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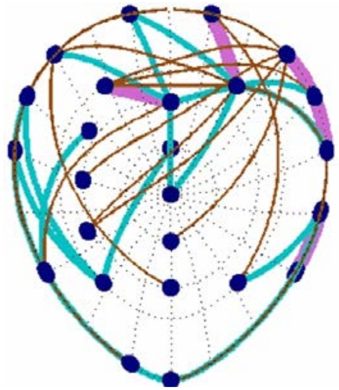
Contract No. W911NF-11-C-0081
01 April 2011 – 31 May 2014

Neurosensory Optimization of Information Transfer (NOIT)



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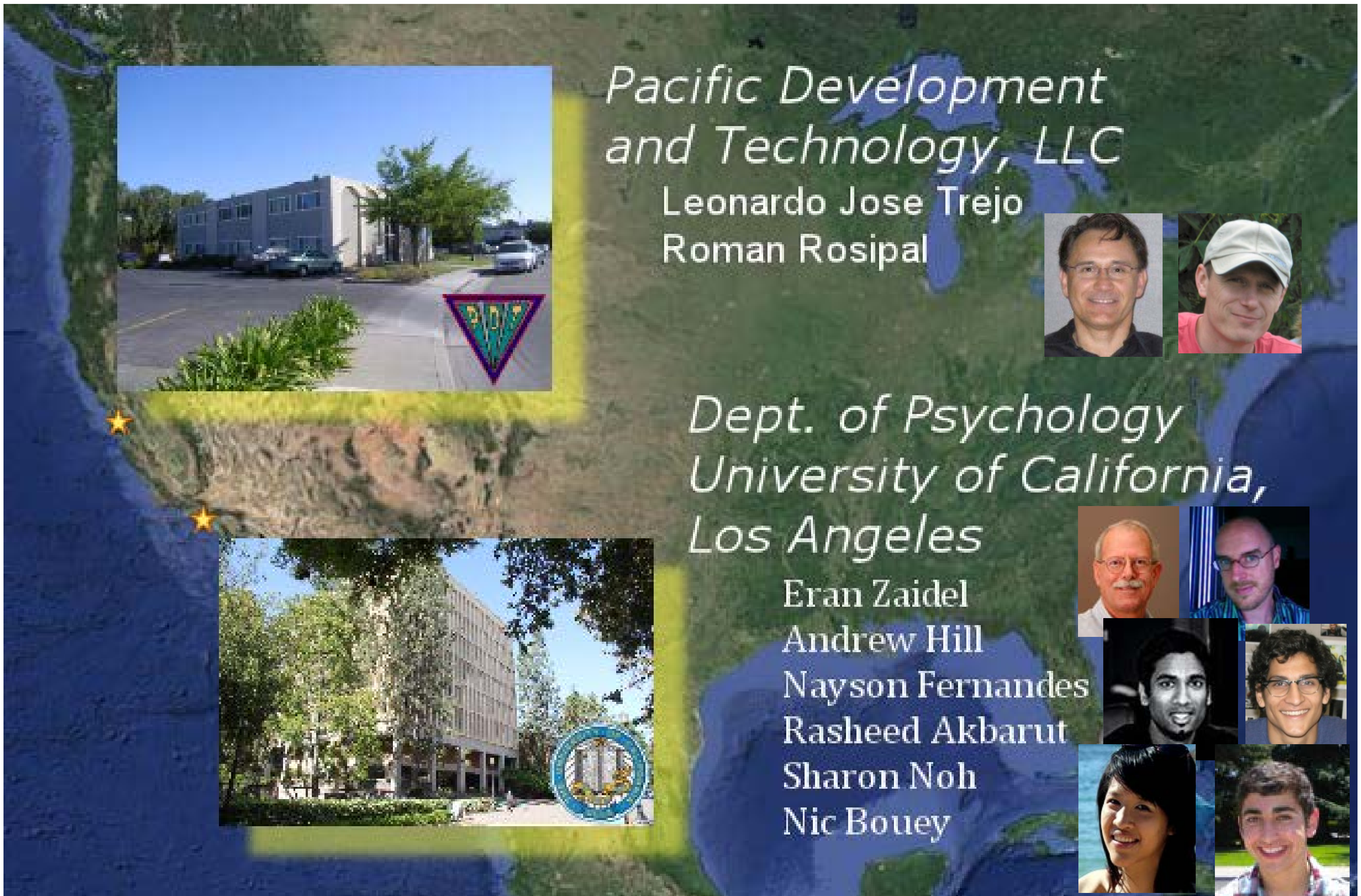
The *Neurosensory Optimization of Information Transfer* (NOIT) project aims to show that we can counteract the effects of sleep deprivation and fatigue on cognition with the aid of EEG biofeedback (EBF). EBF may enhance situational awareness, sustain cognitive engagement in supervisory control tasks, and lower the risk of errors associated with fatigue, inattention, or overload. At a basic research level, we are using advanced behavioral attention network tests and multivariate EEG measures to discover brain networks of attention and describe their operation.

A practical aim of the project is to test whether EBF train people to develop skills for managing brain resources of attention, which can diminish the devastating effects of fatigue or sleepiness on cognition. We may use EBF to train particular cognitive processes in the left or right hemisphere, thereby optimizing performance on tasks that specialize in that hemisphere.

Another practical aim will be to test whether EBF can serve as part of an operational countermeasure, which detects states of fatigue or sleepiness in an individual and applies attention switching interventions that prevent or delay cognitive impairment.

Who we are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Overview

The NOIT Project has three main aims:

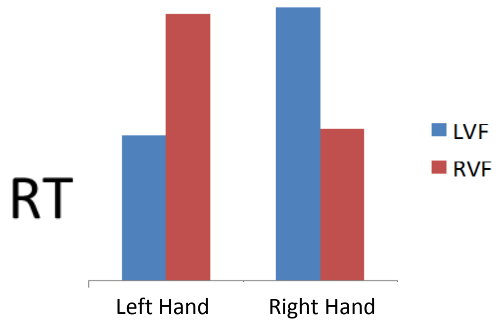
1. Model the networks of human attention and performance in each brain hemisphere using advanced behavioral and physiological measures
2. Develop neurofeedback training for hemispheric attention skills that sustain or enhance performance under adverse conditions such as mental fatigue
3. Develop methods to detect states of fatigue or sleepiness in an individual and apply countermeasures that prevent or delay cognitive impairment

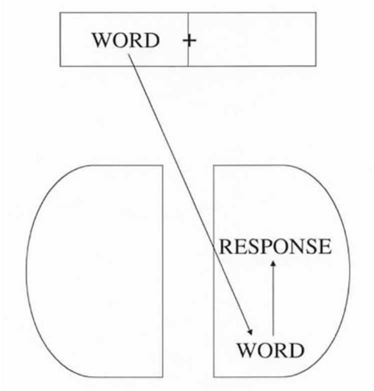
Brain Networks of Human Attention and Performance

Patterns of Hemispheric Specialization and Interaction

- Left and right brain hemispheres processes task information differently, independently and simultaneously
- Modes of hemispheric interaction
    - There is complementary hemispheric specialization
        - The left hemisphere is linguistic, numerical, analytic, individualistic, non-conventional
        - 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

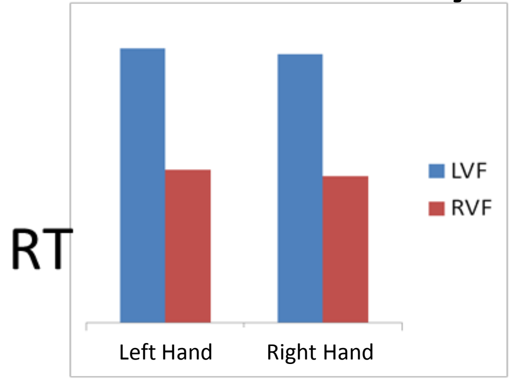
- Direct Access

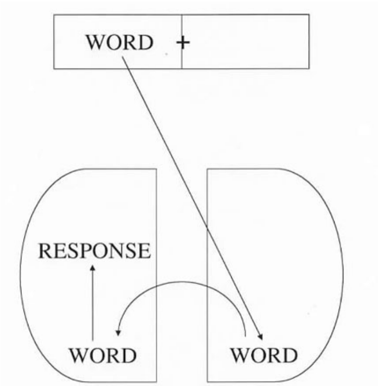




Direct Access

- Callosal Relay





Callosal Relay

Lateralized Attention Network Test (LANT)

- We developed the LANT for *measuring selective attention in each hemisphere. It includes:*
  - *Conflict Resolution*
  - *Spatial Orienting*
  - *Alerting*
  - *Inhibition of Return*
- *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 complementary 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
    - meditation / relaxation
    - EEG Biofeedback

