Computational Modelling of Auditory Processing in the Brain

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Overview

1. The Problem: A Cacophony of Sound
2. Model of Auditory Cortex and Recent Results
3. Ongoing and Future Pursuits

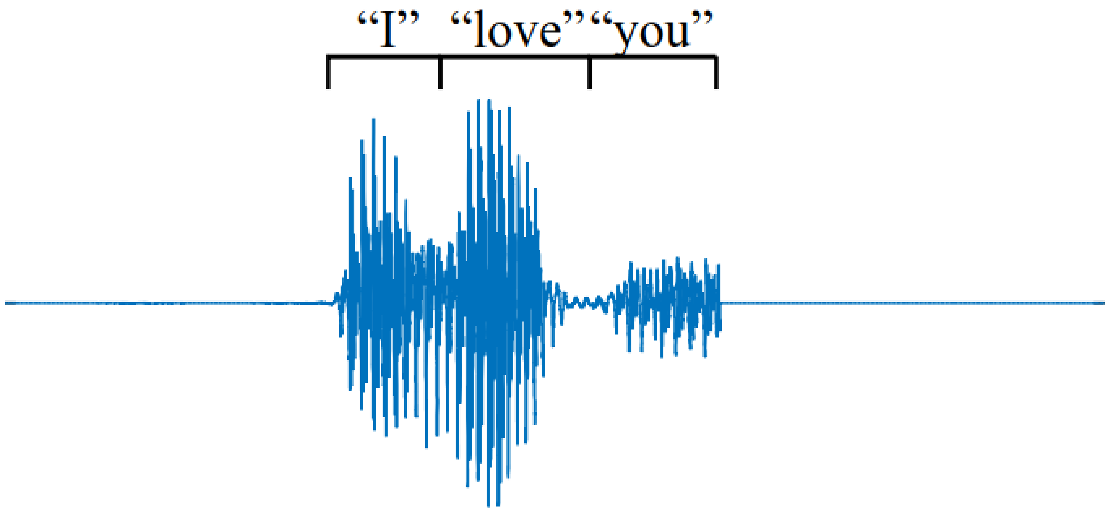
1. The Problem: a Cacophony of Sound

The Complexity of Hearing

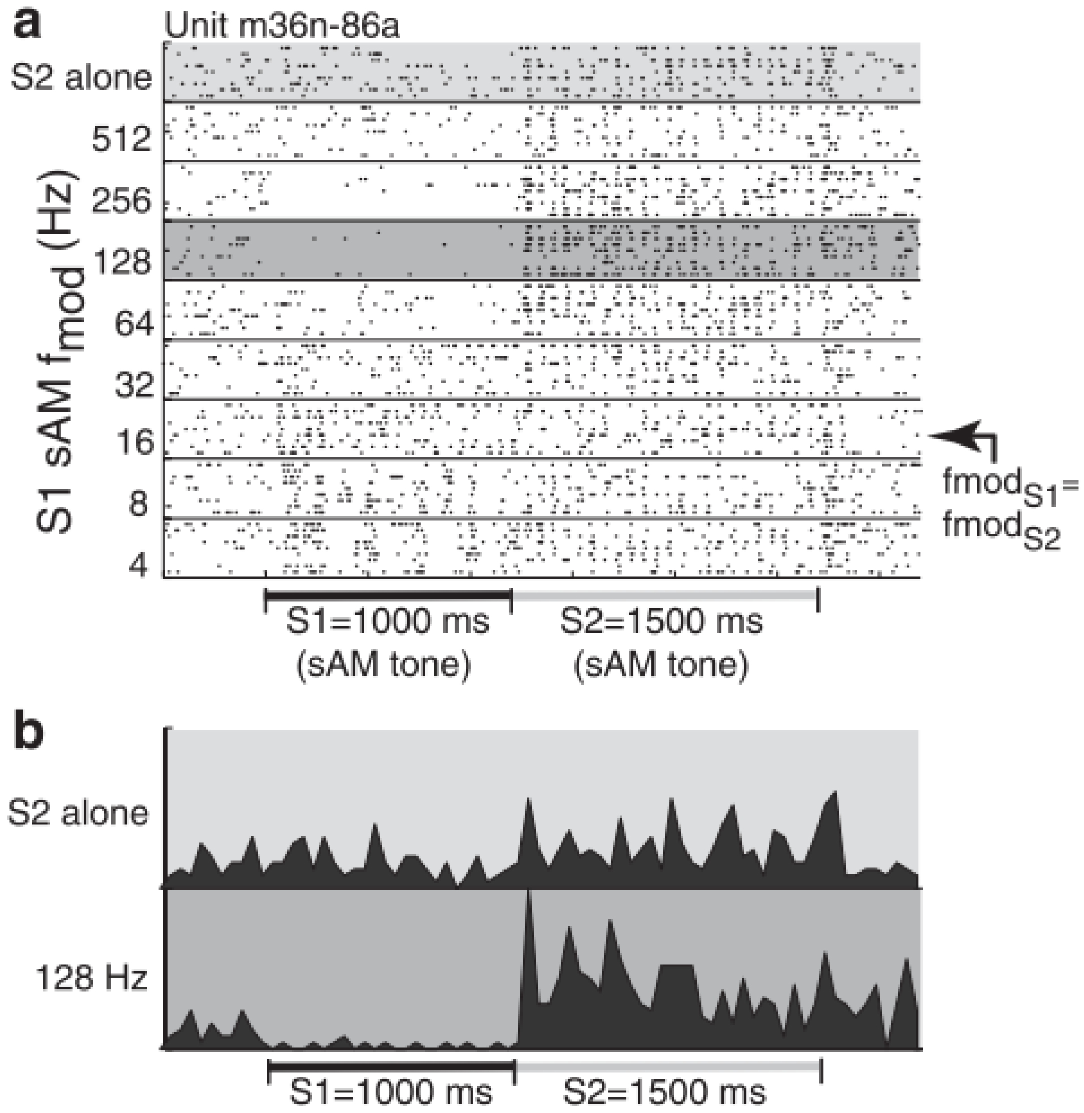
- The input signal to the auditory system is a set of two one-dimensional time series, one hitting each ear drum.
- In natural environments, the time series represent the superposition of multiple overlapping sound sources.
- From this time series data the auditory system is able to extract vast amounts of information
  - Separation of sound sources
  - Location of each source in 3D
  - Assignation of meaning to each source

