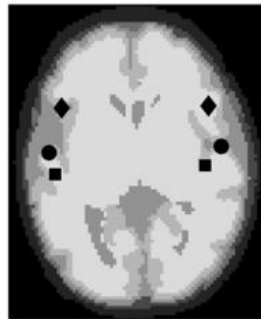


Rhythm Perception, an immature mechanism?

In the premature brain

- Is rhythm processing a low-level processing limited to the primary auditory cortex?
- Or does it involve a hierarchy of cortical processing with bottom-up and top-down dialogs?

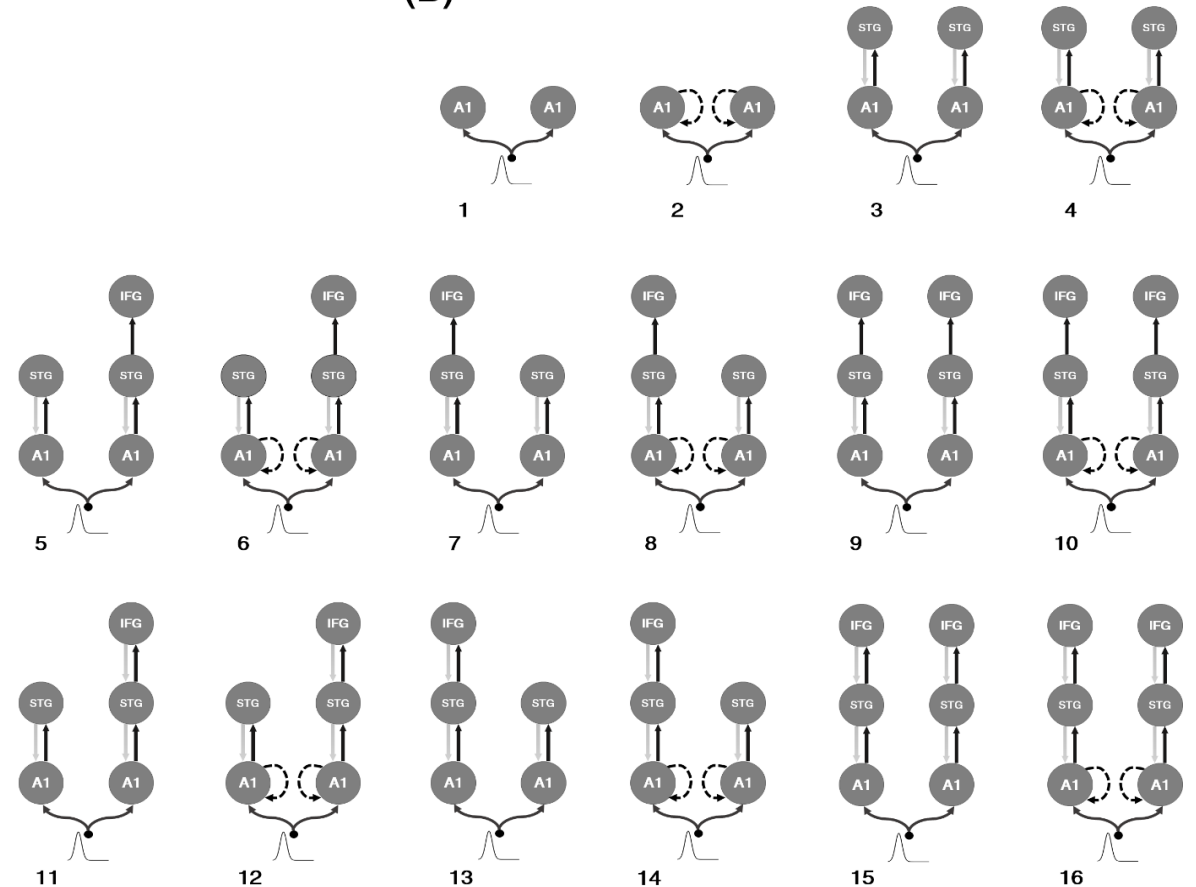
(A)



