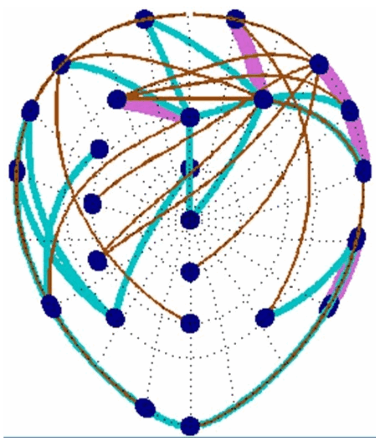
Modeling EEG-band Neurofeedback:

Modulating Internal States without Conditioning of EEG Sources

Eran Zaidel[1], Roman Rosipal[2], Andrew Hill[1], Nayson Fernandes[1], Rasheed Akbarut[1], Sharon Noh[1], Leonardo Jose Trejo[2]

[1]University of California, Los Angeles
[2]Pacific Development and Technology, LLC, Palo Alto, CA



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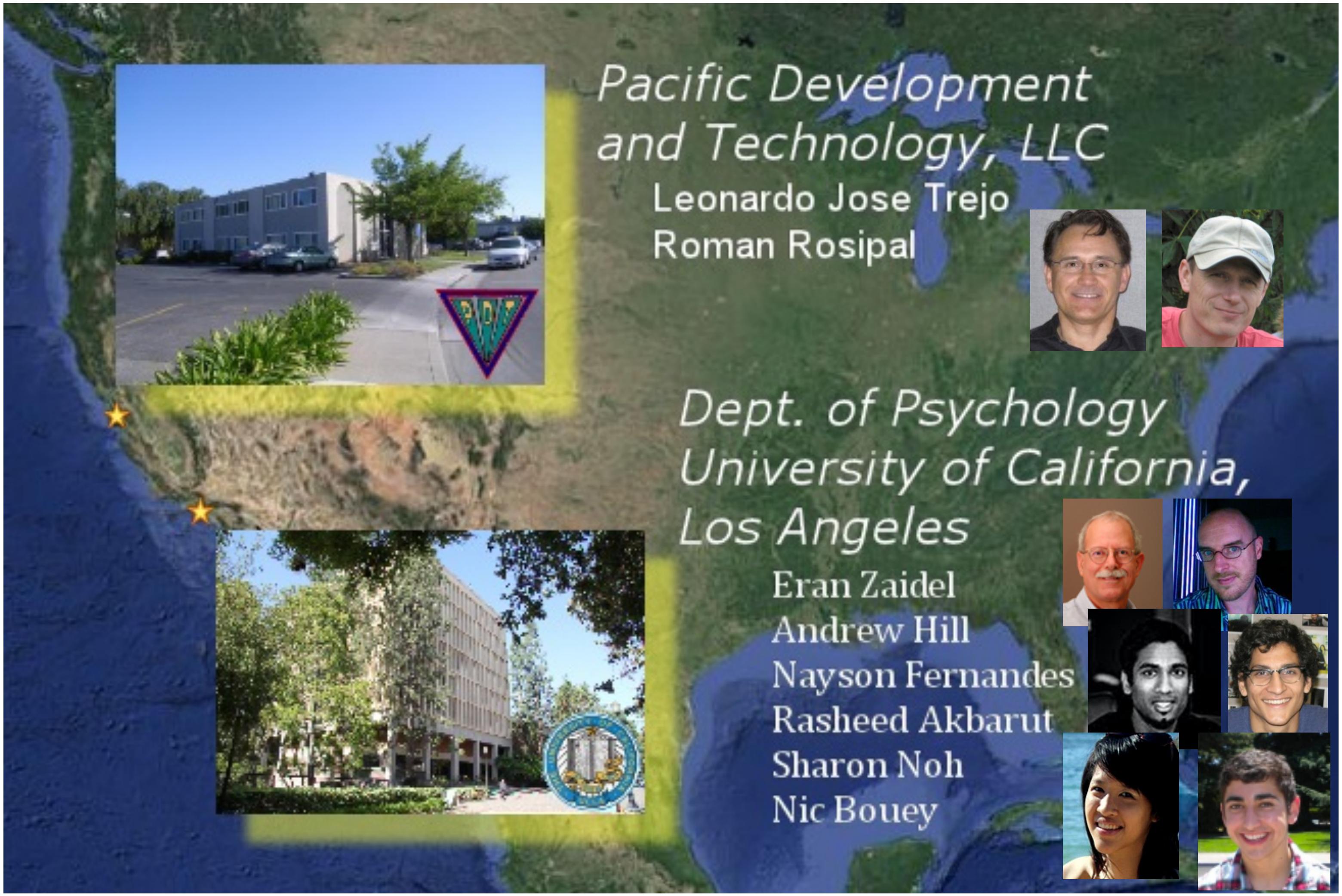
Neurosensory Optimization of Information Transfer

Who we are


Pacific Development and Technology, LLC
Leonardo Jose Trejo
Roman Rosipal
Dept. of Psychology
University of California, Los Angeles
Eran Zaidel
Andrew Hill
Nayson Fernandes
Rasheed Akbarut
Sharon Noh
Nic Bouey

Can EEG Biofeedback Improve Performance?

The literature is mixed on this question (Vernon, 2005)

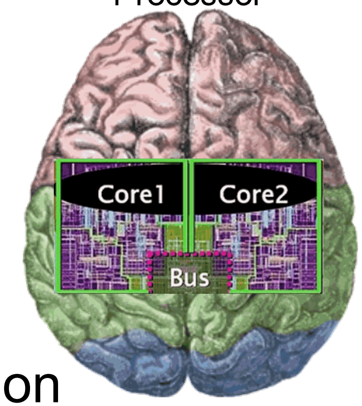
Study	Protocol	Sessions	EEG changed	Result
Beatty et al, 1973	Suppress 3-7 Hz Enhance 3-7 Hz	2 2	suppressed enhanced	Better radar perf. Worse radar perf.
Egner & Gruzelier 2001	+C3 15-18 Hz -(4-7, 22-30 Hz)	10	No	Reduced errors in TOVA
Egner & Gruzelier 2004	+Cz 12-15 Hz, -(4-7, 22-30 Hz)	10	No	Increased d', TOVA , less error
Vernon et al 2003	+Cz 12-15 Hz, -(4-7, 22-30 Hz)	8	No	No change in attention CPT
	-Cz 0-4 Hz, -8-12 Hz	8	Increased 12-15 Hz	Increased memory recall

Background

- Problem: stress, fatigue, inattention, overload
- Approach: neuroergonomic models and control systems
  - Create useful definitions of cognitive states
  - Measure, model and optimize cognitive states
- Model Development
  - EEG-based models of mental states (PLS, KPLS)
  - Successes and failures: +Fatigue +BCI +Engagement -Workload
- Current Research
  - Multiway sensor-process models (PARAFAC, N-PLS)
  - Real-time countermeasures
  - Neurofeedback for hemispheric resource management and adaptive self-control