The Problem of Time

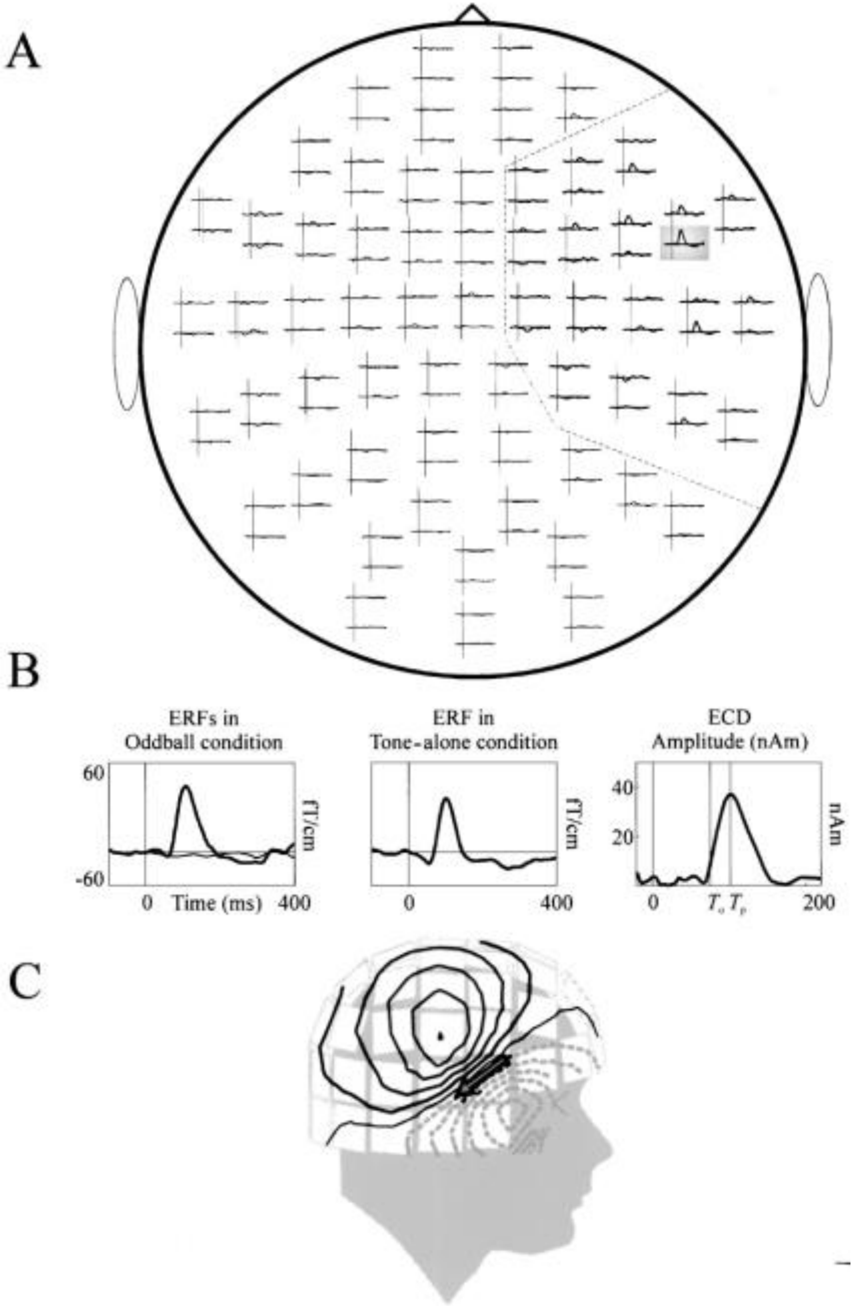
- Frequency is represented in tonotopic maps in the auditory system.
- Sound meaning is completely context-dependent.
- How is information integrated over time? Some kind of memory is required, but what?