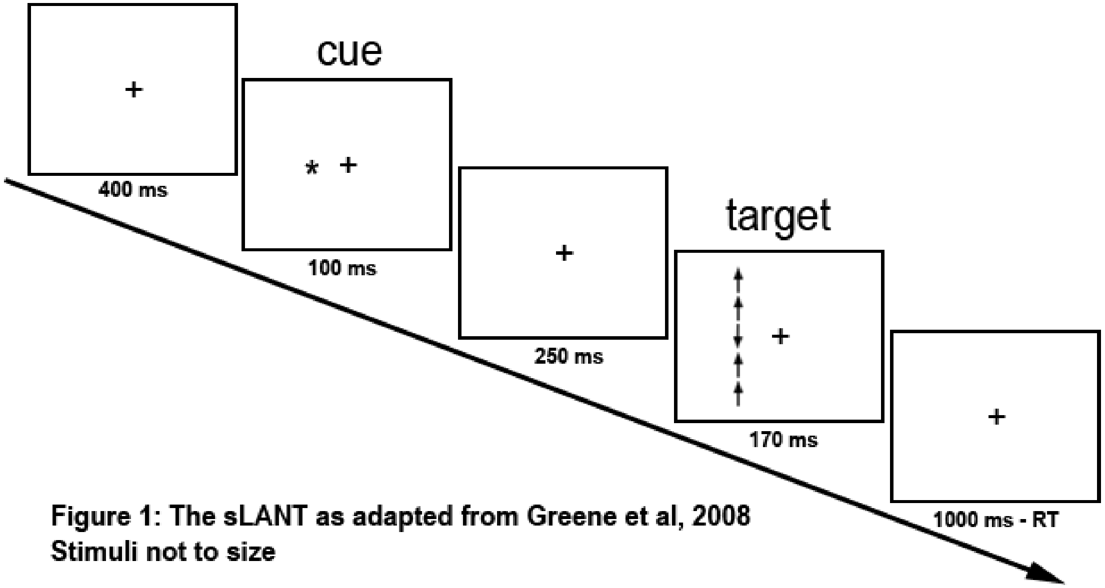
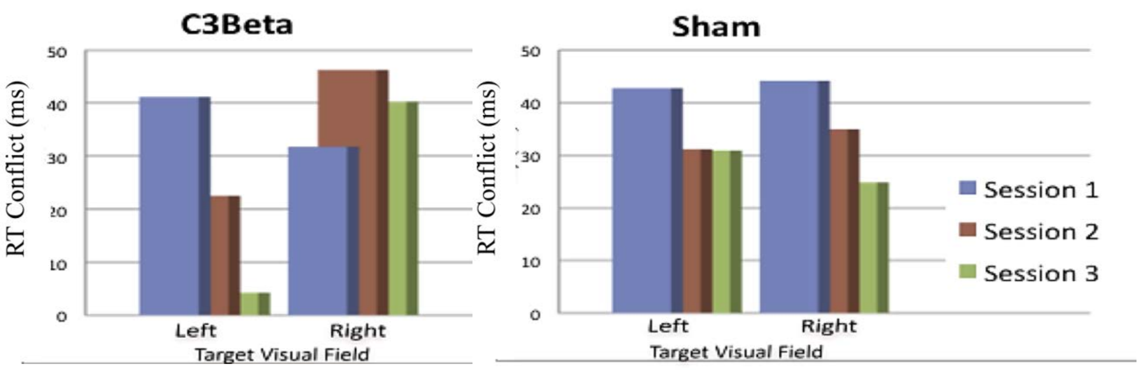
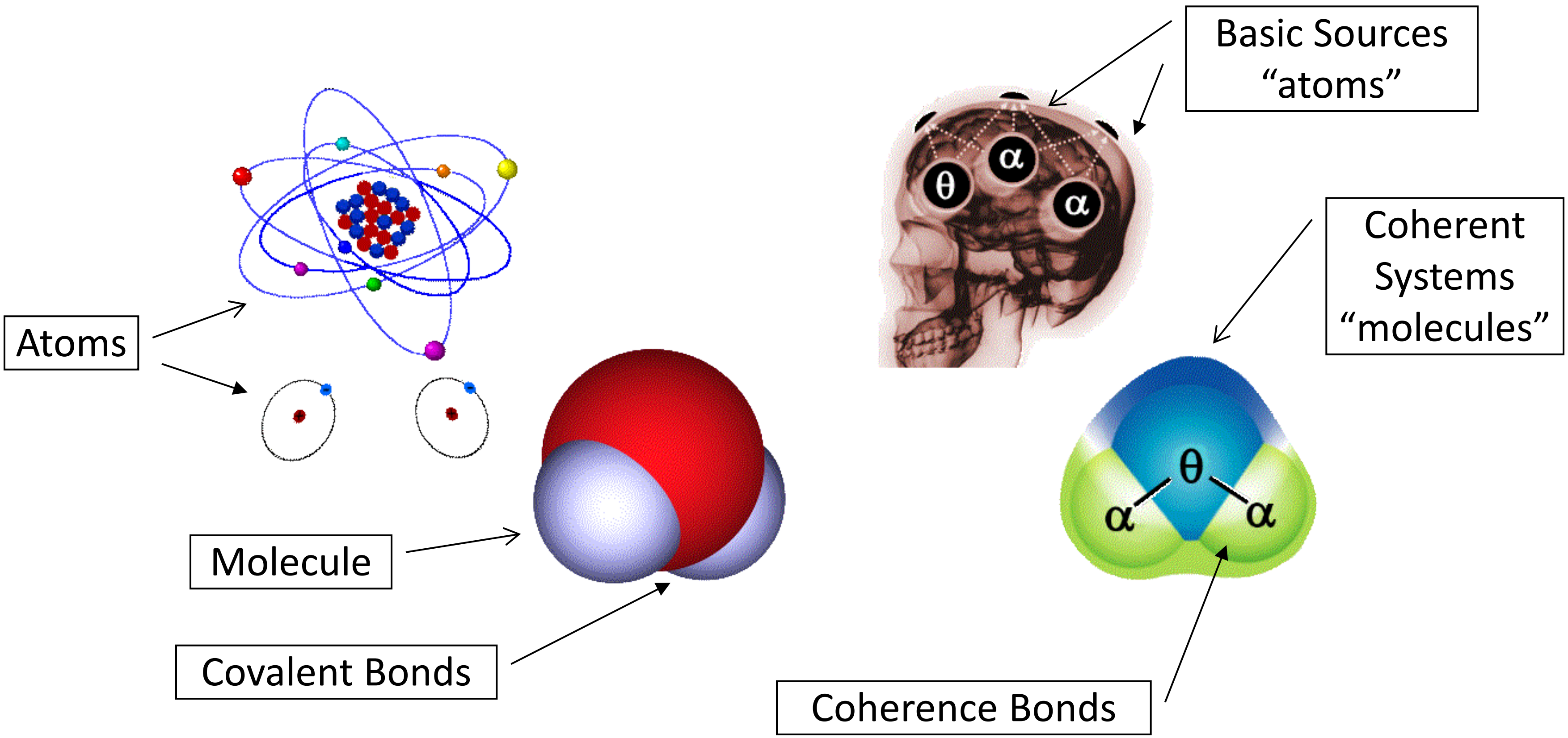


Figure 1: The sLANT as adapted from Greene et al, 2008
Stimuli not to size

Training Beta at C3 Selectively Reduced Conflict in the Right Hemisphere



EEG "Atoms"


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

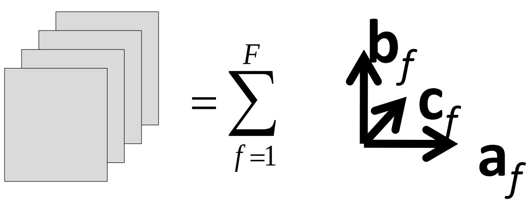
Brain Networks of Human Attention and Performance

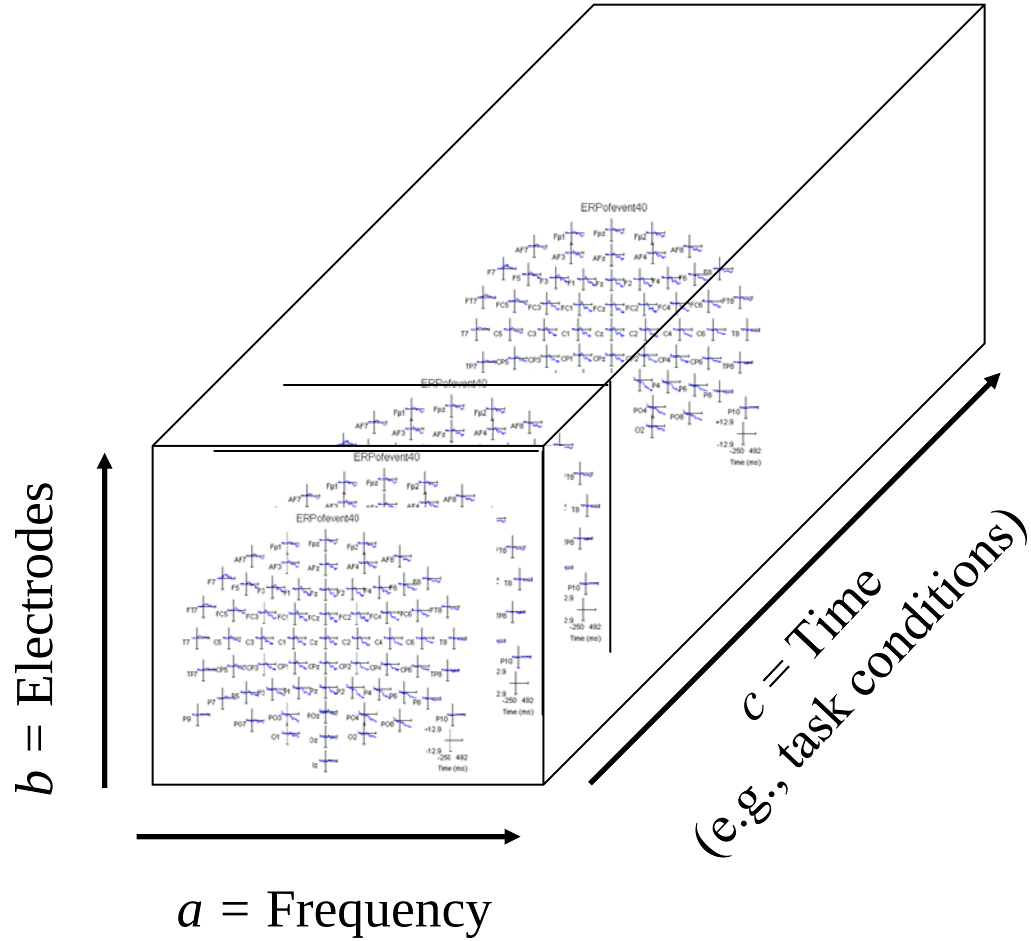
Atomic Decomposition of EEG with PARAFAC

Parallel Factor Analysis Model:

- Recorded EEG is treated as a tensor product of three modes: frequency, electrode, and time + random error
- The modes are simultaneously decomposed into a unique set of latent variables or "atoms."
- Unlike PCA or ICA, atoms are uniquely determined by the EEG
- Any given sample of EEG is composed of a mixture of atoms