- ◆ IFG
- STG
- A1

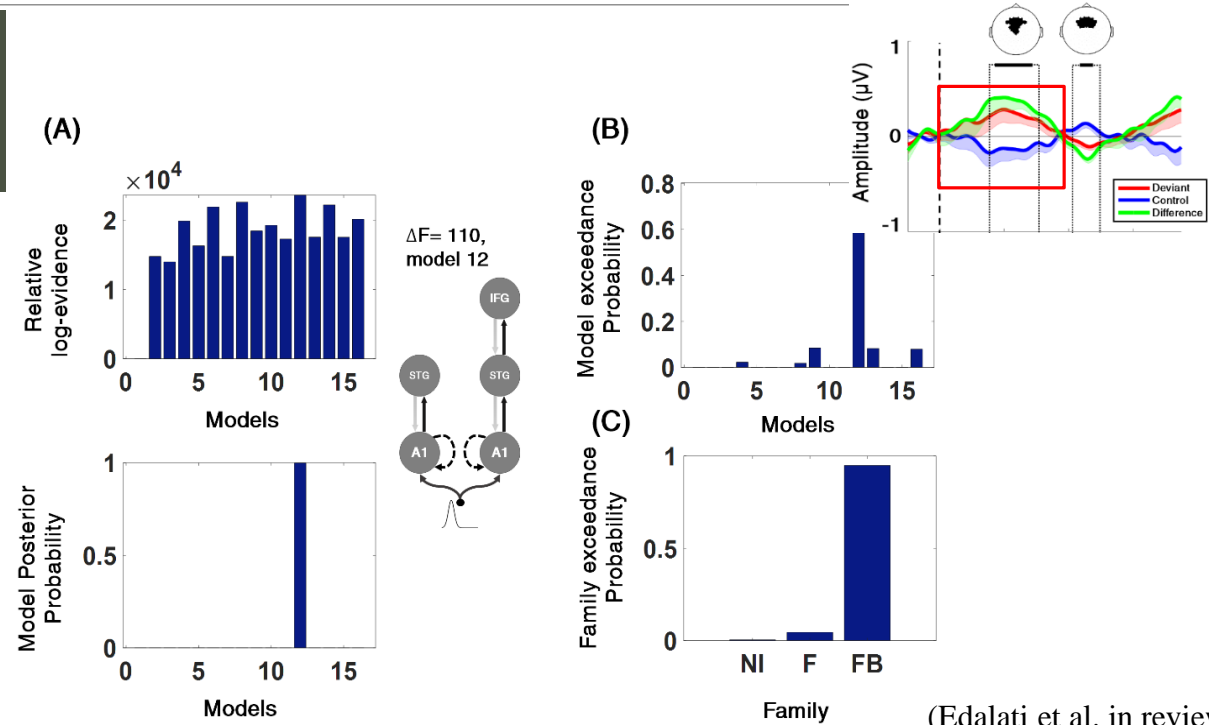
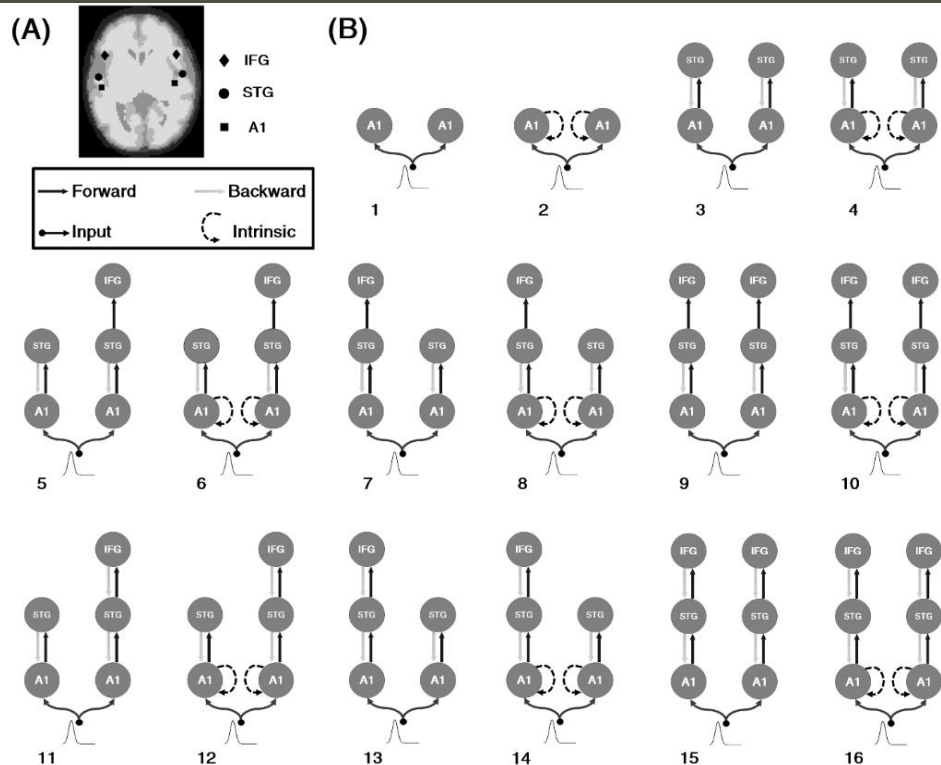
A1, primary auditory cortex; STG, superior temporal gyrus; IFG, inferior temporal gyrus