Hemispheric Specialization and Interaction

Dual-Core Processor

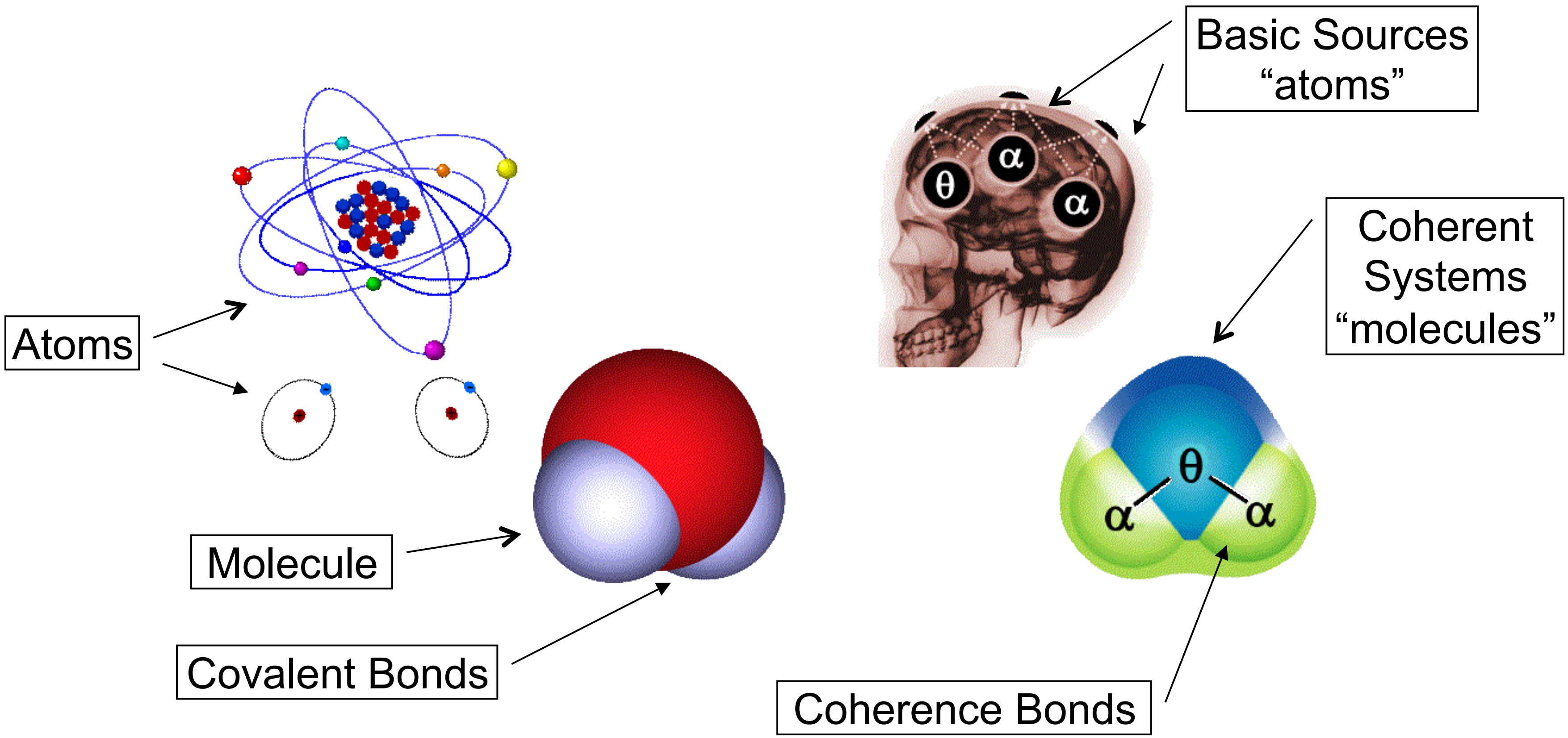


- Left and right brain hemispheres process task information differently, independently and simultaneously
- Modes of hemispheric interaction
  - There is complementary hemispheric specialization
    - The left hemisphere is linguistic, numerical, analytic, individualistic
    - The right hemisphere is visuo-spatial, synthetic, social, emotional
  - Complex tasks can be optimized by division of labor
  - When resources are limited each hemisphere can monitor errors in the other
  - Conditions of overload and fatigue can be ameliorated by modulating attention in the two hemispheres

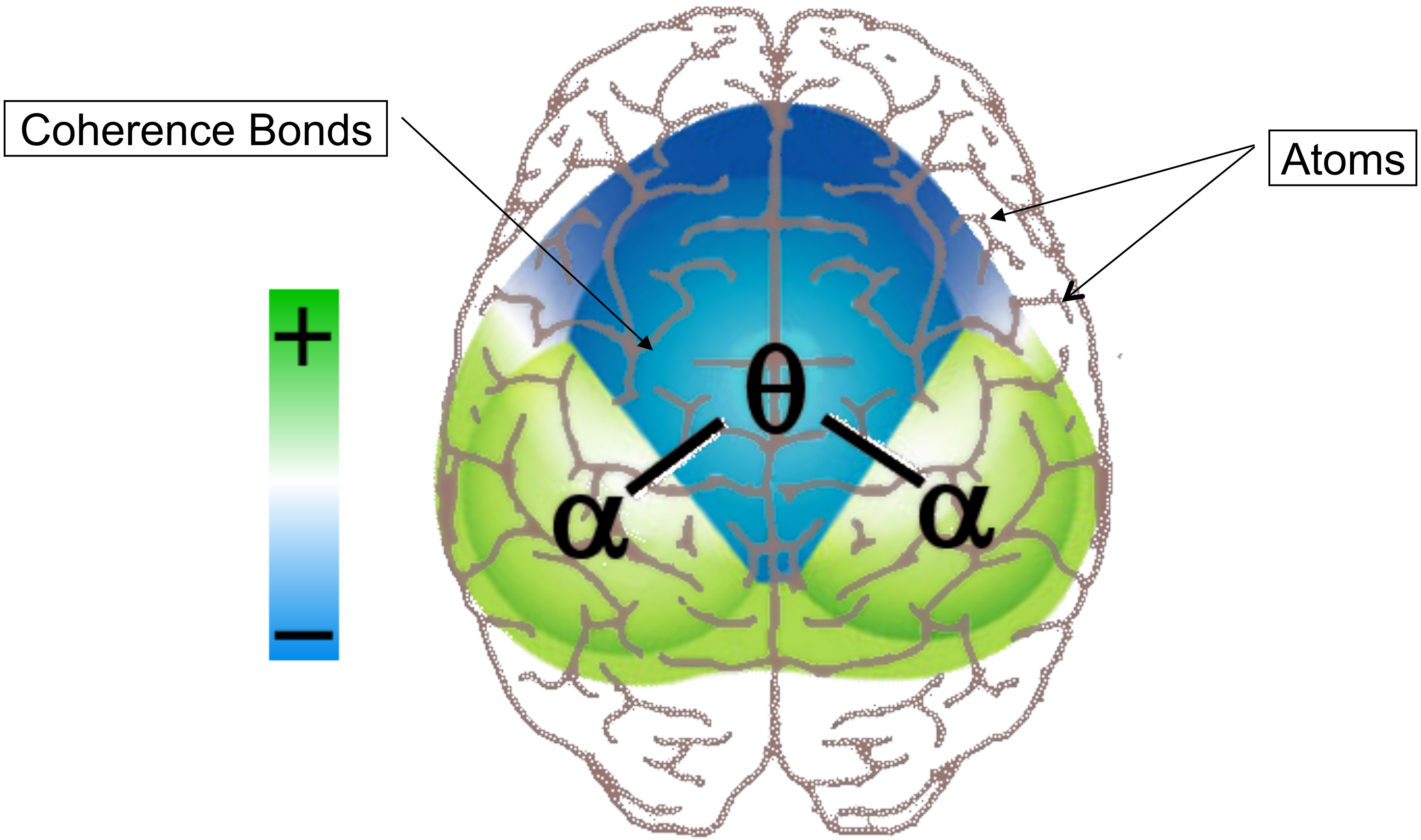
Lateralized Attention Network Test (LANT)

- UCLA developed the LANT for measuring selective attention in each hemisphere. It includes:
  - Conflict Resolution, Spatial Orienting, Alerting
- The LANT is sensitive to individual differences
  - In Handedness and in Gender
  - In Personality. E.g., anxiety, empathy
  - In Social Relations, e.g., Sensitivity to discrimination , Conditions of teamwork
- Performance can be optimized by:
  - Adapting to the diurnal rhythms of the attentional networks in the two hemispheres
  - Providing individually emotionally relevant background and spatial cues
  - Modulating the attention networks of the two hemispheres, e.g., by using EEG Biofeedback

EEG “Atoms”


Basic Sources
“atoms”
θ
α
α
Coherent
Systems
“molecules”
Atoms
Molecule
Covalent Bonds
θ
α
α
Coherence Bonds