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

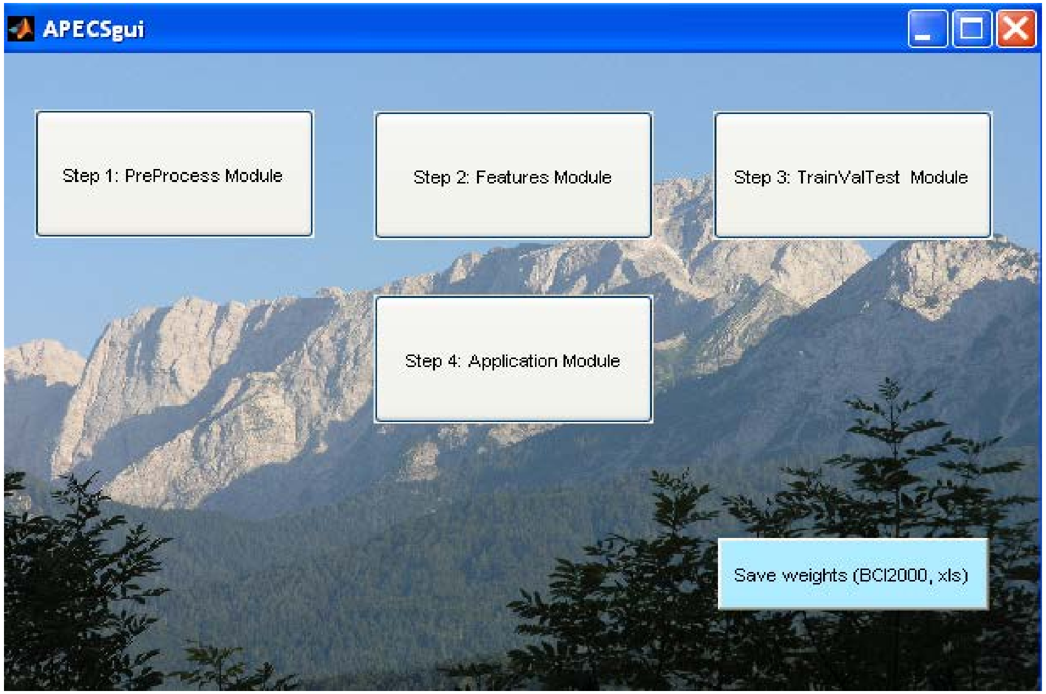




APECSgui

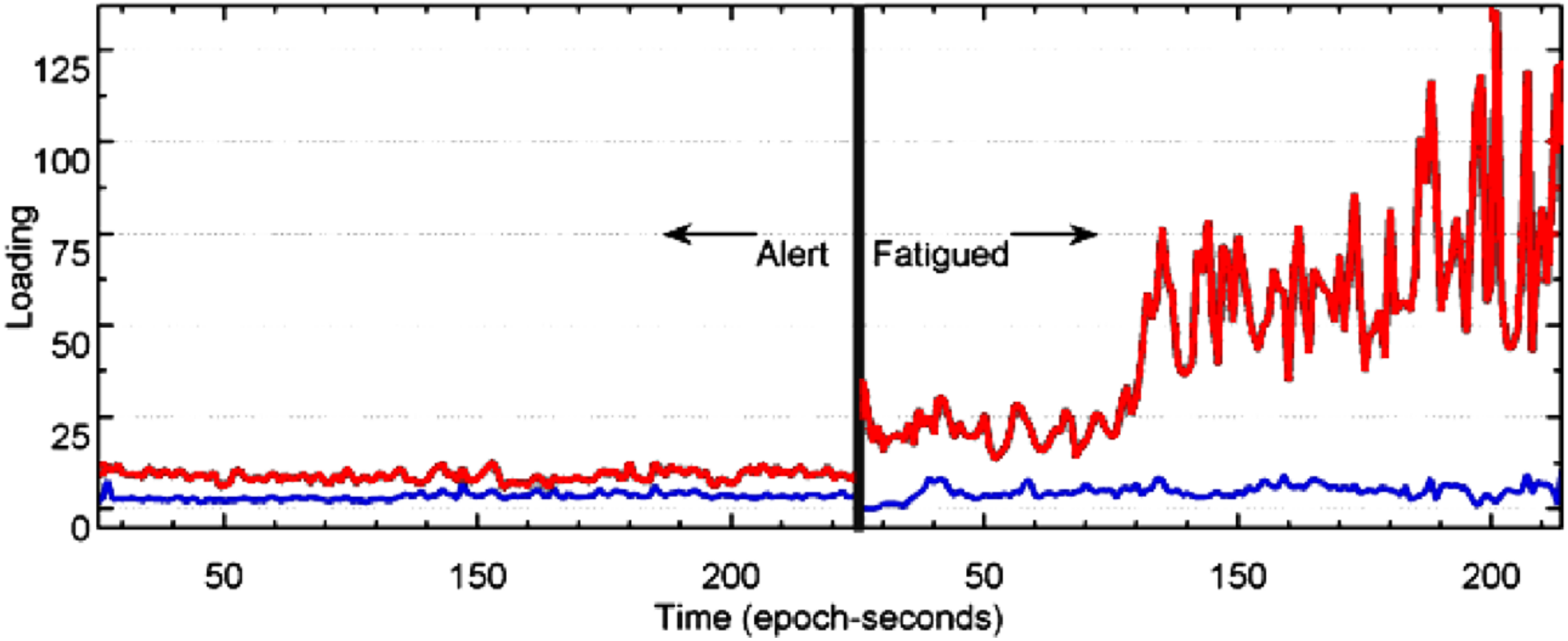
APECSgui: A MATLAB Toolbox for EEG Processing and Multiway Analysis

- APECSgui was developed by PDT and partly supported by ARO / ARL Infrastructure Funds and the NOIT Project
  - Import various EEG formats
  - Preprocessing (filter, resample, reference, reject artifact, etc.)
  - Spectral and coherence features
  - Compute machine-learning models including: PCA, PLS & KPLS, PARAFAC, NPLS
  - Validate models with various sampling methods
  - Export models to EETrac for real-time applications
- New interoperability:
  - Spherical & 3D Mesh Laplacian (Nunez & Srinivasan)
  - sLORETA (Key Institute)
  - Brain Vision Analyzer 2 (Brain Products GMBH)
- APECSgui and EETrac are transition options with 6.2 or SBIR support