Animal and Human Data



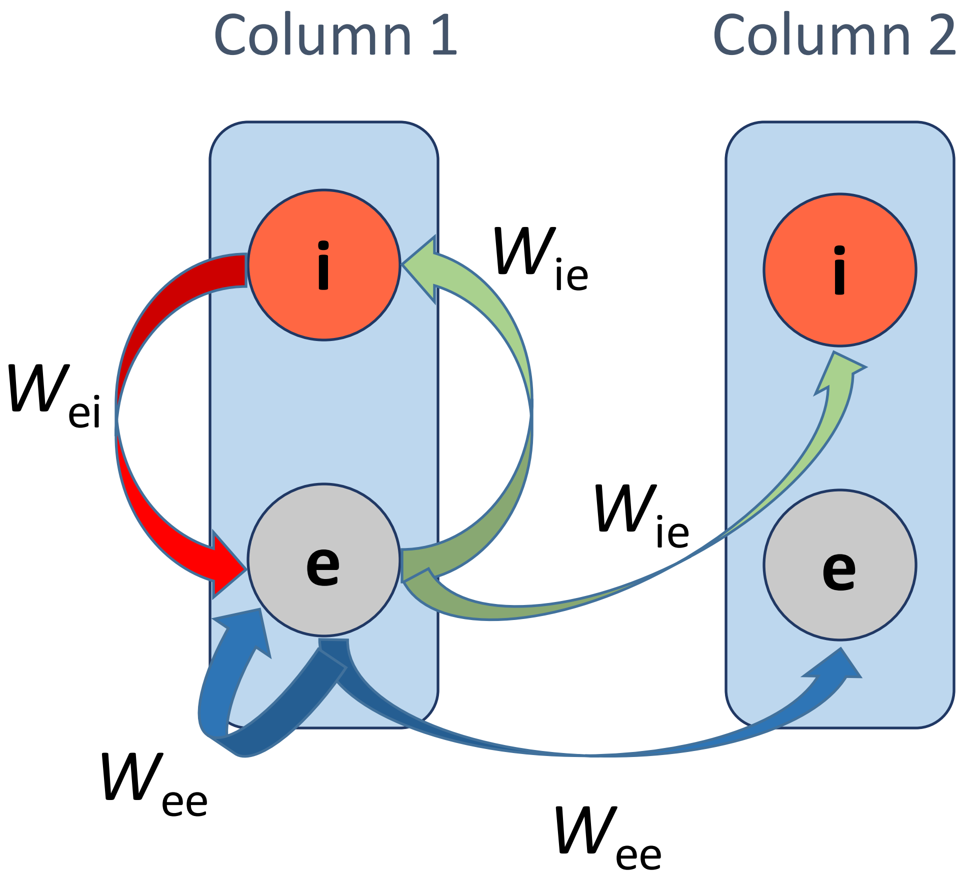
Bartlett & Wang (2005) J. Neurophysiol.



May et al. (1999) *J. Comput. Neurosci.*

2. Model of Auditory Cortex & Recent Results

The Column: Computational Unit



- The cortex has granular, column structure.
- A column is a complex, local (vertical) collection of neurons which have similar response properties.
- We cut though the complexity, and model the column in the simplest possible way.