"Molecular" EEG Processes

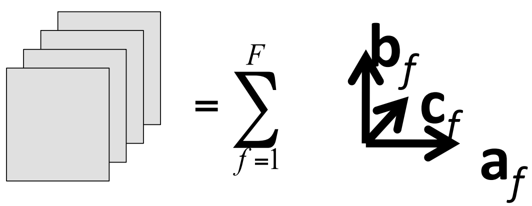


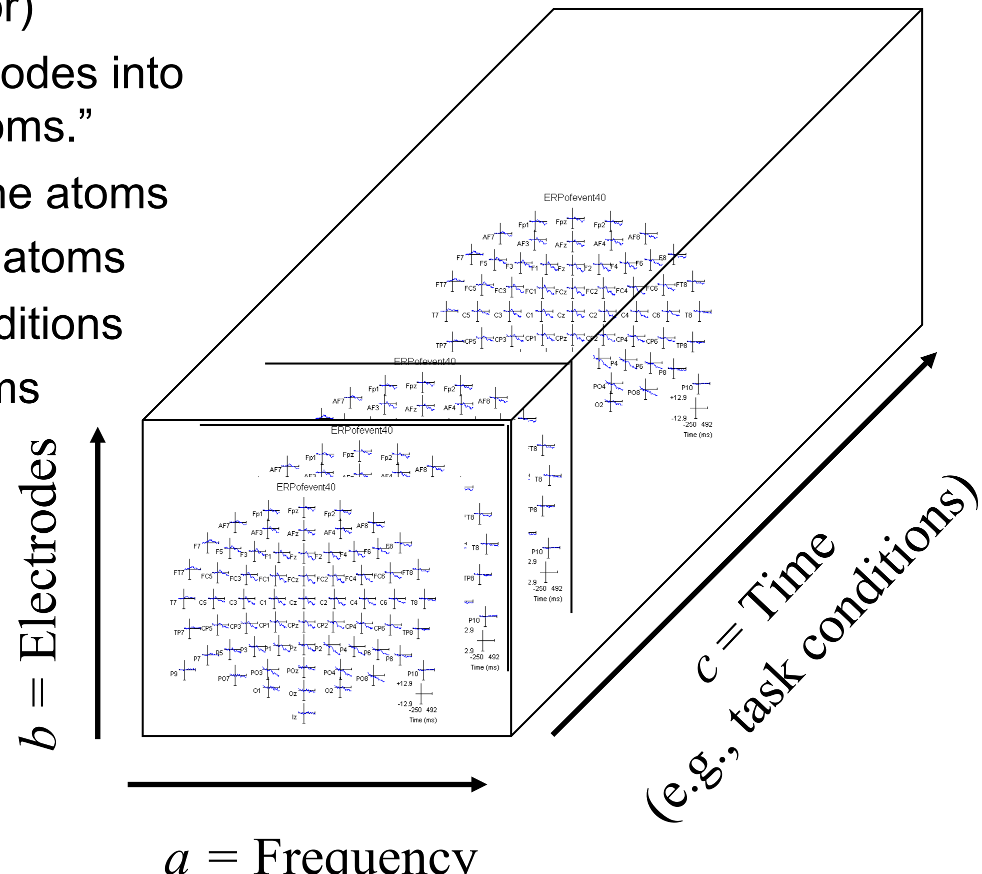
Atomic Decomposition of EEG with PARAFAC

Parallel Factor Analysis Model:

- We treat EEG spectra as a tensor product of three modes: frequency, electrode, and time (+ error)
- We simultaneously decompose the modes into a unique set of latent variables or "atoms."
- The EEG itself uniquely determines the atoms
- EEG segments consist of mixtures of atoms
- The mixture varies over time and conditions
- We can also estimate coherence atoms

$$x_{ijk} = \sum_{f=1}^{F} a_{if} b_{jf} c_{kf} + e_{ijk}$$



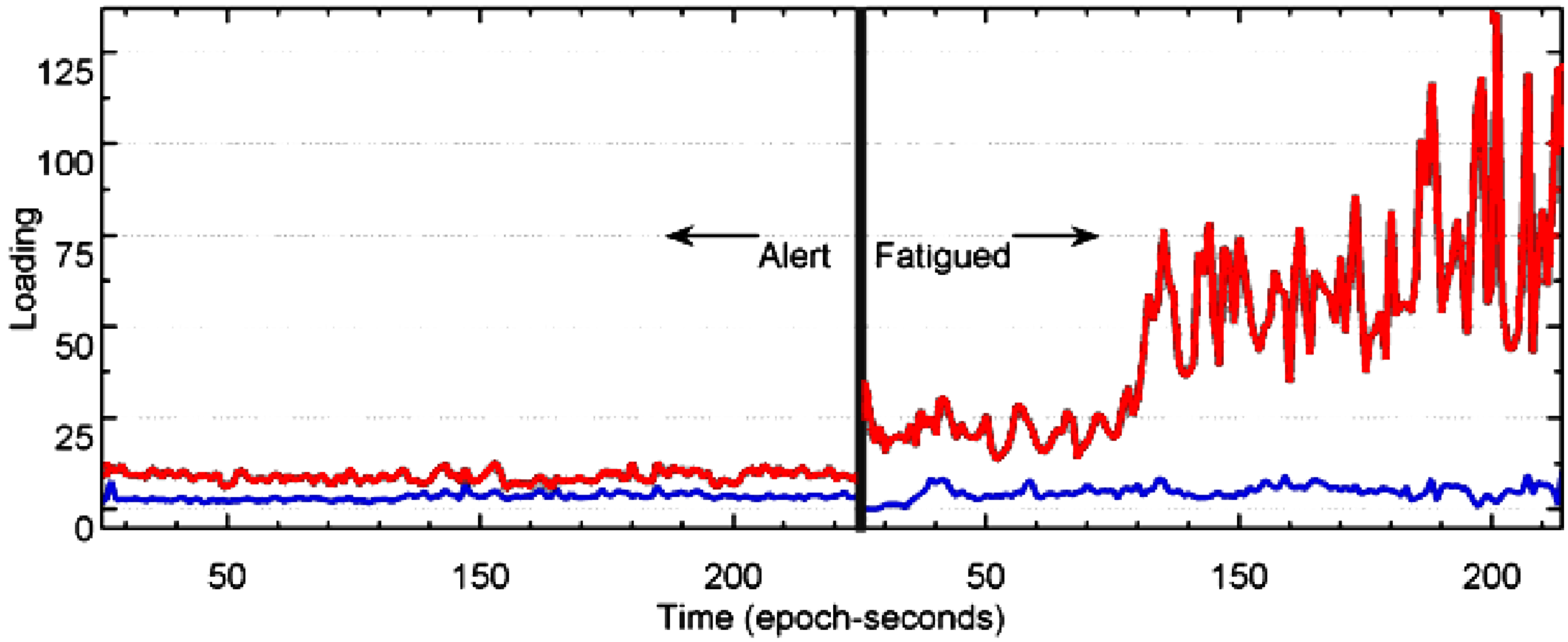


Do EEG Atoms inform us about Mental States?

Yes, they do!