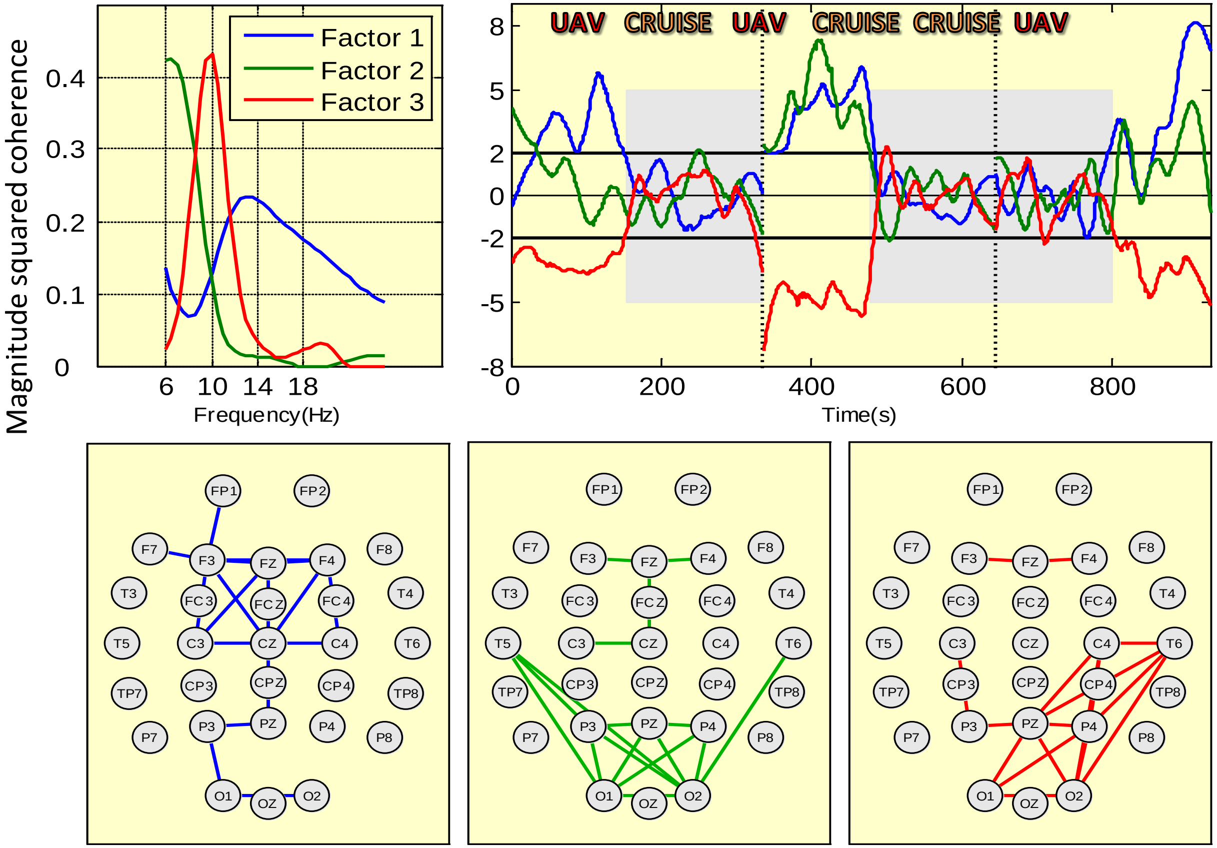
EEG Atoms Track Mental Fatigue

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

Brain Networks of Human Attention and Performance

Repeatability of EEG Atom Measurement

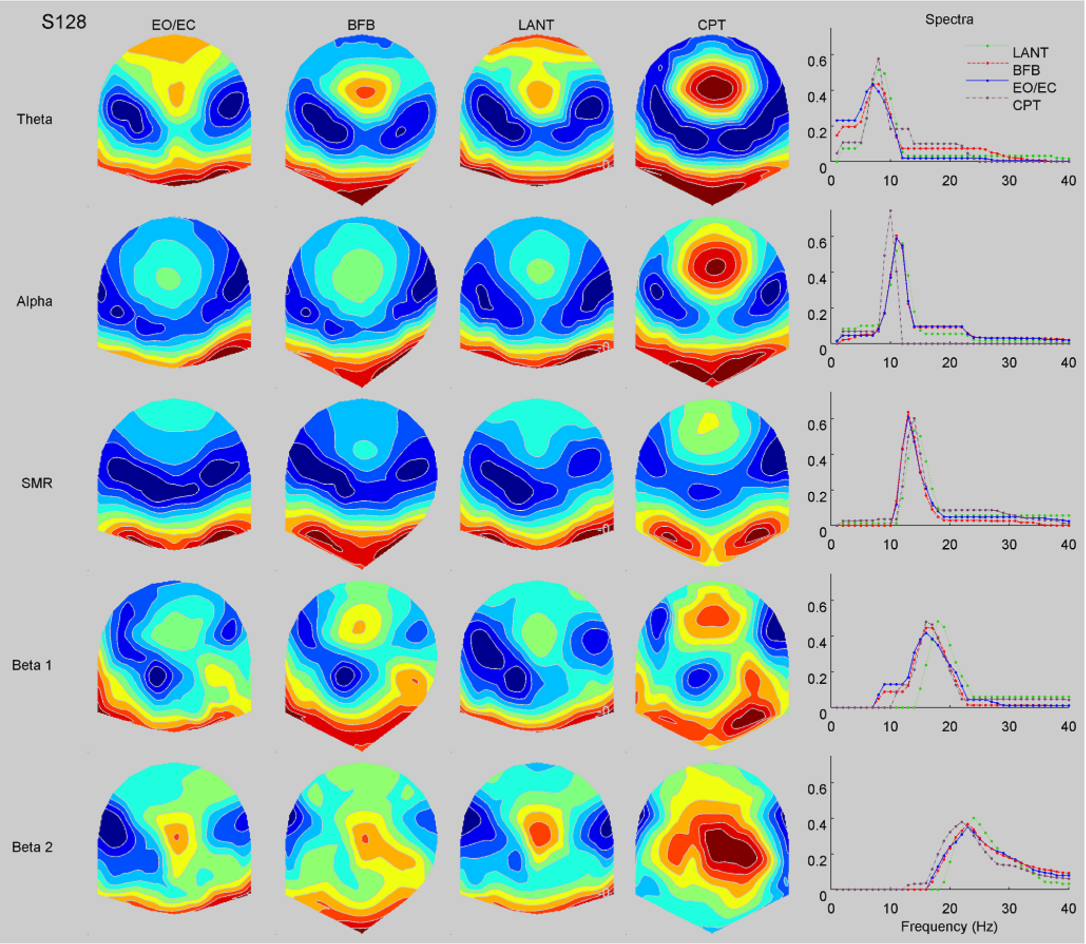
Objective: determine consistency of EEG atoms within and among subjects performing various tasks.

Approach:

- EEG data from 35 healthy UCLA undergrads
- Measured with 64 electrodes on four separate days over a period of one month.
- Each task repeated every test day
    - Eyes closed and eyes open resting states; pre & post session
    - EEG Biofeedback training
    - sLANT – speeded lateralized attention network test
    - CPT – continuous performance test

Result:

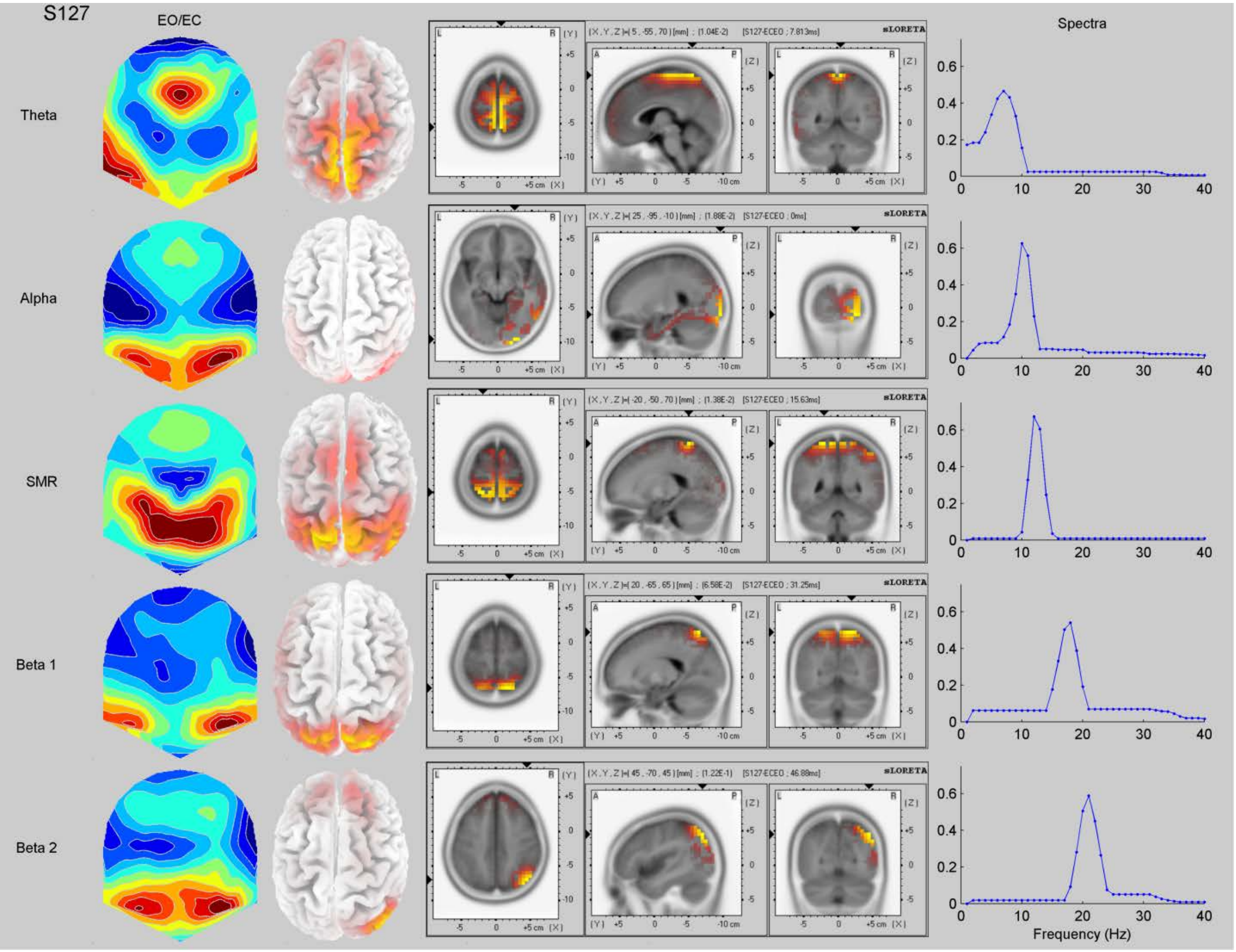
- EEG atoms show good consistency within subjects across tasks in frequency and electrode loadings
- Individual differences appear in frequency and electrode loadings, but general pattern is preserved



Brain Networks of Human Attention and Performance

Sources of EEG Atoms Localized with sLORETA

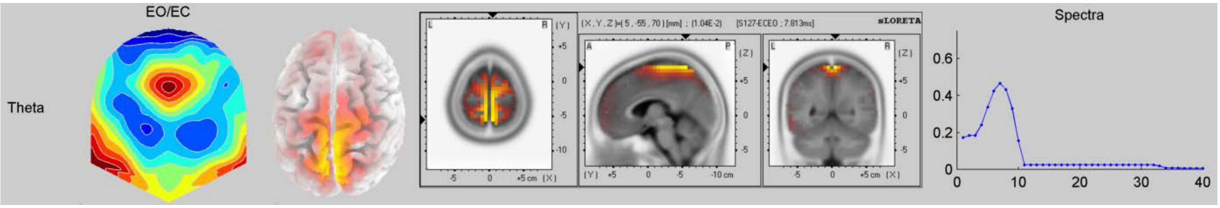
- Pseudo-inverse methods such as sLORETA may be applied to EEG atom loadings for source localization.
- We are using these methods to correlate EEG atoms with brain networks (some of them overlapping) identified with other methods (e.g. fMRI)
  - Default mode network
  - Dorsal attention network
  - Self network
  - Control network
  - Visual, auditory, and verbal processing networks

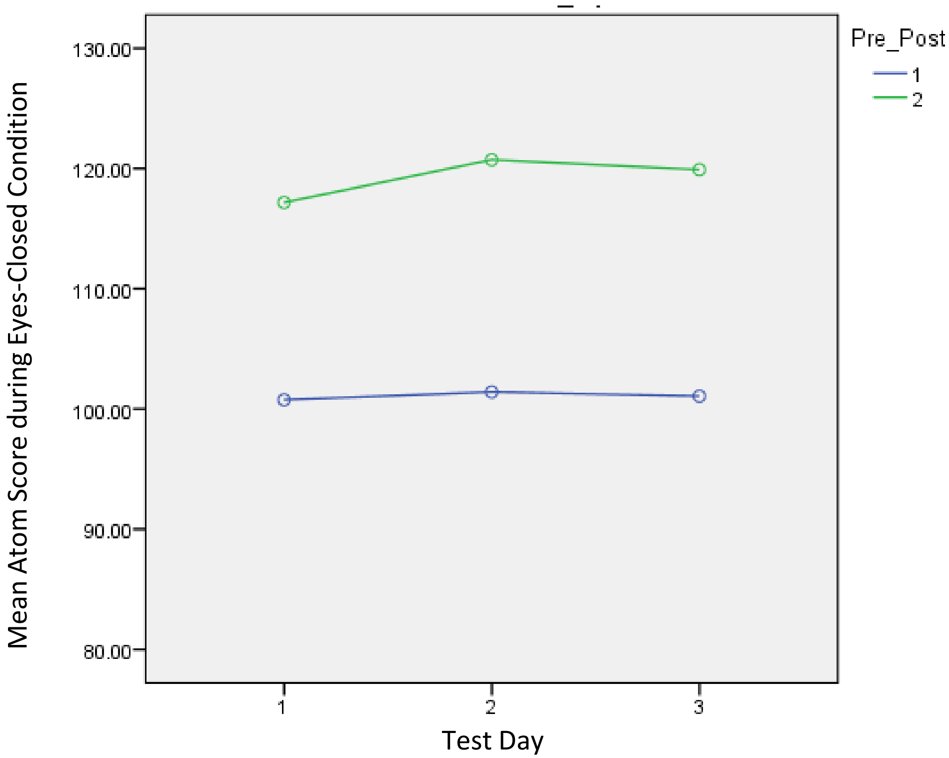


Brain Networks of Human Attention and Performance

Estimate Cognitive State using EEG Atoms: Fatigue

- 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)