i: inhibitory population

e: excitatory population

W_{ee}, W_{ie}, W_{ie}

connectivity matrices

Neural Dynamics

Equations describing neural interactions: LIN firing rate model

Hopfield & Tank, 1986; May et al. 2010, 2013, 2015

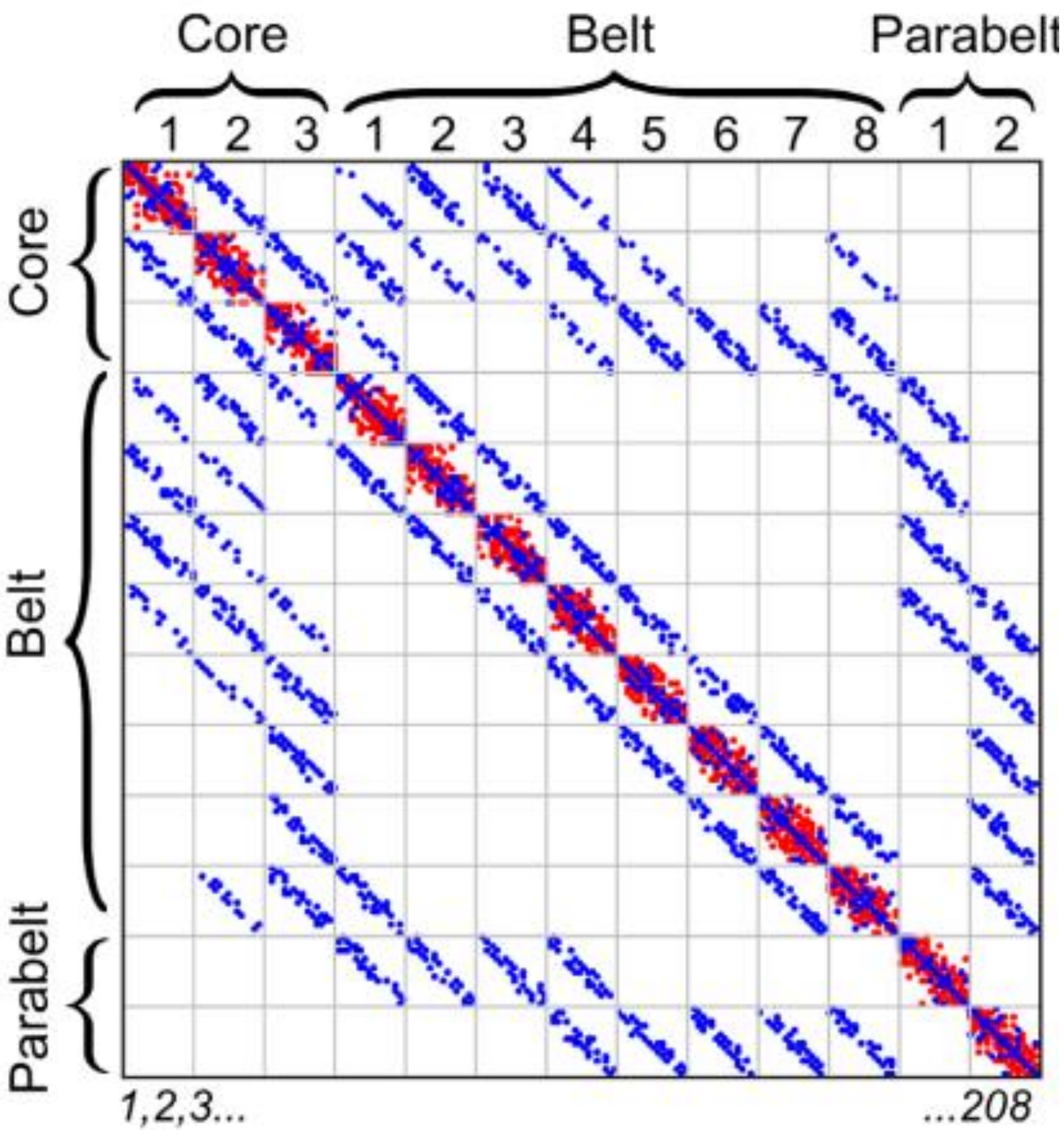
$$\tau_{\mathrm{m}} \frac{d\boldsymbol{u}(t)}{dt} = -\boldsymbol{u}(t) + A_{\mathrm{ee}}(t).* W_{\mathrm{ee}}.\, g[\boldsymbol{u}(t)] - W_{\mathrm{ei}}.\, g[\boldsymbol{v}(t)] + \boldsymbol{I}_{\mathrm{aff}}(t)$$

$$\tau_{m} \frac{d\boldsymbol{v}(t)}{dt} = -\boldsymbol{v}(t) + A_{ie}(t).* W_{ie}.\, g[\boldsymbol{u}(t)]$$

$\boldsymbol{u}$	state variable of excitatory cell population
$\boldsymbol{v}$	state variable of inhibitory cell population
τ_{m}	membrane time constant
g	firing rate – nonlinear function of u and v
$\boldsymbol{I}_{\mathrm{aff}}$	afferent input from auditory pathway
W_{ee} W_{ie} W_{ei}	connectivity matrices
A_{ee} A_{ie}	synaptic plasticity (adaptation) terms
t	time

Model Construction

- AC has multiple fields (each defined by tonotopic map)
- Multiple *Core-Belt-Parabelt* streams: feedforward activation progresses *serially* from core to belt to parabelt fields along many, *parallel* routes.
- This structure can be translated into the weight matrices W_{ee}, W_{ie}, and W_{ei}



Simulations

Major advantage over real experiments: Modelling allows us to simulate non-invasive MEG (summed activity of columns) and to simultaneously observe ”invasive” activity on the single-column level.

Single-column (firing rate) observations:

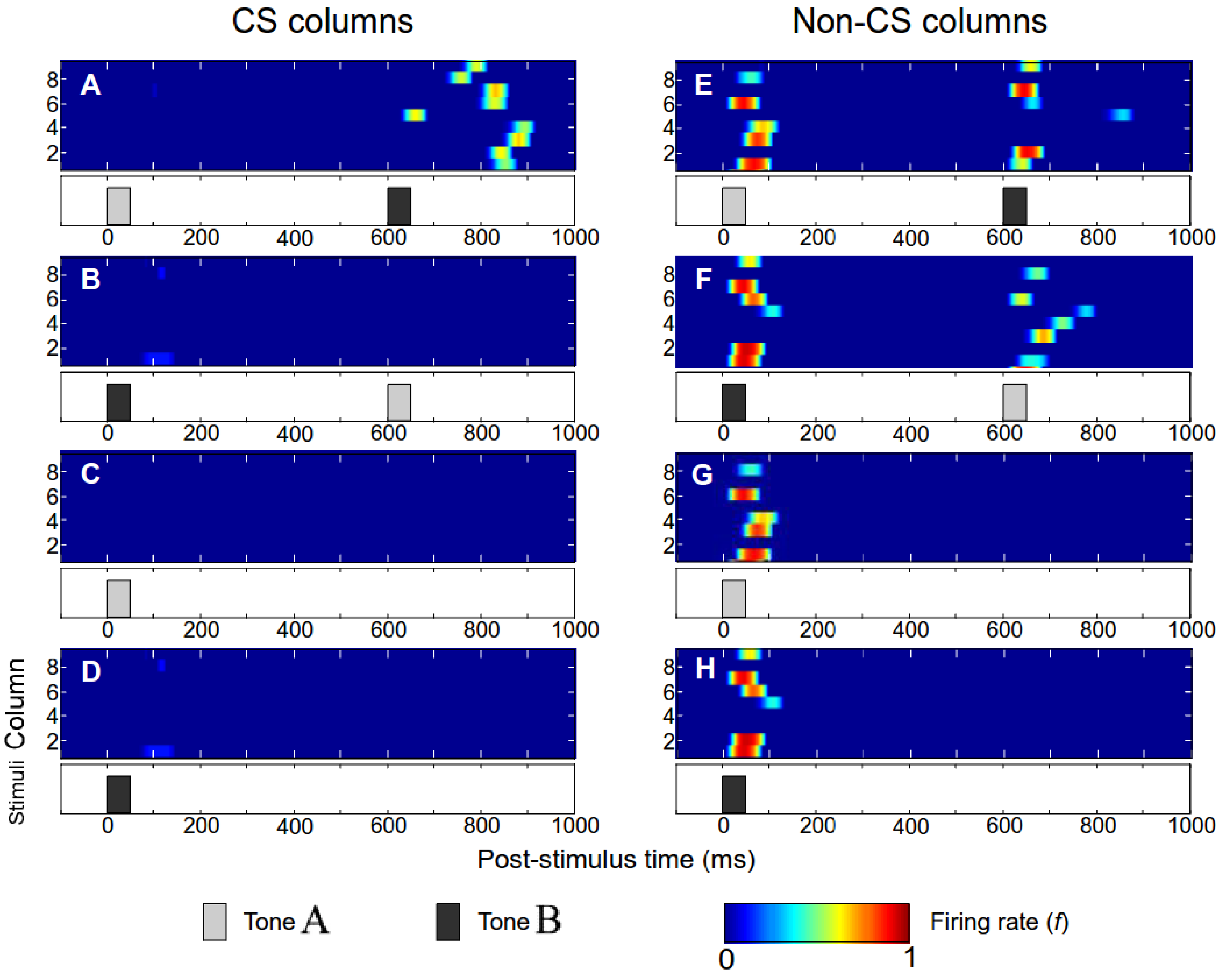
- Forward masking: stimulus repetition leads to suppressed responses.
- Stimulus-specific adaptation (SSA): response recovery by stimulus change (i.e,. supression in not generalized).
- Two-tone facilitation: With AB tone pairs, response to tone B is enhanced if preceeded by tone A
- Temporal intergration: tuning to the temporal structure of tone sequences, speech stimuli, and monkey calls.

MEG (summed activity) observations:

- Adaptation: stimulus repetition leads to suppressed responses.
- Mismatch responses: Statistical structure of stimulation is reflected in response amplitude.
- Temporal intergration: mismatch responses also when tones are replaced by more complex stimuli.
- These MEG effects can be traced back to single-column behaviour

Temporal Binding of Tone Pairs

- Columns are tuned to the temporal structure of stimulation.
- Combination sensitivity (CS): selectivity to pair AB vs. (1) reveresed pair BA, (2) isolated tones (A or B).
- This phenomenon has mystified auditory neuroscientists.
- Explanation: CS is due to synaptic depression (adaptation) and the serial structure of AC (May & Tiitinen, 2013; May et al. 2015).
- Similar CS for four-tone sequences, speech sounds, & monkey calls