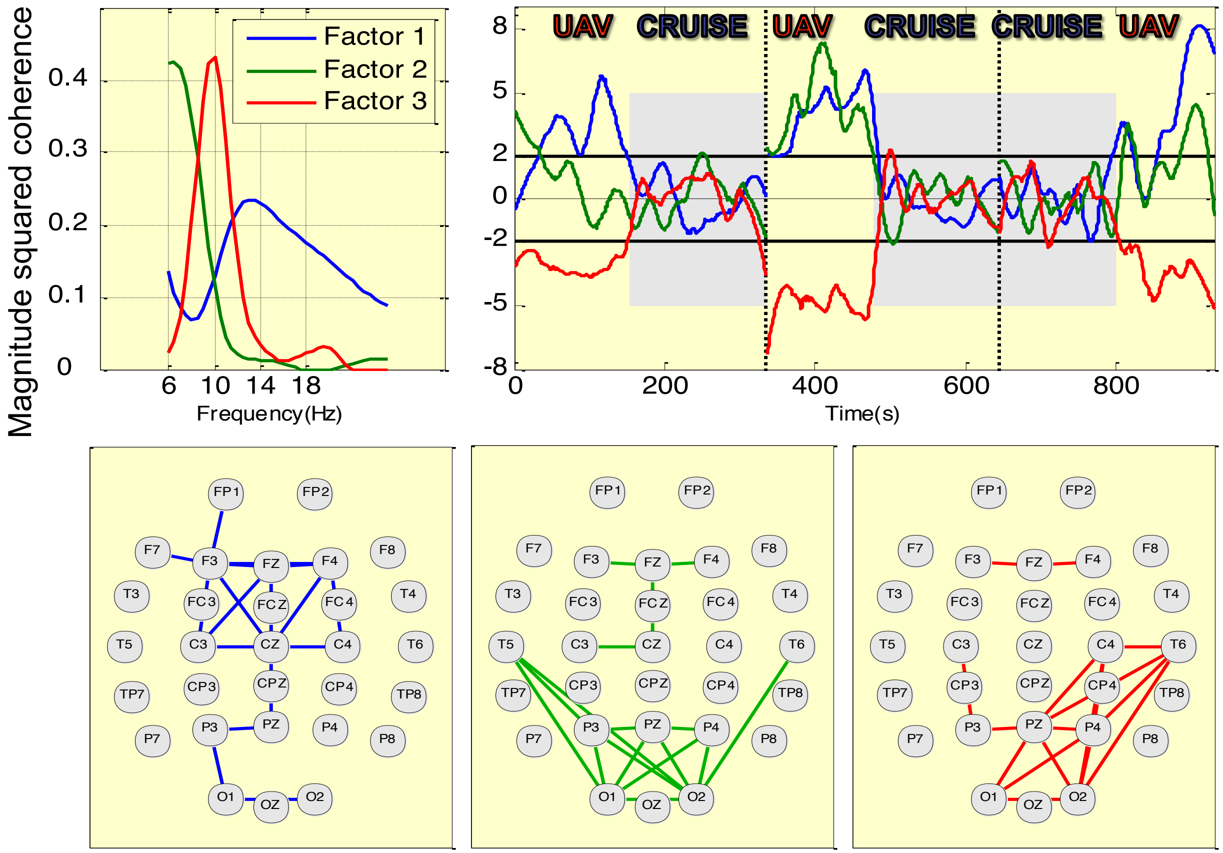
EEG Atoms Track Mental Fatigue

PARAFAC *power atoms* during first and last 15 minutes of a 3-hour *mental arithmetic* task performance in one participant. Atom 1 (blue) did not change over time. Atom 2 (red) reflected the development of mental fatigue.



EEG Atoms Track Mental Workload

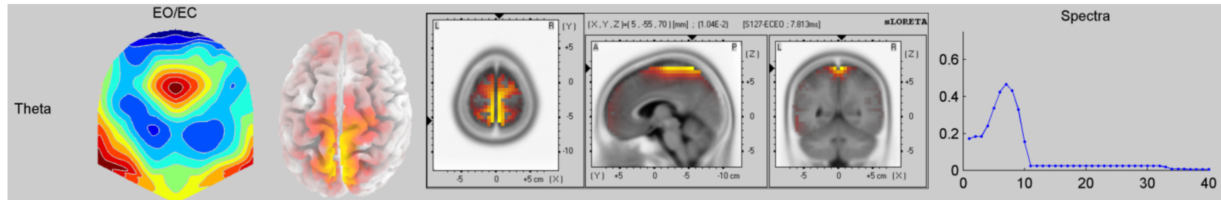
PARAFAC EEG *coherence atoms* during UAV task performance in one participant

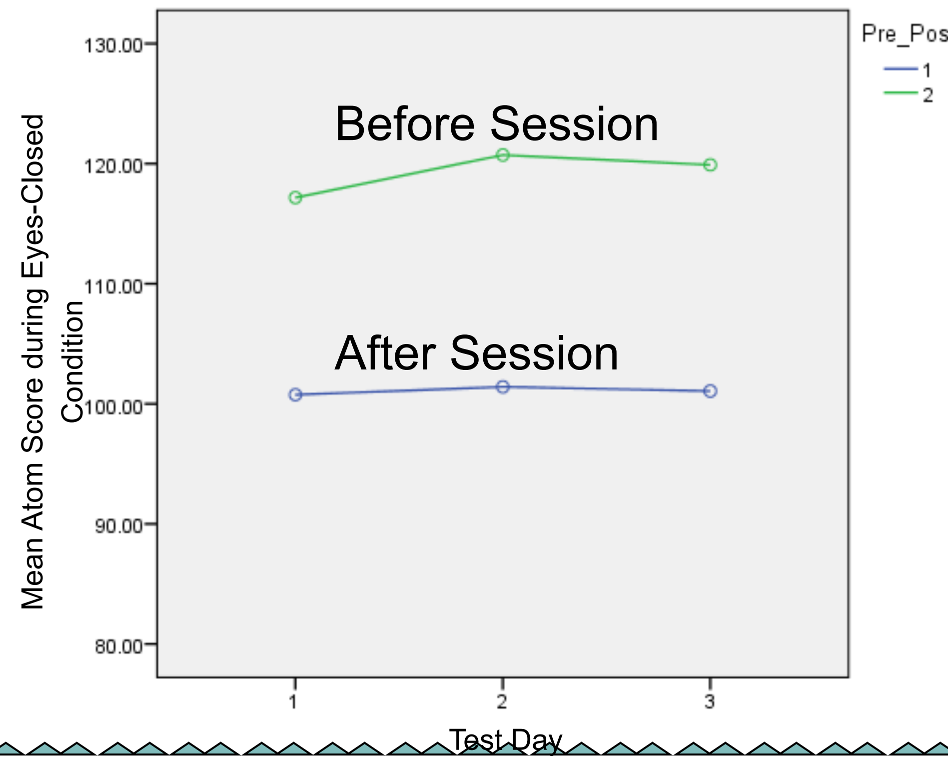


Top 10% of inter-electrode coherences

EEG Atoms Gauge Mental Fatigue in the LANT

- Our prior work with KPLS has shown that EEG atoms can track development of mental fatigue in real-time
- This project is developing a system and EEG-atom based methods to detect and monitor mental fatigue in real-time
- The EEG **theta atom** significantly increased from pre-test to post-test over a 1.5-hour session of performing various tasks (LANT, BFB, CPT) (n = 35 subjects)