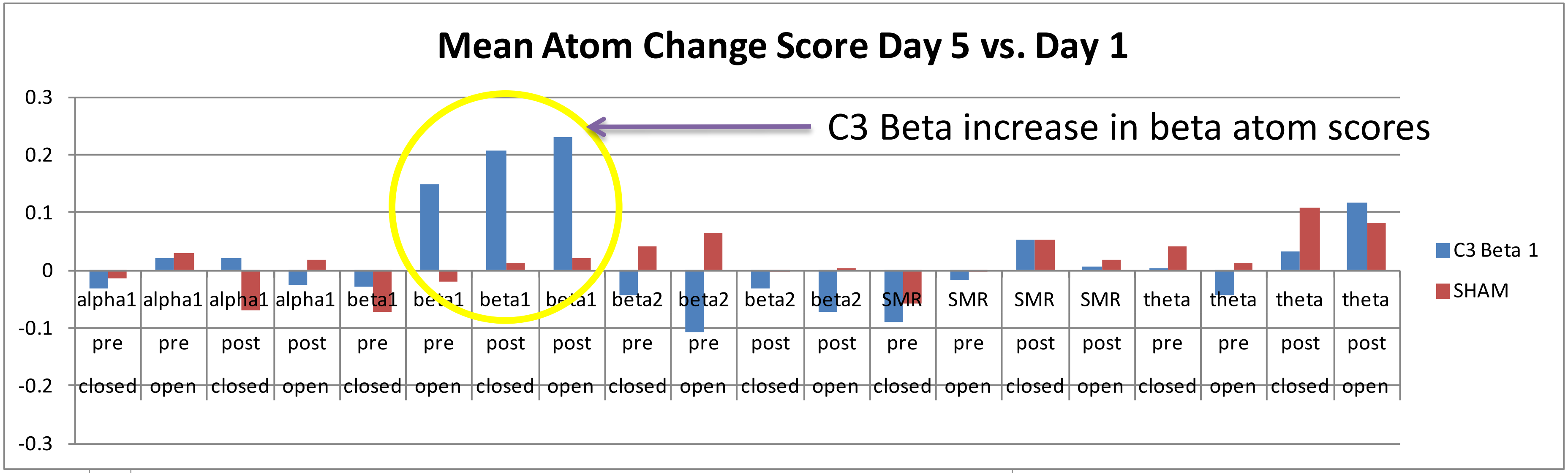


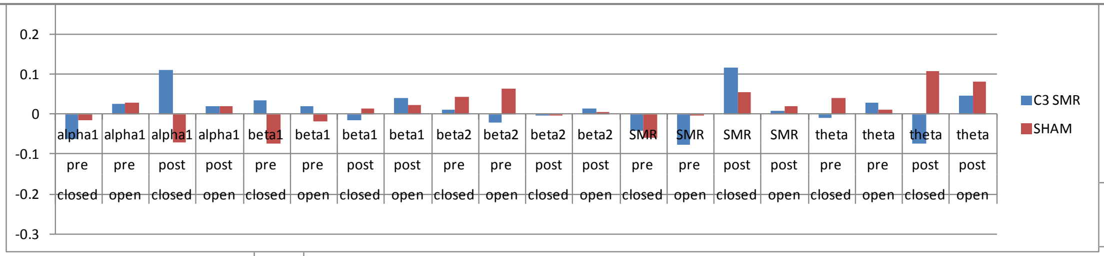


Neurofeedback Experiment

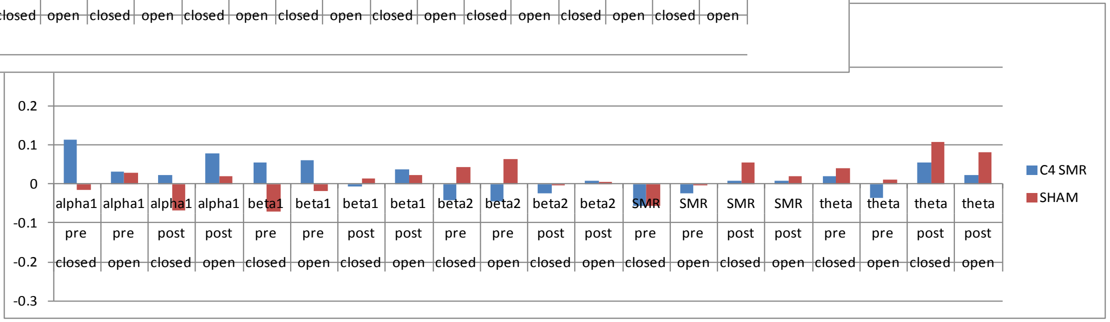
- 30 right-handed college undergraduate students served as participants
- Each performed six sessions of neurofeedback training on separate days, inlcuding eyes open/closed baselines before and after the session
- LANT performance was tested on four of the training days
- Controls for placebo effects and tests for site of training and site of action specificity included:
  - Trained using C3 beta, or C3 SMR, C4 SMR or Sham
  - Experiment was double blind concerning the type feedback
  - The sham group got a random mix of other's feedback
- Only the C3 beta group changed LANT performance: they improved response speed for conflicting targets in the left visual field
- Traditional EEG measures showed no changes due to feedback in the trained band or at trained electrode
- EEG atom analyses showed an increase in the baseline (eyes open/closed) beta 1 atom scores for the C3 beta group only

Atom Changes after 5 NFT Sessions





C3 SMR



C4 SMR

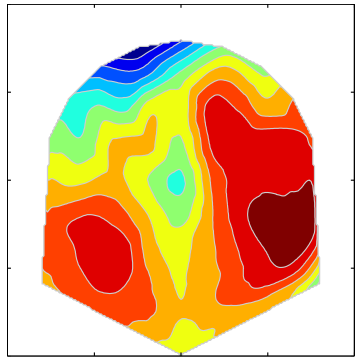
LORETA (CSD) Changes for Specific EEG Atoms

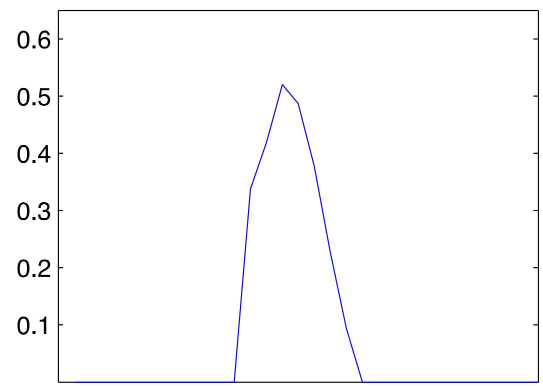
How can we find the LORETA solutions for EEG atoms?

- We use atom time scores to pick EEG segments in which the atoms contributed a high level of power to the EEG
    - 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
- Then we compute the average LORETAs of many such pure EEG segments and compare averages of different conditions

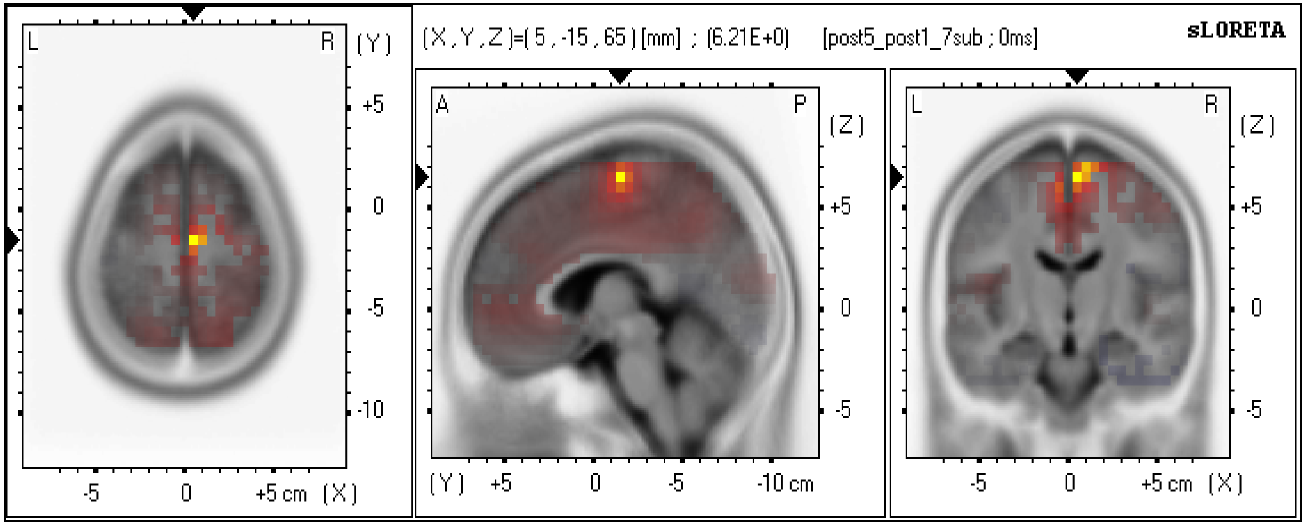
Beta 1 Atom Estimated from Seven C3-beta and Seven Sham Subjects

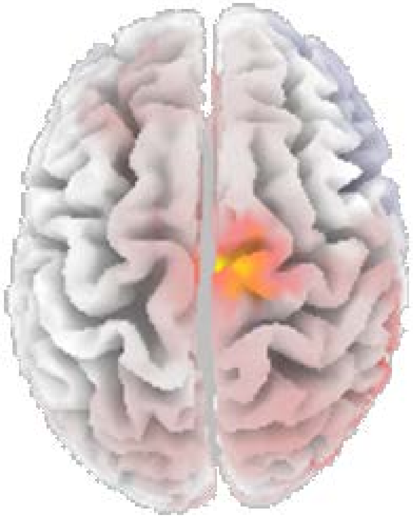
Separate atom estimates for EO Pre conditions and EO Post conditions