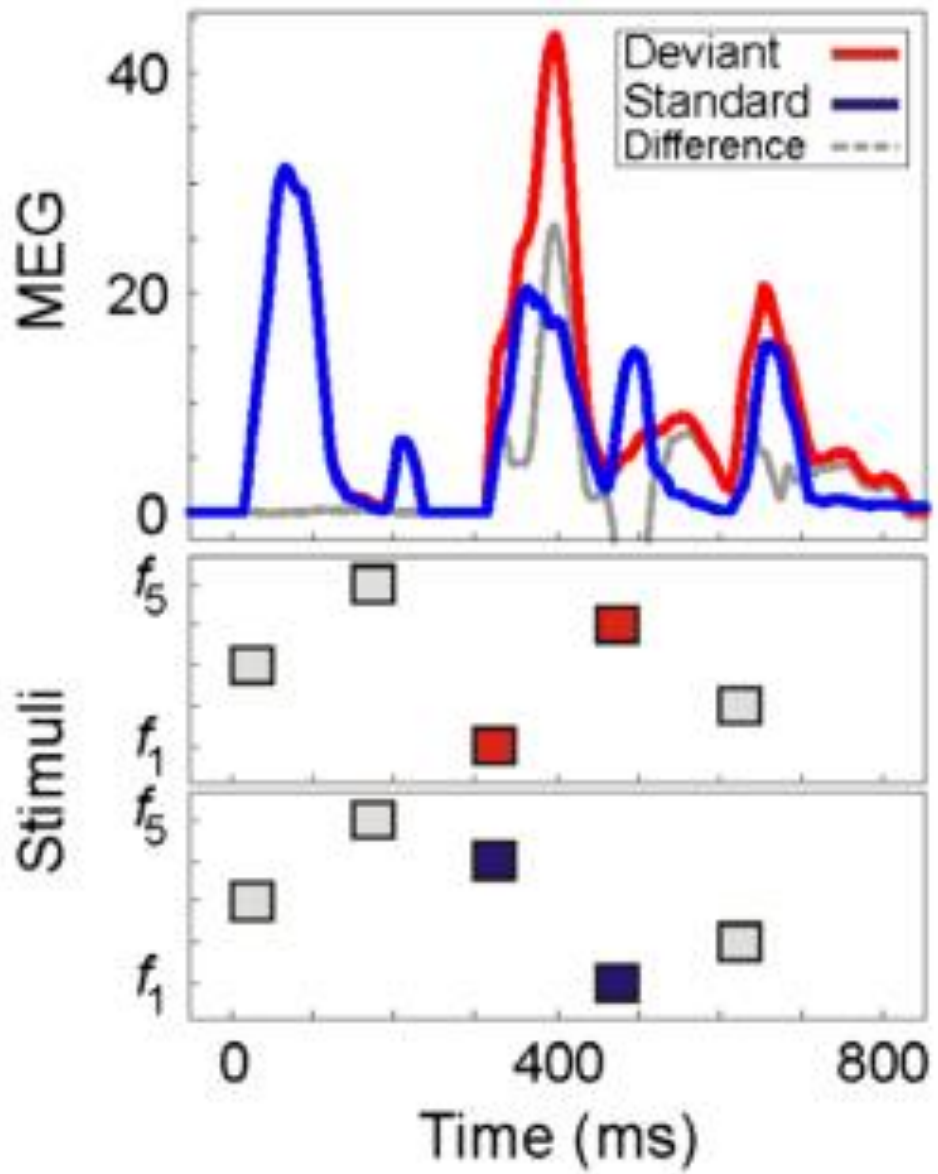
May et al. (2015) *EJNS*

MEG Examples

- Presenting a stimulus (A) repeatedly leads to attenuated MEG responses
- When the series of repeated stimuli is interrupted by a stimulus with a different structure (B), the MEG response is much larger.

  A A A A A A B A A A A A A A B A A A A A B A ...

- This phenomenon is the so-called mismatch response, and its neural origins have been hotly debated for two decades.
- Our computational approach has provided an adaptation-based explanation which replaces a previous, more complex, information-processing models (May & Tiitinen, 2010).



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3. Ongoing and Future Pursuits

Analytical Approach

$$\tau_{\mathrm{m}} \frac{d\boldsymbol{u}(t)}{dt} = -\boldsymbol{u}(t) + A_{\mathrm{ee}}(t) .* W_{\mathrm{ee}} .\, g[\boldsymbol{u}(t)] - W_{\mathrm{ei}} .\, g[\boldsymbol{v}(t)] + \boldsymbol{I}_{\mathrm{aff}}(t)$$

Analytical Approach

Linearization (slow adaptation, quasi-static)

$$\ddot{\mathbf{u}}(t) + 2\Gamma\dot{\mathbf{u}}(t) + \Omega_0^2\mathbf{u}(t) = \mathbf{q}(t)$$

$$\frac{\widetilde{W}_{\mathrm{ei}}\widetilde{W}_{\mathrm{ii}}\widetilde{W}_{\mathrm{ei}}^{-1} - \widetilde{W}_{\mathrm{ee}}}{2} = \Gamma$$

$$\widetilde{W}_{\mathrm{ei}}\widetilde{W}_{\mathrm{ie}} - \widetilde{W}_{\mathrm{ei}}\widetilde{W}_{\mathrm{ii}}\widetilde{W}_{\mathrm{ei}}^{-1}\widetilde{W}_{\mathrm{ee}} = \Omega_0^2$$

$$\widetilde{W}_{\mathrm{ei}}\widetilde{W}_{\mathrm{ii}}\widetilde{W}_{\mathrm{ei}}^{-1}\mathbf{I}_{\mathrm{e}}(t) - \widetilde{W}_{\mathrm{ei}}\mathbf{I}_{\mathrm{i}}(t) + \dot{\mathbf{I}}_{\mathrm{e}}(t) = \mathbf{q}(t)$$

Diagonalization & Uncoupling

$\Upsilon\Gamma_{\mathrm{d}}\Upsilon^{-1} = \Gamma$ damping

$\mathbf{u}_{\mathrm{d}}(t) = \Upsilon^{-1}\mathbf{u}(t)$ uncoupling

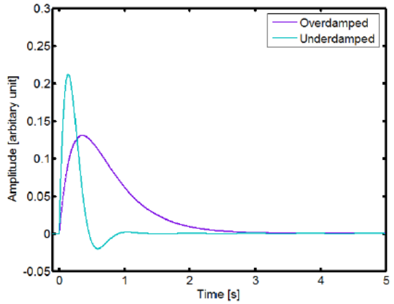
$\Upsilon\Omega_{0_{\mathrm{d}}}^2\Upsilon^{-1} = \Omega_0^2$ normal frequency

$$\ddot{\mathbf{u}}_{\mathrm{d}}(t) + 2\Gamma_{\mathrm{d}}\dot{\mathbf{u}}_{\mathrm{d}}(t) + \Omega_{0_{\mathrm{d}}}^2\mathbf{u}_{\mathrm{d}}(t) = \mathbf{q}_{\mathrm{d}}(t)$$