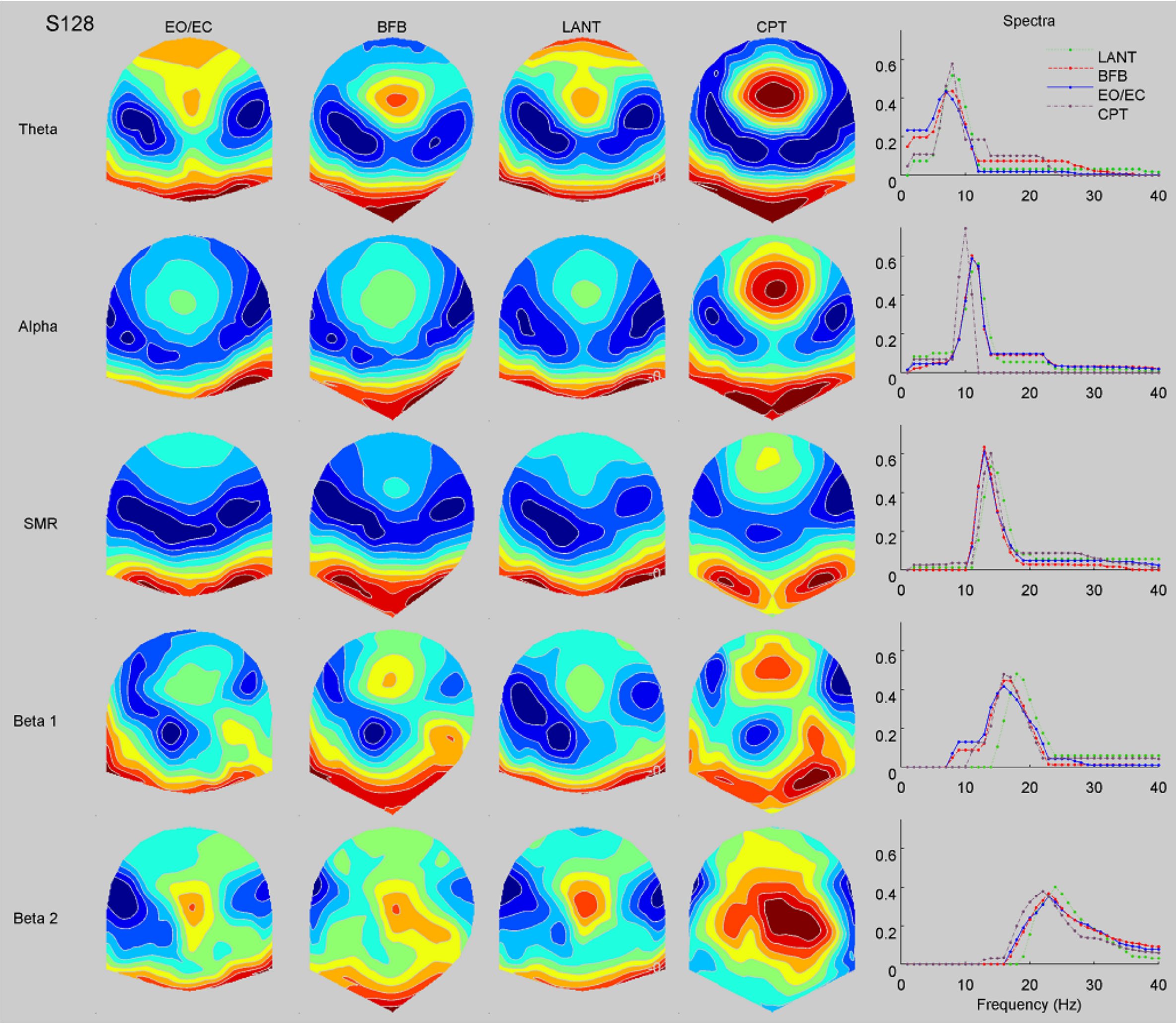




Are EEG Atoms Reliable?

Yes, they are!

Reliability of EEG Atom Measurement

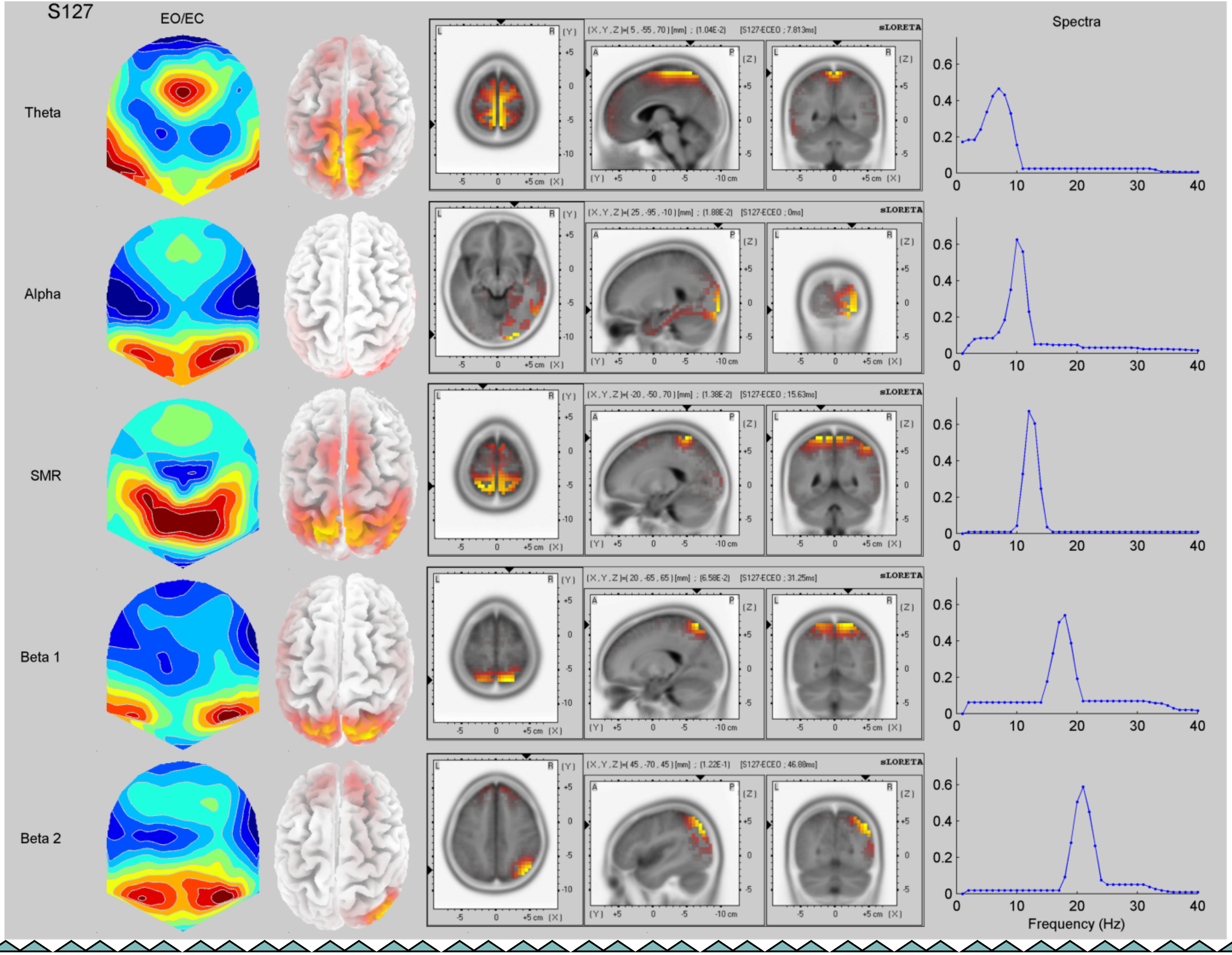


Do we know where in the brain EEG Atoms come from?

Yes, but only roughly ...

It's impossible to know for sure where EEG sources come from using scalp electrodes, but we can make reasonable educated guesses with pseudo-inverse methods like LORETA or surface Laplacians

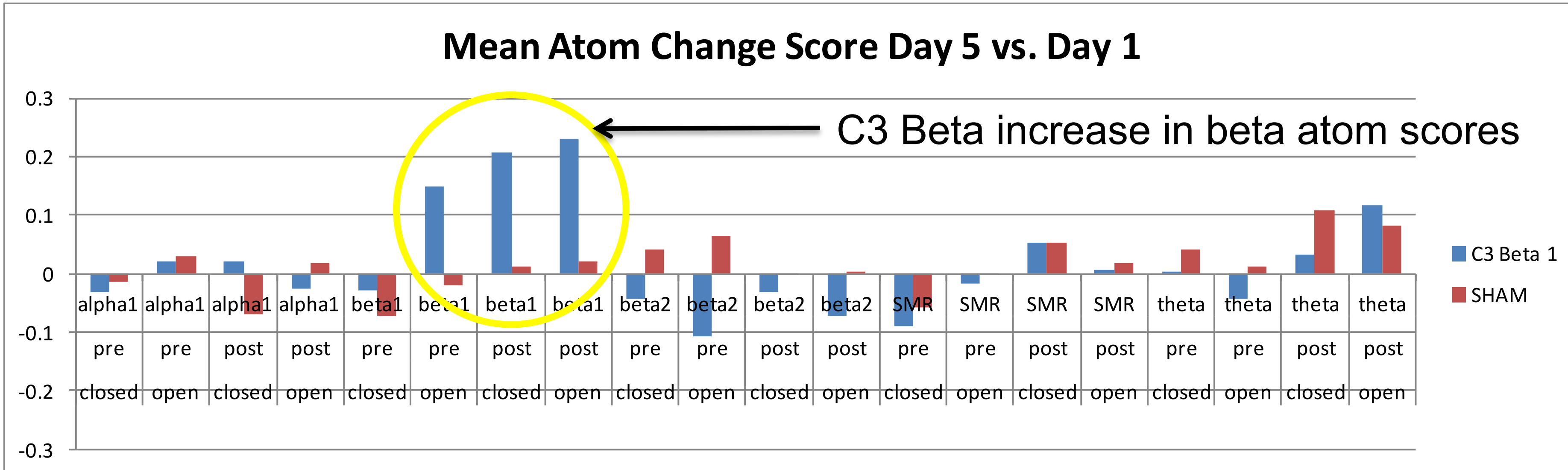
Sources of EEG Atoms Estimated with sLORETA

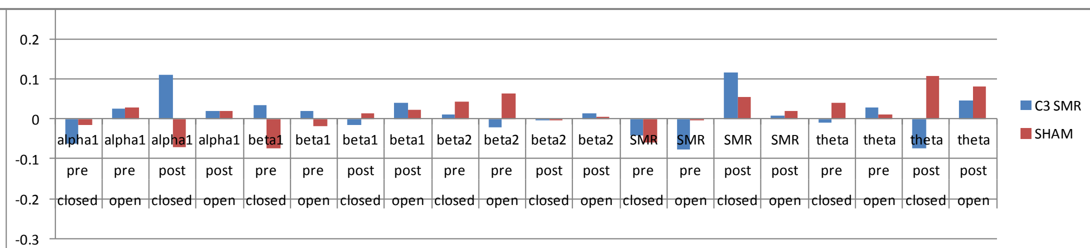


What happened in the Neurofeedback Experiment?