Beta 1 Atom LORETAs Estimated from Seven C3 beta Subjects

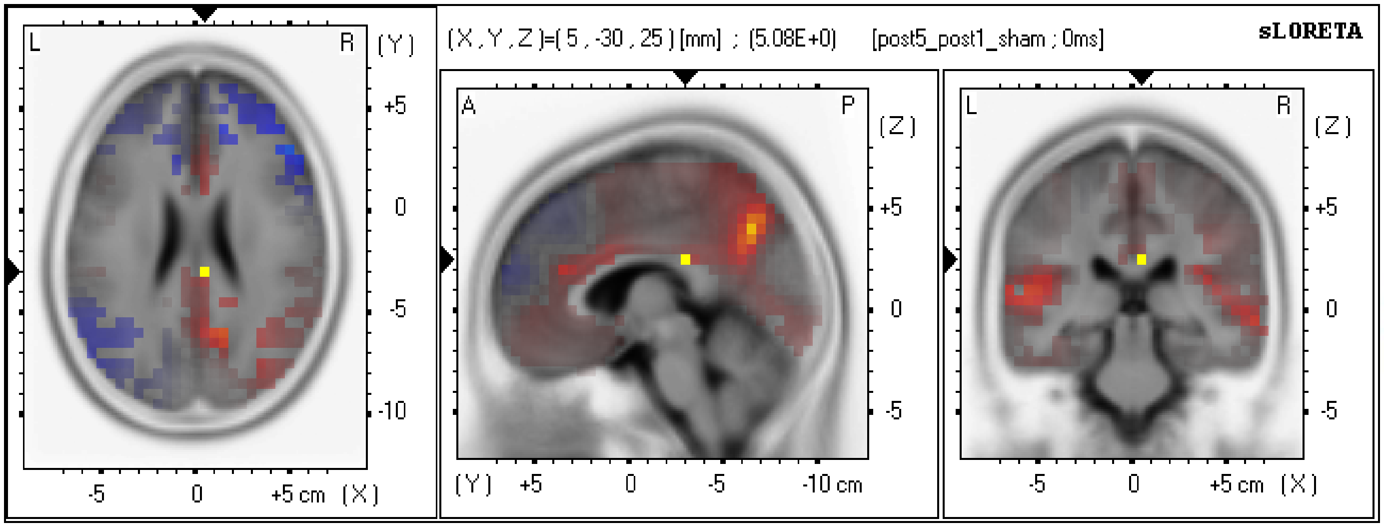


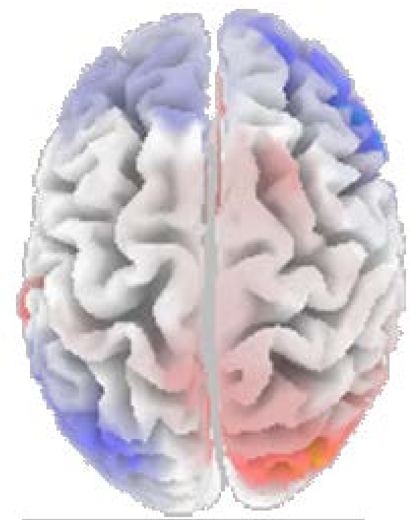


This is a parametric statistical test of the difference between the average LORETA for pure beta-1 atom segments from Day 5 minus same segments for Day 1 in the seven **C3 Beta** subjects.

The maximum t-statistic value was **marginally significant** (t = 6.2 p = 0.078), and was located in the right Brodmann area 6, medial frontal gyrus, which may correspond to a **sensorimotor network**.

Beta 1 Atom LORETAs Estimated from Seven C3 Sham Subjects



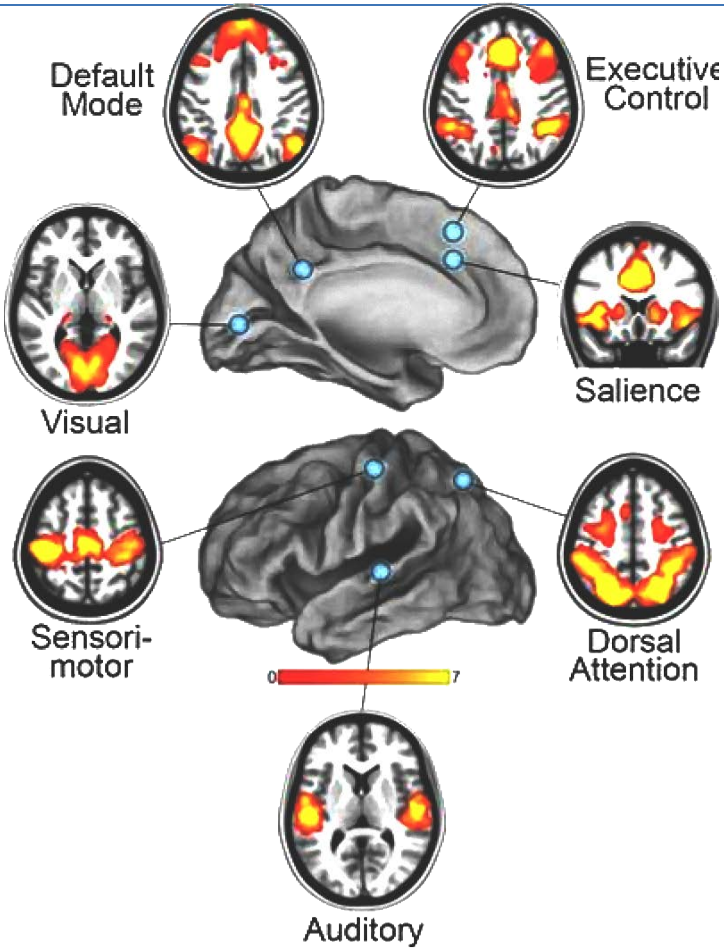


This is a parametric statistical test of the difference between the average LORETA for pure beta-1 atom segments from Day 5 minus same segments for Day 1 in the seven **SHAM** subjects.

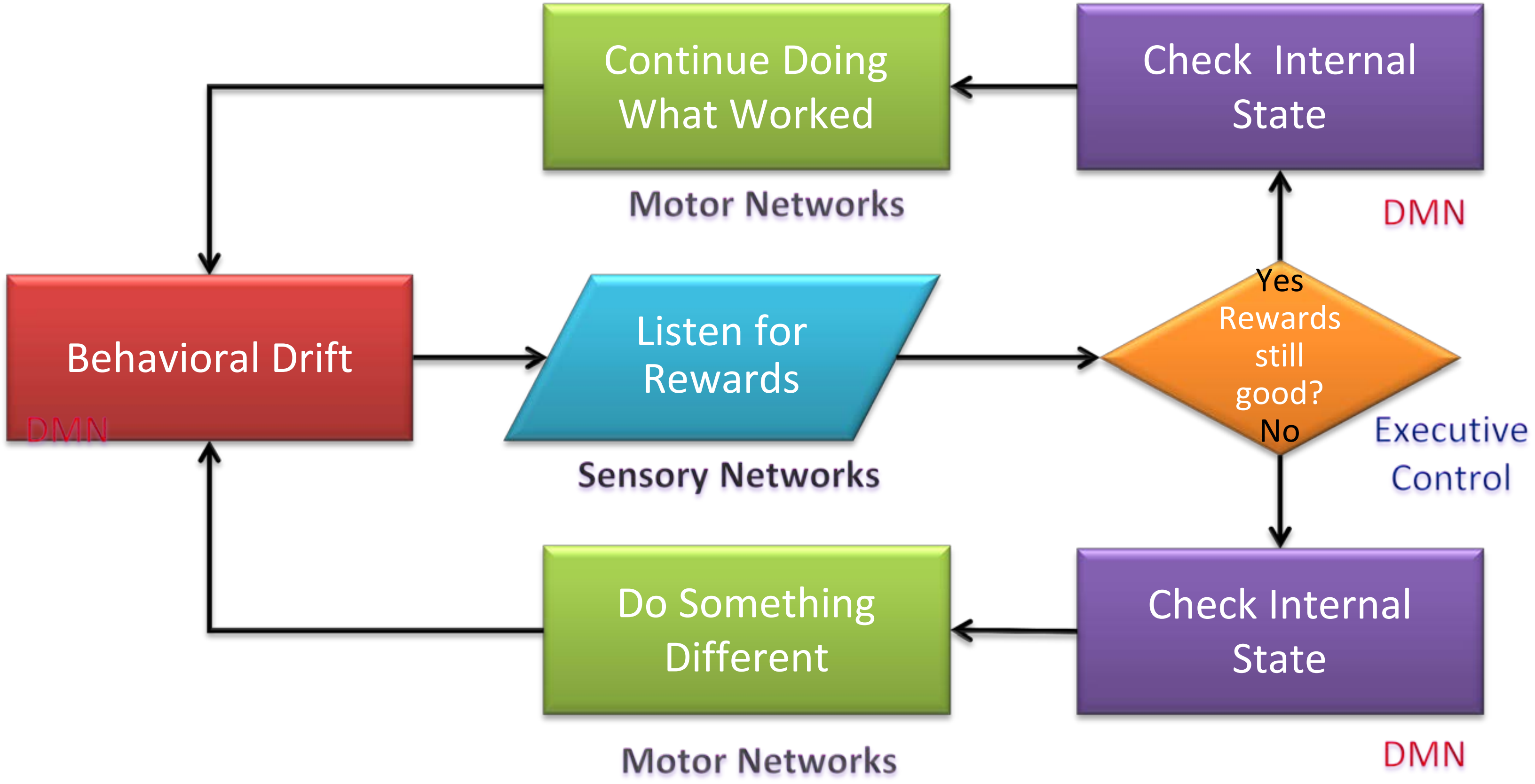
The maximum t-statistic value was **not significant** (t = 5.1 (p = 0.32) and was located in Brodmann area 23, posterior cingulate cortex

Do EEG Atoms or Functional Networks Relate Models of Neurofeedback Training?