Solution: normal modes are damped oscillators

$$u_{\mathrm{d}}(t) = \exp(-\gamma_{\mathrm{d}}t)(a_{u_{\mathrm{d}}}\sin(\delta_{\mathrm{d}}t) + b_{u_{\mathrm{d}}}\cos(\delta_{\mathrm{d}}t)) + f_{u_{\mathrm{d}}}$$

$$\begin{cases} a_{u_{\mathrm{d}}} = \frac{w_{\mathrm{ei}}\gamma_{\mathrm{d}}}{\omega_{0_{\mathrm{d}}}^2\delta_{\mathrm{d}}}I_{\mathrm{i}}(t) + \frac{\omega_{0_{\mathrm{d}}}^2 + w_{\mathrm{ei}}w_{\mathrm{ie}}w_{\mathrm{ii}}^2}{2\omega_{0_{\mathrm{d}}}^2\delta_{\mathrm{d}}}I_{\mathrm{e}}(t) + \frac{w_{\mathrm{ii}} + w_{\mathrm{ee_d}}}{2\delta_{\mathrm{d}}}u_0 - \frac{w_{\mathrm{ie}}}{\delta_{\mathrm{d}}}v_0 \\ b_{u_{\mathrm{d}}} = \frac{w_{\mathrm{ei}}}{\omega_{0_{\mathrm{d}}}^2}I_{\mathrm{i}}(t) - \frac{w_{\mathrm{ii}}}{\omega_{0_{\mathrm{d}}}^2}I_{\mathrm{e}}(t) + u_0 \\ f_{u_{\mathrm{d}}} = -\frac{w_{\mathrm{ei}}}{\omega_{0_{\mathrm{d}}}^2}I_{\mathrm{i}}(t) + \frac{w_{\mathrm{ii}}}{\omega_{0_{\mathrm{d}}}^2}I_{\mathrm{e}}(t), \end{cases}$$

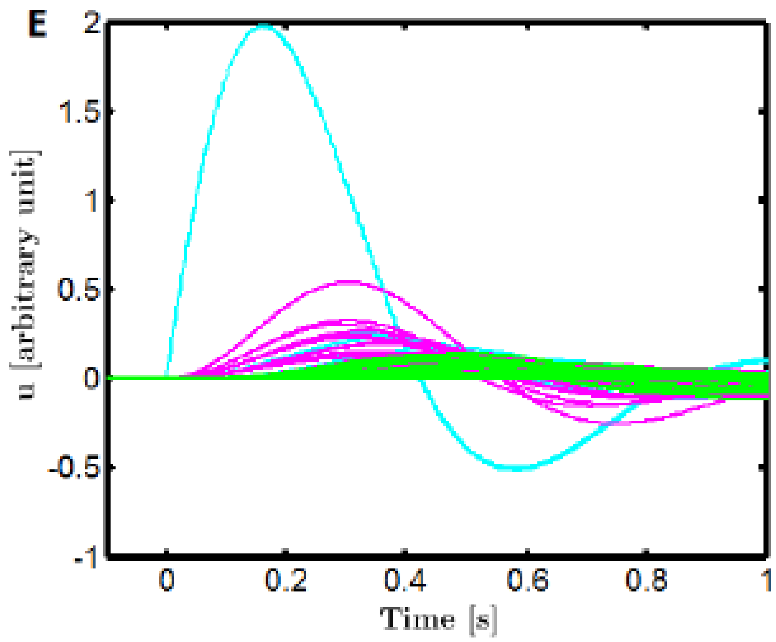


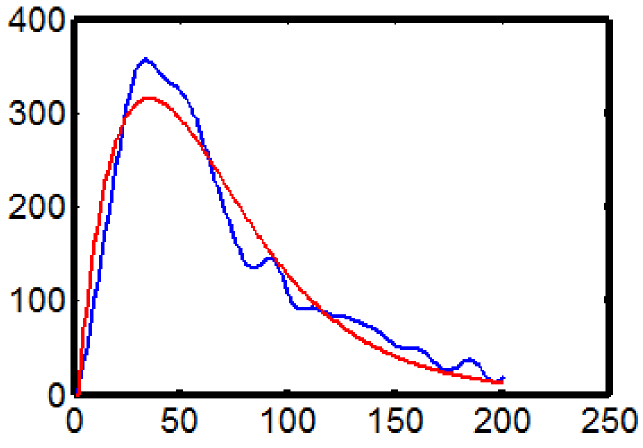
Coupling: linear combination of normal modes, can explain any waveform