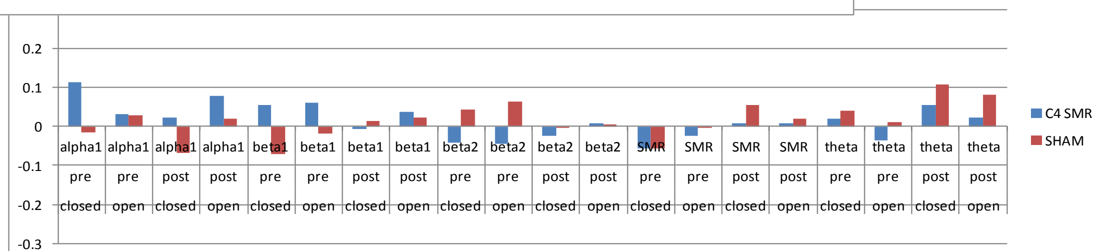
- Only one group changed performance: the C3 beta group improved response speed for conflicting targets in the left visual field
- Traditional EEG measures showed no changes due to NFT in the trained band or at trained electrode
- EEG atom analyses showed an increase in the beta 1 atom scores for the C3 beta group only but it was not significant
- We had good controls for placebo effects and tests for site of training and site of action specificity
  - Double blind concerning feedback
  - Trained using C3 beta, or C3 SMR, C4 SMR
  - Sham group got random mix of other's feedback

Atom Changes after 5 NFT Sessions





C3 SMR



C4 SMR

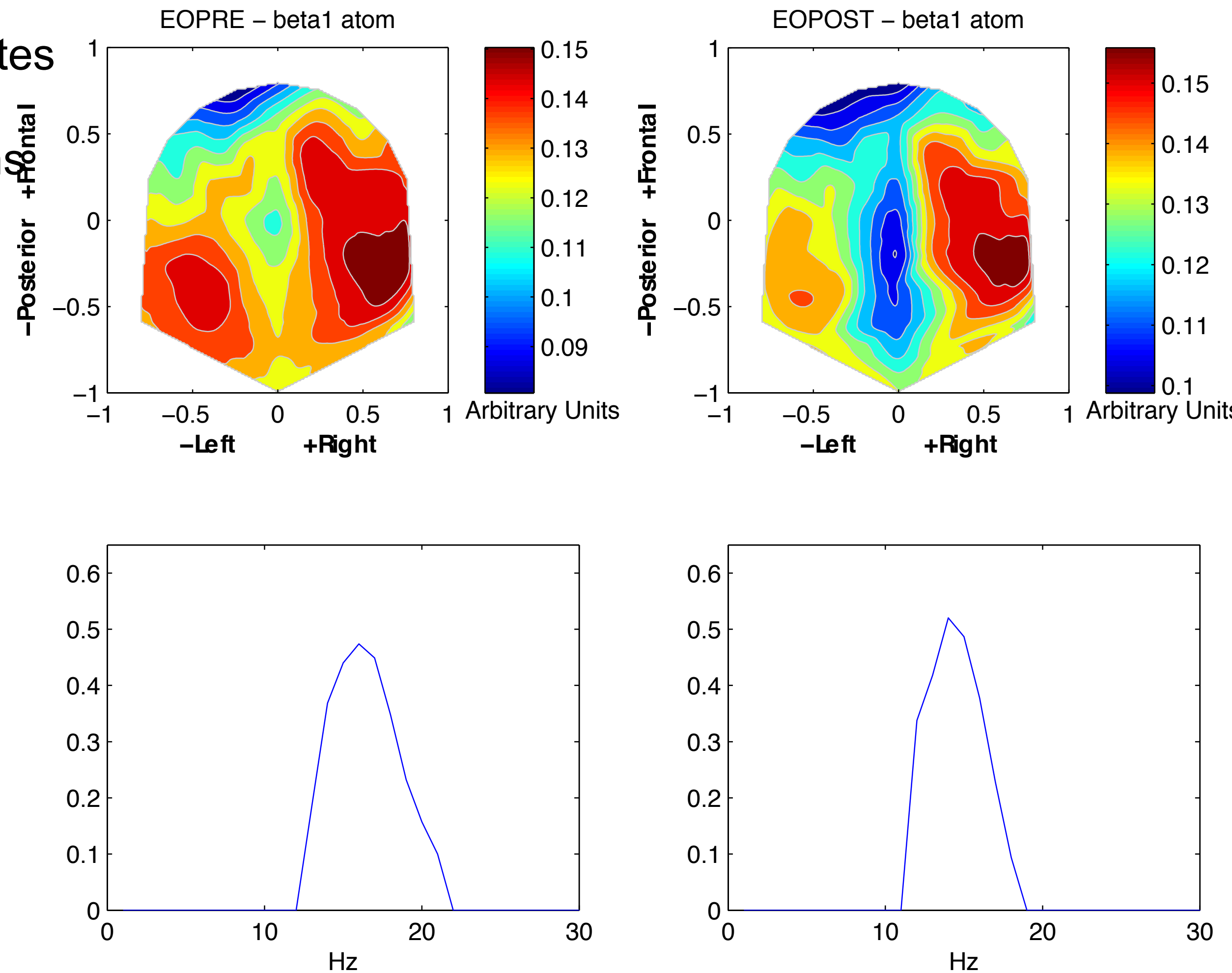
LORETA (CSD) Changes for Specific EEG Atoms

How can we find the LORETA solutions for EEG atoms?

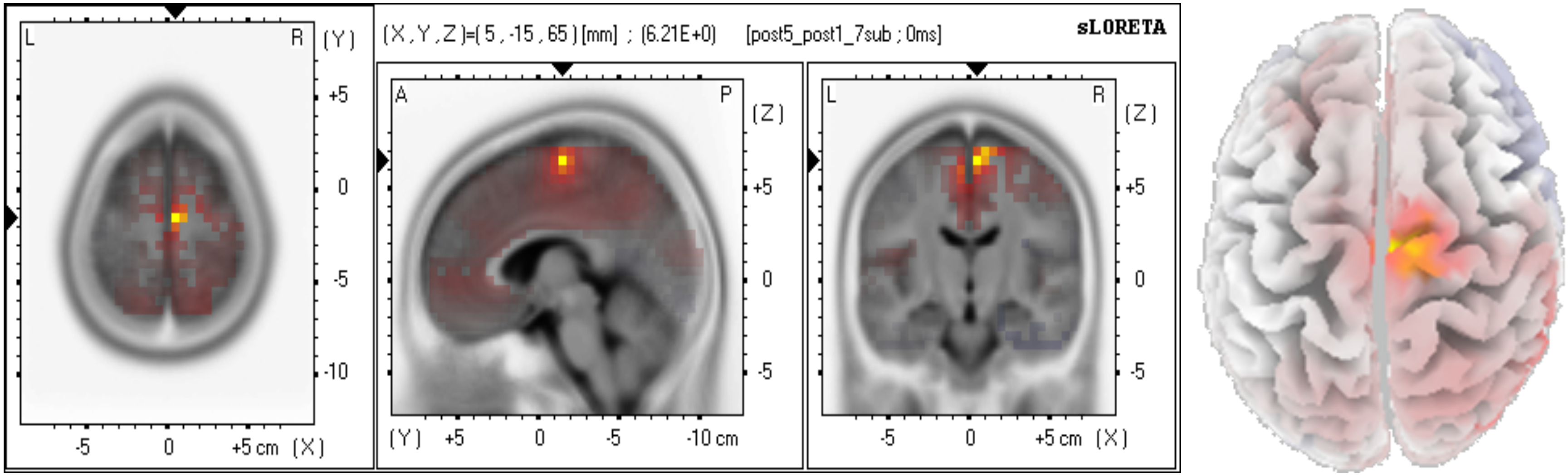
- We cannot "input" atoms scores to LORETA
- We **can** use atom time scores to pick EEG segments in which the atoms had high scores
    - Segments can have high absolute atom time scores
    - Or high scores relative to other atoms
    - We use relative scores to get EEG segments that are relatively "pure" for a given atom
- Atom scores "mine the EEG" for segments that are rich in a given atom, like finding a pure vein of gold ore in a mine!
- Then we compare the average LORETAs of many such pure EEG segments from different conditions