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 IFS 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

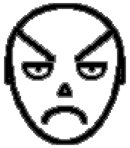


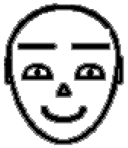
A (Network) Model of EEG Biofeedback for Performance Enhancement



The eLANT Experiment

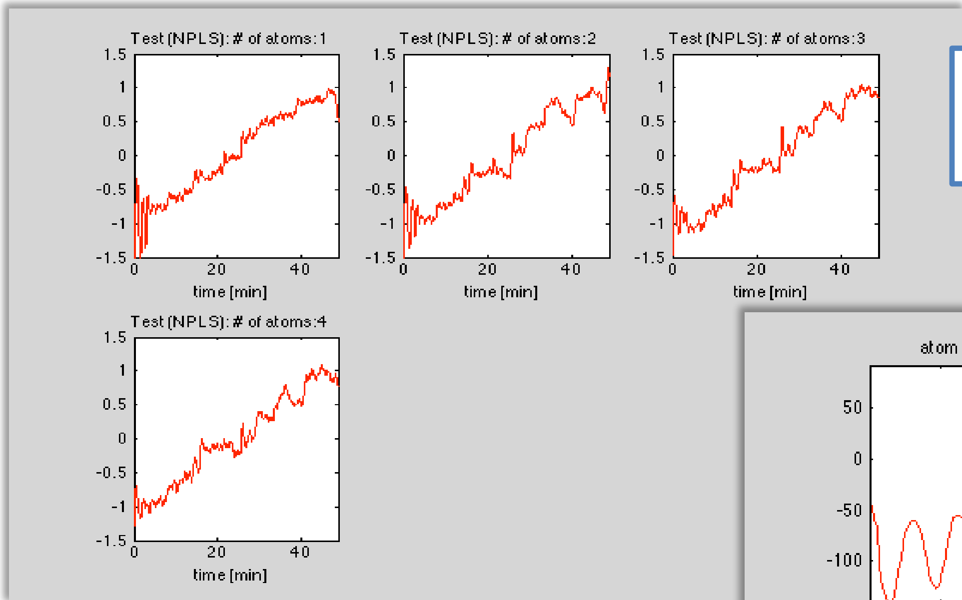
- eLANT: an ecologically valid version of the LANT
- Timing, stimulus location and targets are similar to the LANT
- Recorded high-density 64 channel EEG + 2 channel EOG
- Differences from the LANT:
  - Backgrounds with varying emotional valence (happy, fearful)
  - Cues with varying emotional valence (happy, sad)
  - Self-paced



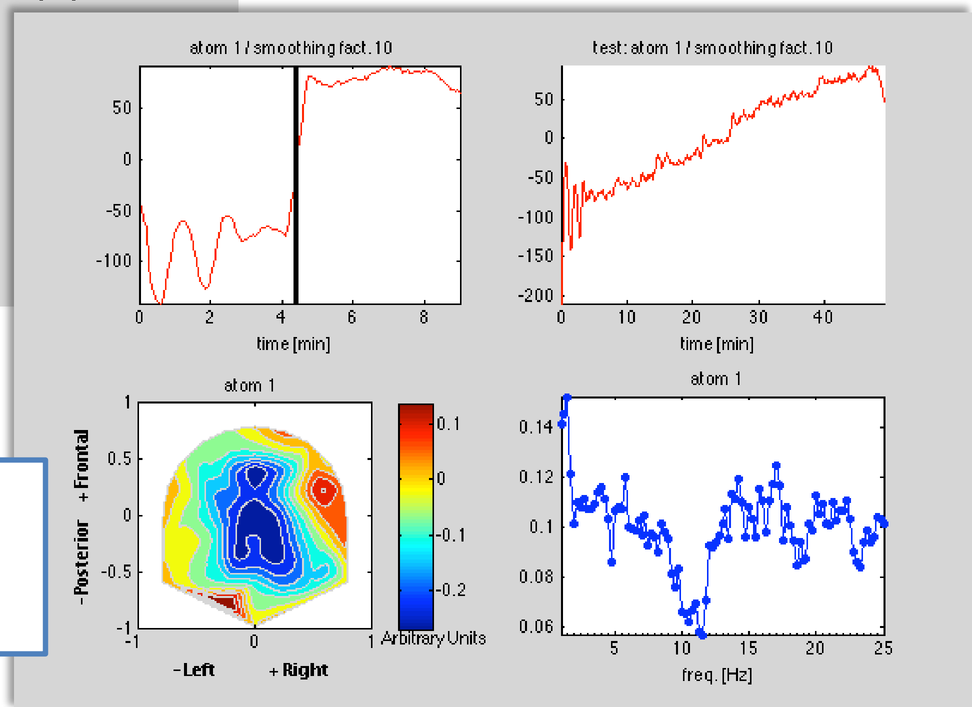


- Fatigue levels assessed pre- and post-test using POMS and T-MENSTAT questionnaires
- 20 right-handed college undergraduates served as participants