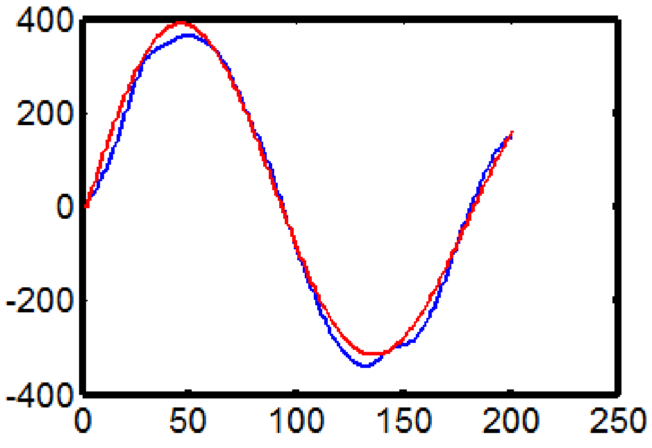
$$\mathbf{u}(t) = \Upsilon\mathbf{u}_{\mathrm{d}}(t)$$

Analytical Approach

- Fast, precise, memory efficient
- Well defined dynamical building blocks -> allows the study of damping, oscillations, resonances
- Coupling -> allows the study of hierarchical (core-belt-parabelt) activations on the single-column level
- Approximates MEG data well.

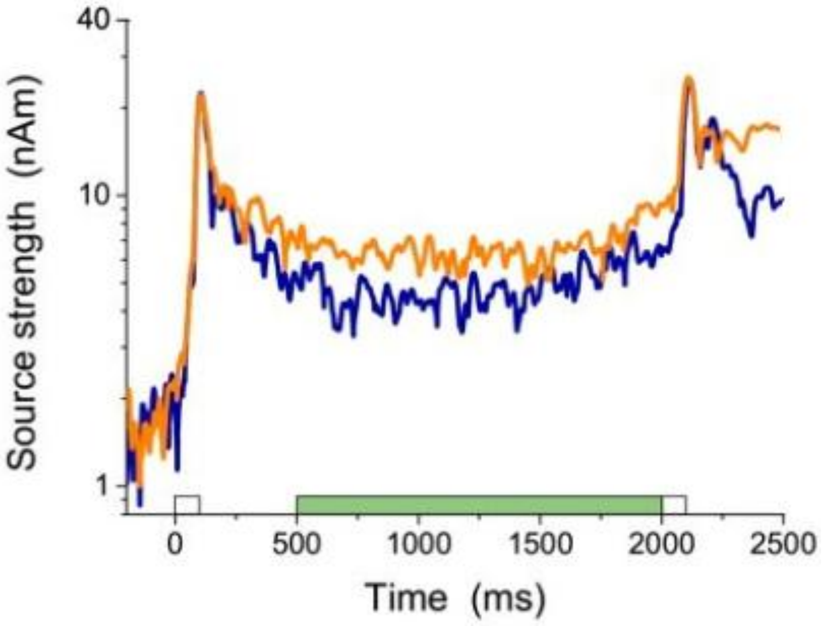


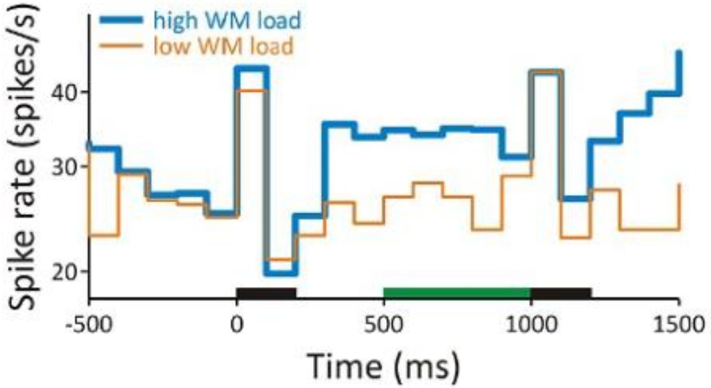


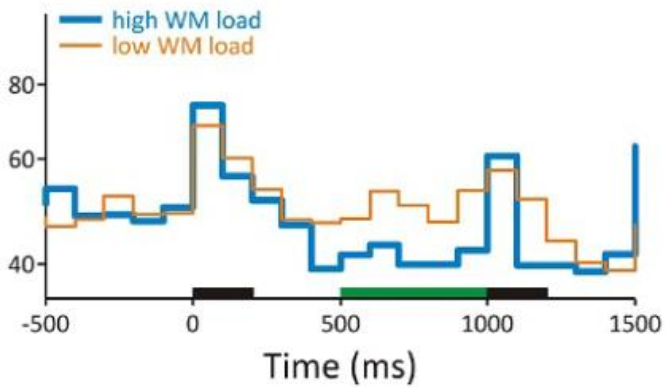


Other Ongoing Projects

- Working memory experiments: Linking human and monkey results in cognitive tasks
- Extension of the model to subcortical processing (using rat model)
- Modelling auditory scene analysis: separating sound sources from each other







Conclusions

- We are studying the auditory system in a computational model based on the anatomical structure of auditory cortex.
- The motivation is to link single-cell observations with MEG
- The model provides explanations for several basic phenomena in auditory neuroscience which have lacked an explanation.
- Fast (firing rate) and slow (synaptic plasticity, adaptation) dynamics coupled with serial stucture of auditory cortex seems to be the explanation.
- We are still a long way from understanding what goes on at a cocktail party.

Thank You