Beta 1 Atom Estimated from Seven C3-beta and Seven Sham Subjects

Separate atom estimates for EO Pre conditions and EO Post conditions



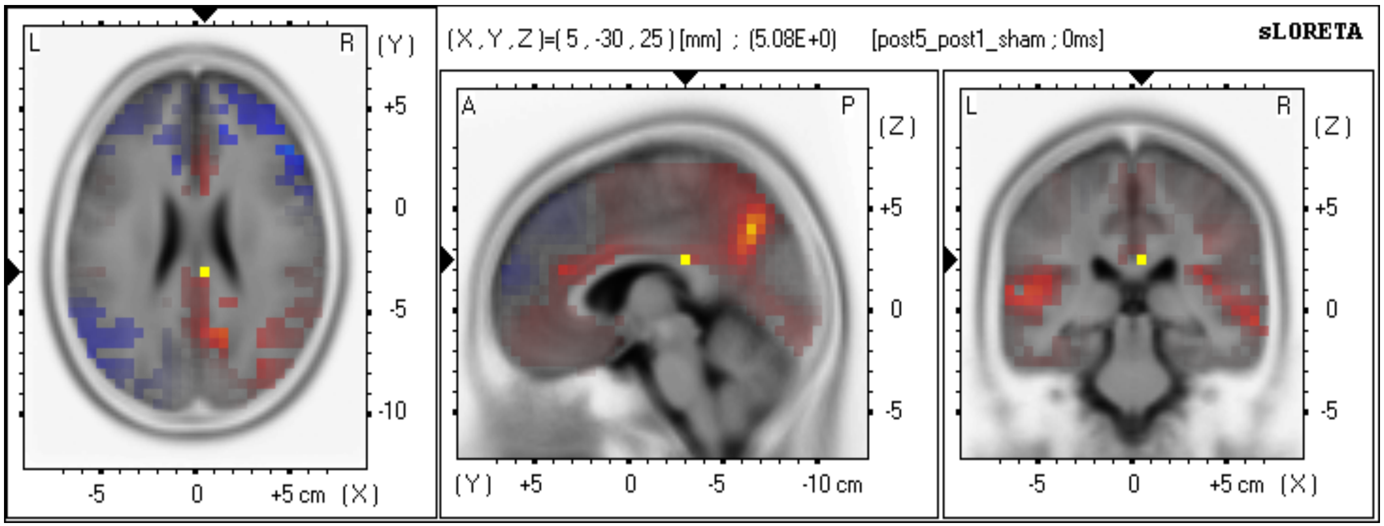
Beta 1 Atom LORETAs Estimated from All Seven C3 beta Subjects

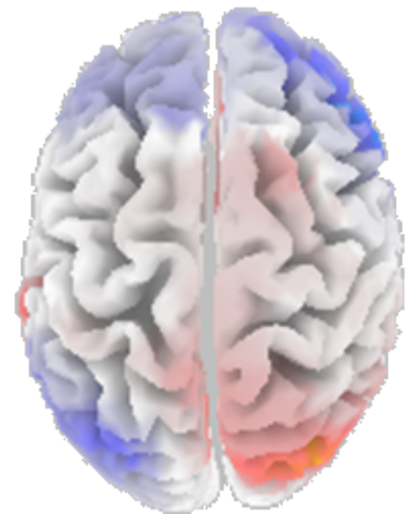


This is a parametric statistical test of the difference between the average LORETA for pure beta-1 atom segments from Day 5 minus same segments for Day 1 in the seven **C3 Beta** subjects.

The maximum t-statistic value was **not significant** (t = 6.2 p = 0.078), and was located in Brodmann area 6, medial frontal gyrus, which may correspond to a **sensorimotor network**.

Beta 1 Atom LORETAs Estimated from All Seven C3 Sham Subjects

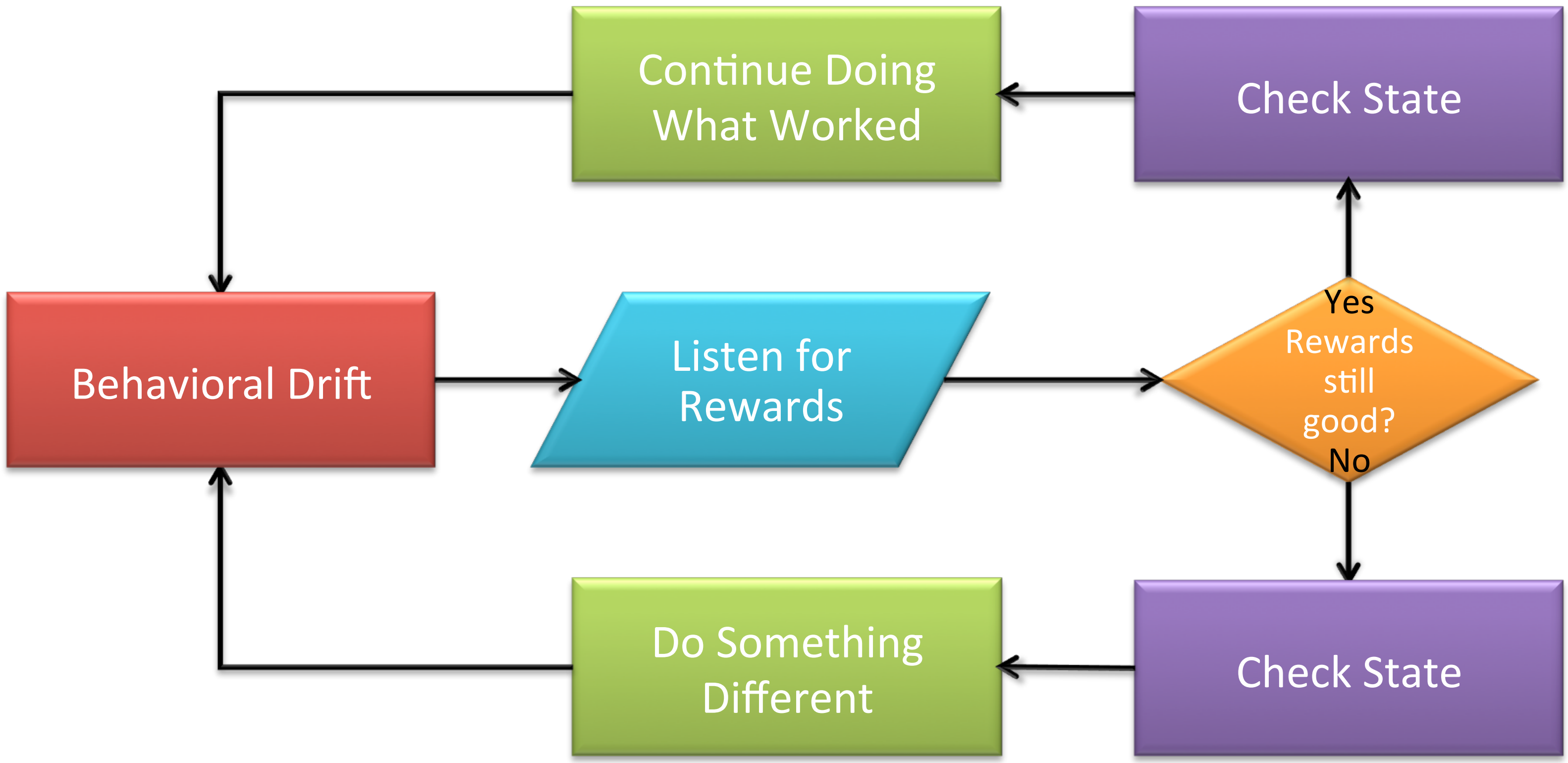




This is a parametric statistical test of the difference between the average LORETA for pure beta-1 atom segments from Day 5 minus same segments for Day 1 in the seven **SHAM** subjects.