(B)



Rhythm Perception, an immature mechanism?

Processing of rhythm deviation in the premature brain is not limited to the primary auditory areas, and as in the case of adults, encompass a hierarchy of temporo-frontal cortical structures in a bottom-up and top-down stream.



(Edalati et al. in review)

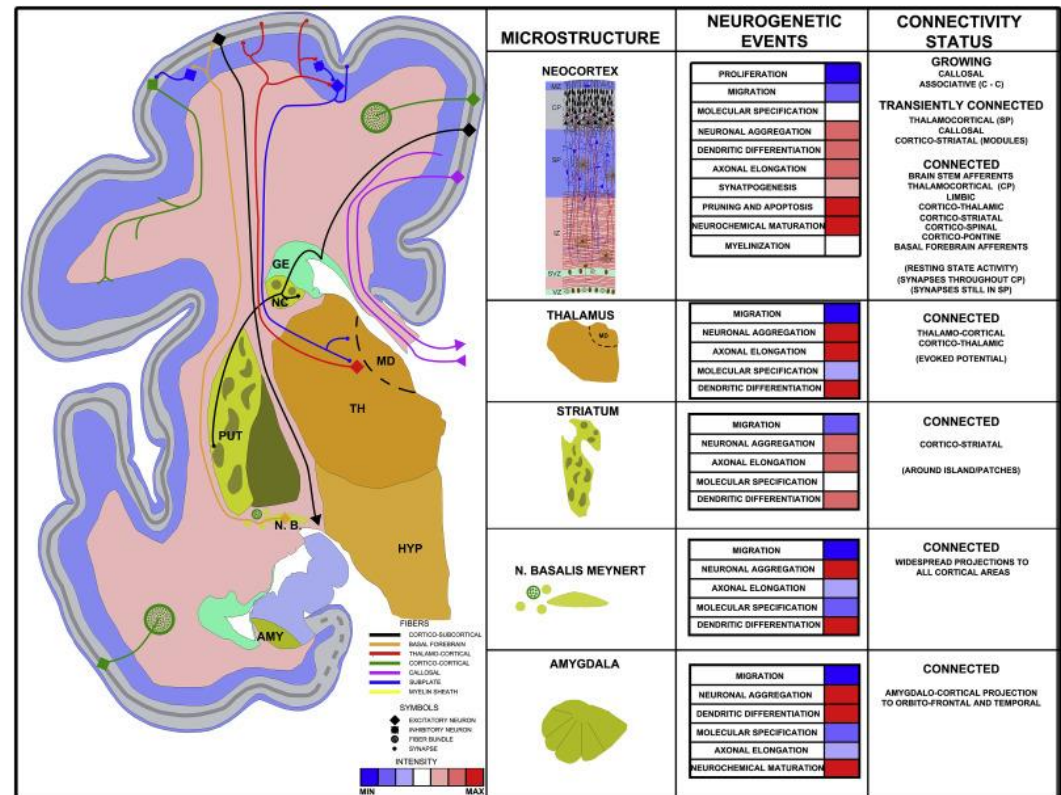
Bayesian model selection over the 16 tested networks. The investigated model families: NI, no IFG models (1 - 4); F, models with only Forward connections between STG and IFG (5 - 10); FB, models with Forward and Backward connections between STG and IFG (11 - 16).

The winning model have both forward and backward connections with the frontal cortex.

Limitations

The neural network dynamics

The local excitatory-inhibitory interactions



Kostovic et al. 2019

Conclusions

Back to the questions

- Can the premature neonate entrain to a rhythm? At what level?
- Can the premature neonate detect the violations from regular rhythmic structures? What are the underlying mechanisms?

What is next?

- From a simple rhythm to more complex structures
- The evolution of the response in the course of development
- The impact of prematurity

Thank you for your attention!