The maximum t-statistic value was **not significant** (t = 5.1 (p = 0.32) and was located in Brodmann area 23, posterior cingulate, which may correspond to a **default mode network.**

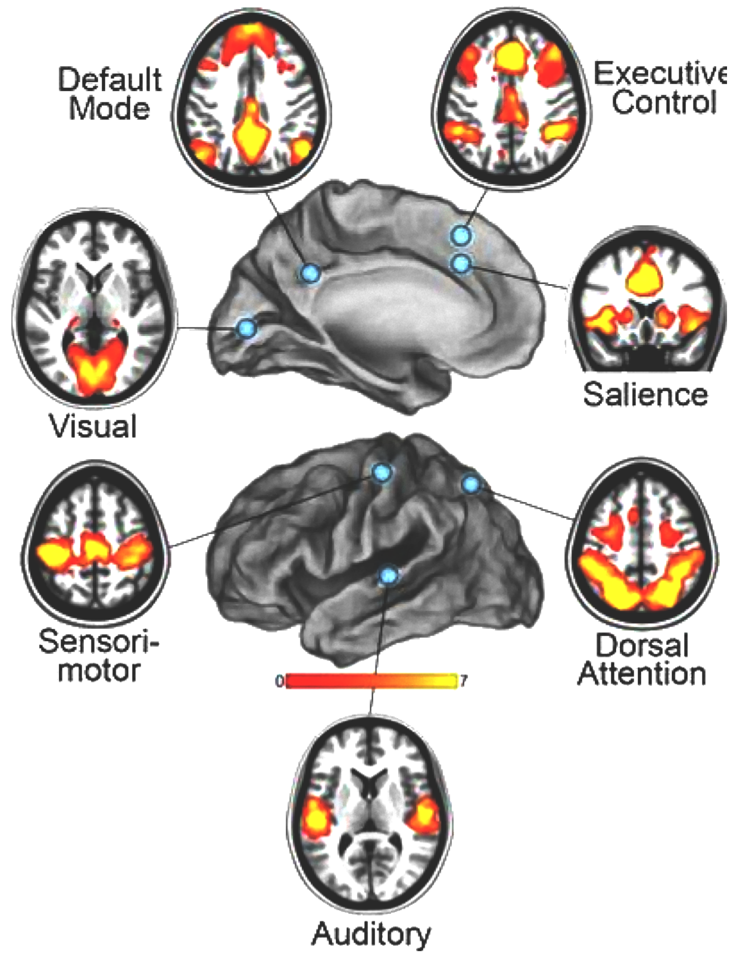
A Model of EEG Biofeedback for Performance Enhancement



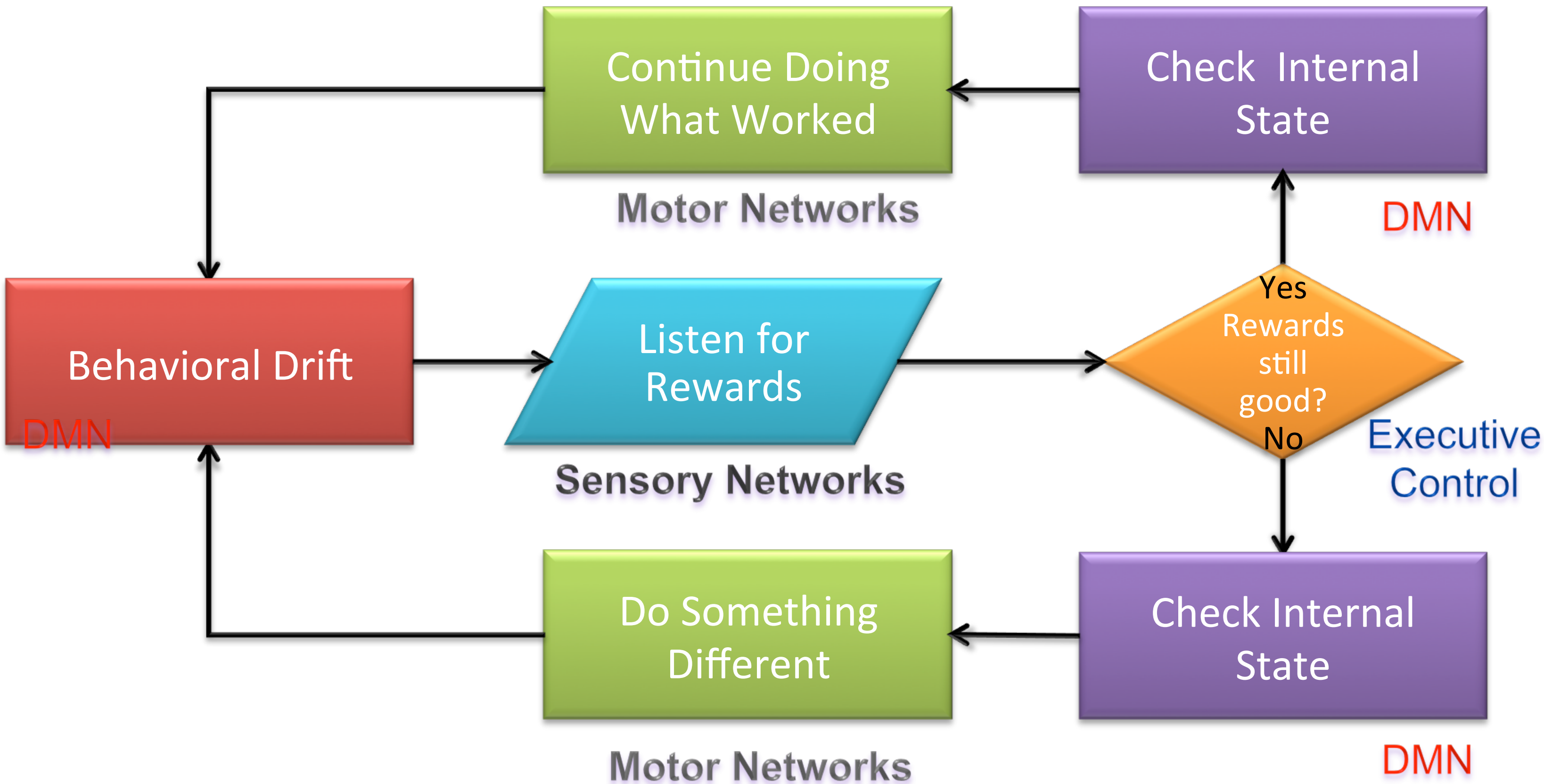
Do EEG Atoms or Functional Networks Relate to the Neurofeedback Model?

We have some ideas about this but more research must be done…

1. EEG alone may not inform us about functional network activity
2. Clinical EEG oscillations are not clearly related to fMRI BOLD signals
3. Some EEG oscillations may be inversely related to fMRI BOLD signals
4. EEG ISF activity correlates with fMRI activations and may modulate faster oscillations by phase-amplitude cross-frequency coupling
5. However, we CAN relate fMRI networks to the model on purely functional grounds



A (Network) Model of EEG Biofeedback for Performance Enhancement



Summary

- EEG atoms can track mental states and may assess outcomes of NFT training
- A beta 1 atom increased in a C3 beta NFT training group after 5 days of training but this was on marginally significant
- This beta 1 group significantly improved performance for conflict targets in the LVF
- No other EEG atom changed and no other group had performance changes

Conclusions

- NFT can enhance cognitive performance without a (substantial) change in the EEG bands and electrodes trained
- However, more sensitive measures like EEG atoms suggest that subtle EEG changes may occur at untrained sites or bands
  - We need new research on sensitive measures of EEG change, including connectivity measures
- Our NFT model has a major role for the DMN in balancing and coordinating activity in other networks (see also Leech et al 2012)
- Rewarding subjects for modulating the beta-1 EEG atom may develop, enhance and maintain a skill of network balancing and coordination that relies on DMN
- This is also consistent with prior beta-1 NFT training studies which found performance enhancement without EEG changes