NPLS Classification of Mental Fatigue in eLANT Task: S999

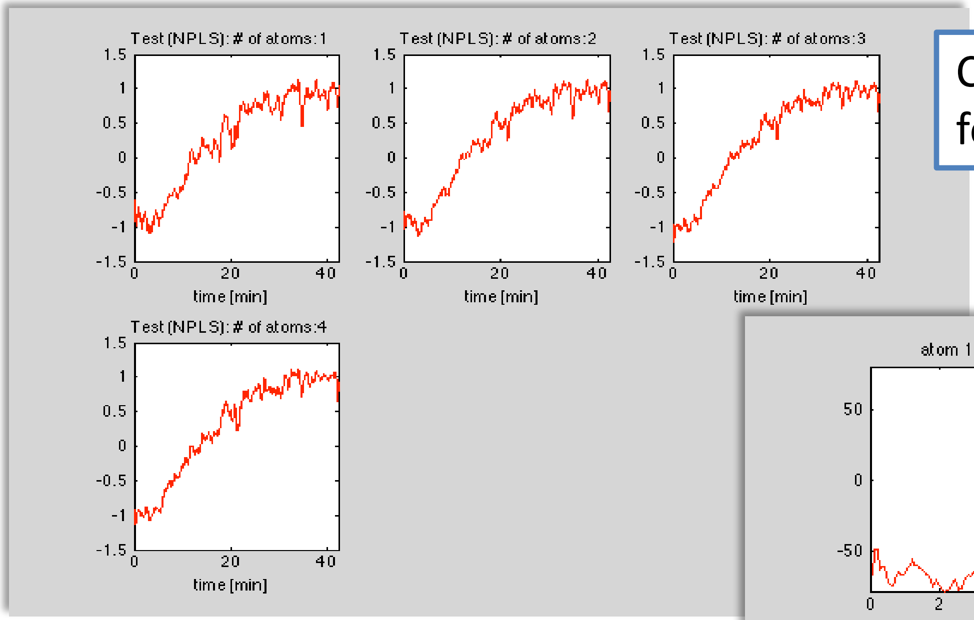


Classifier output over time on task for increasing number of atoms

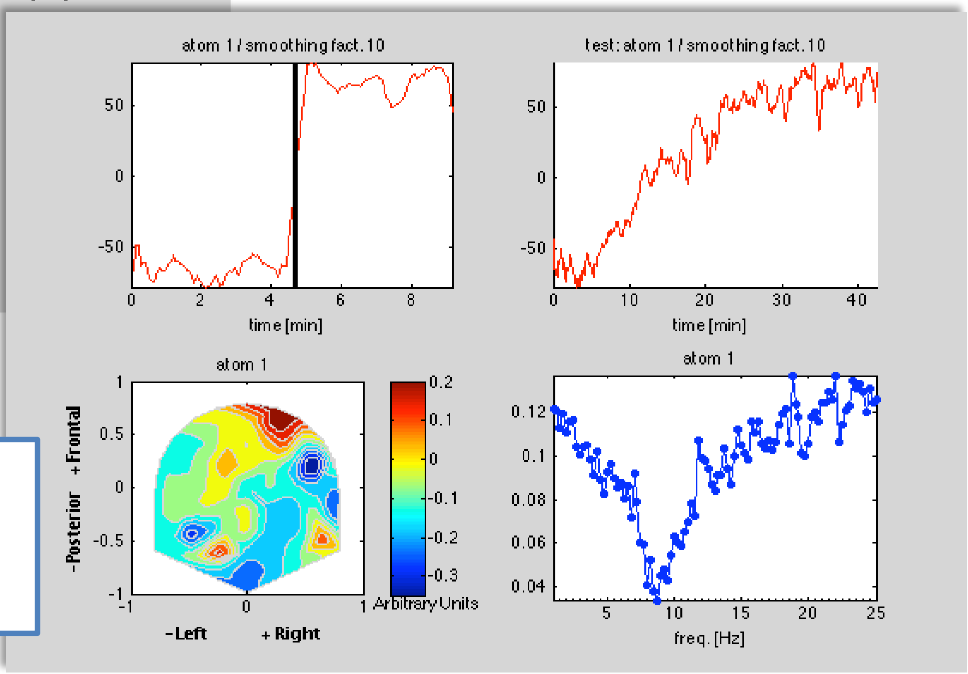


Space-time-frequency loadings and classifier performance for first atom

NPLS Classification of Mental Fatigue in eLANT Task: S100

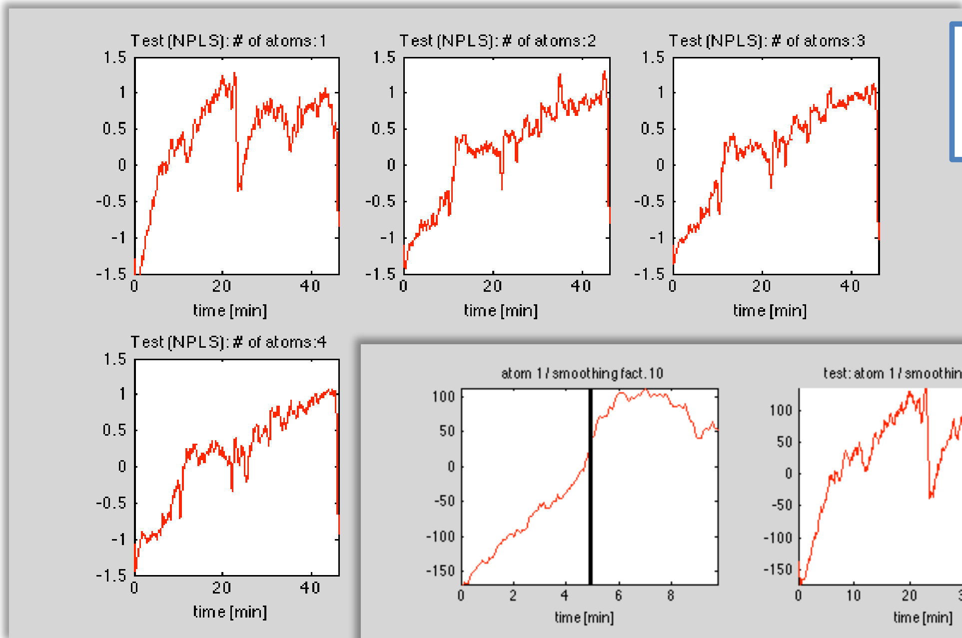


Classifier output over time on task for increasing number of atoms

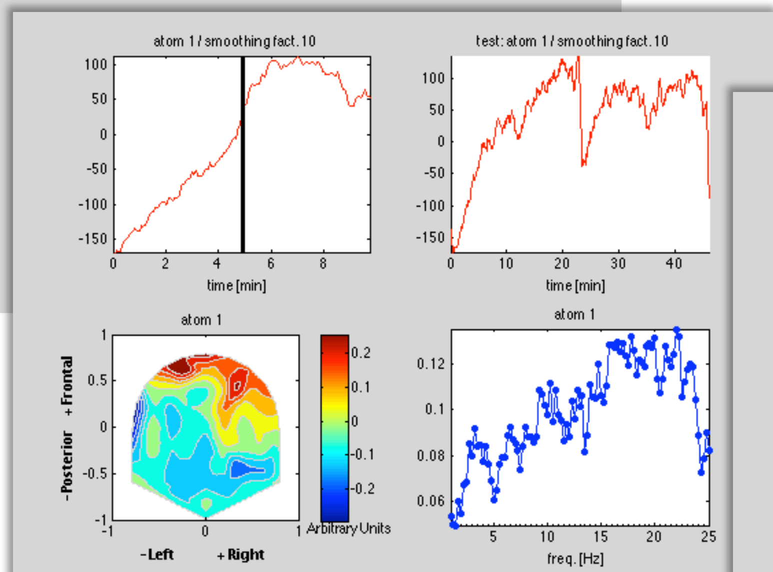


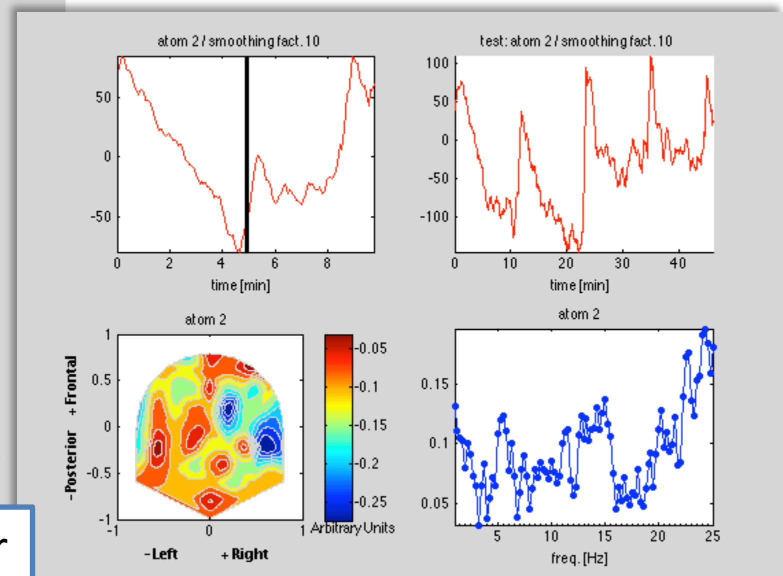
Space-time-frequency loadings and classifier performance for first atom

NPLS Classification of Mental Fatigue in eLANT Task: S101



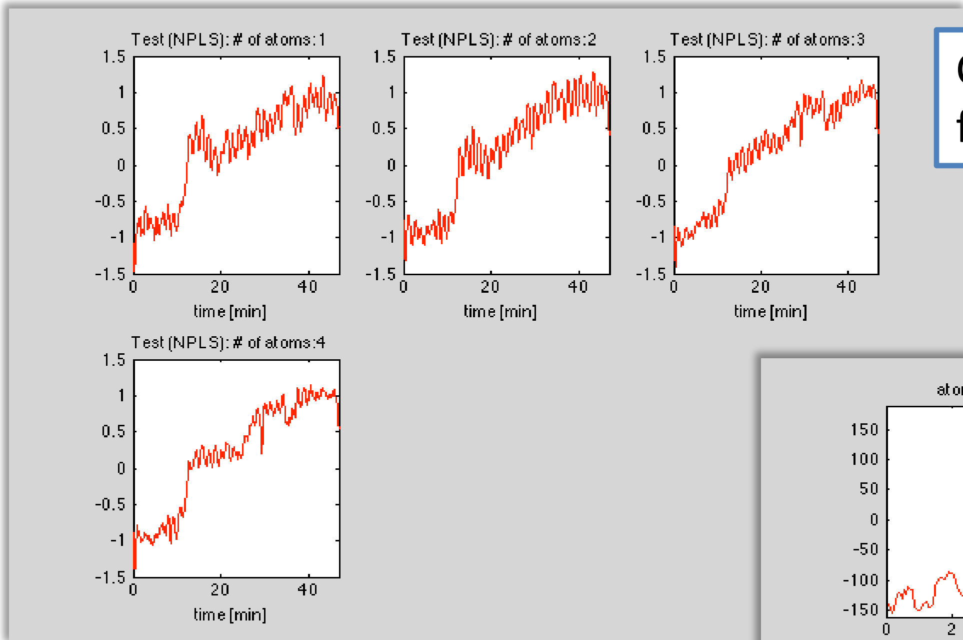
Classifier output over time on task for increasing number of atoms



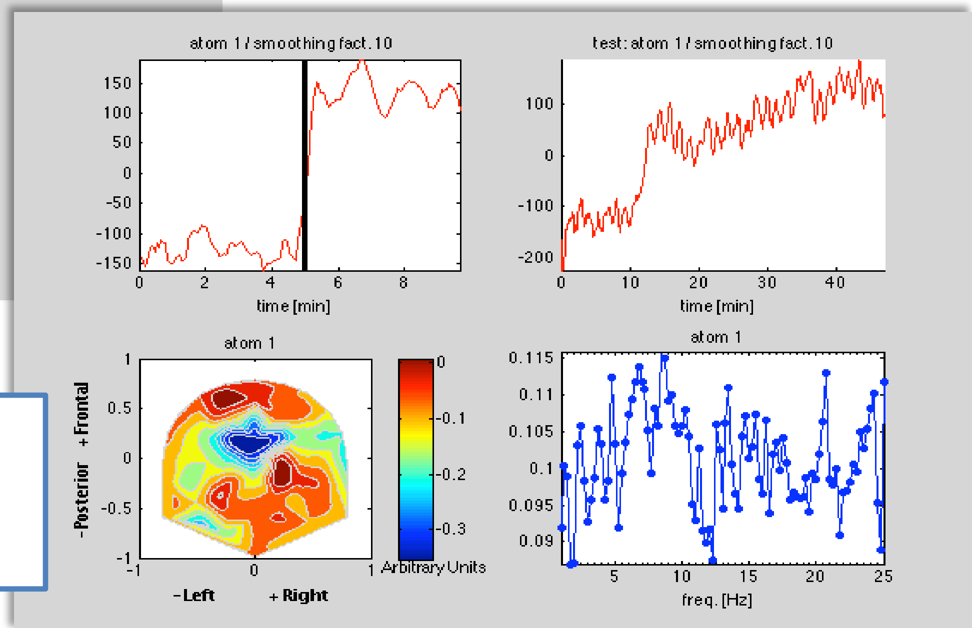


Space-time-frequency loadings and classifier performance for for 1st & 2nd atoms

NPLS Classification of Mental Fatigue in eLANT Task: S103

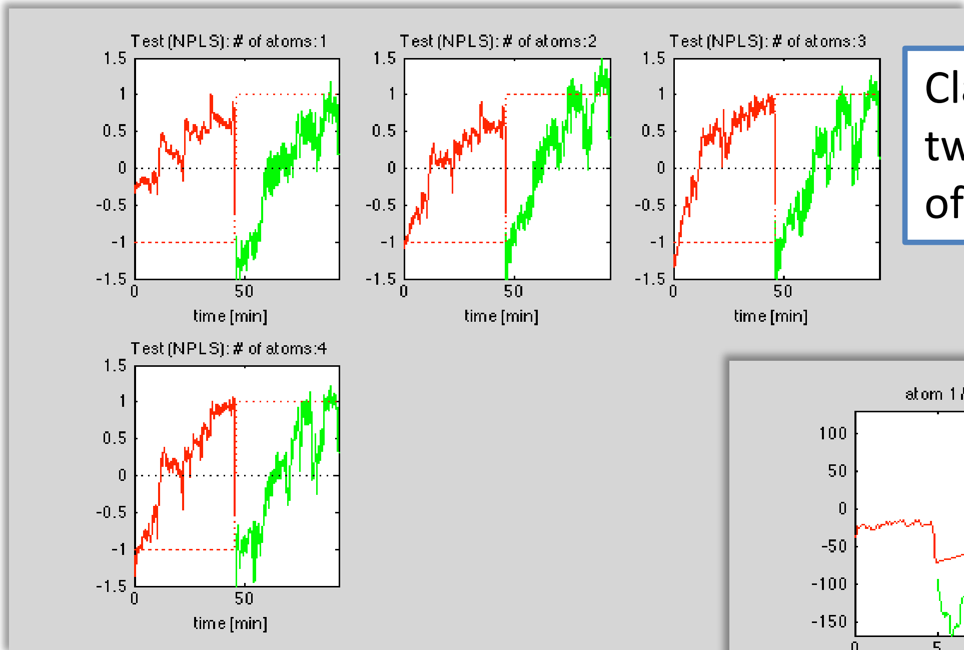


Classifier output over time on task for increasing number of atoms

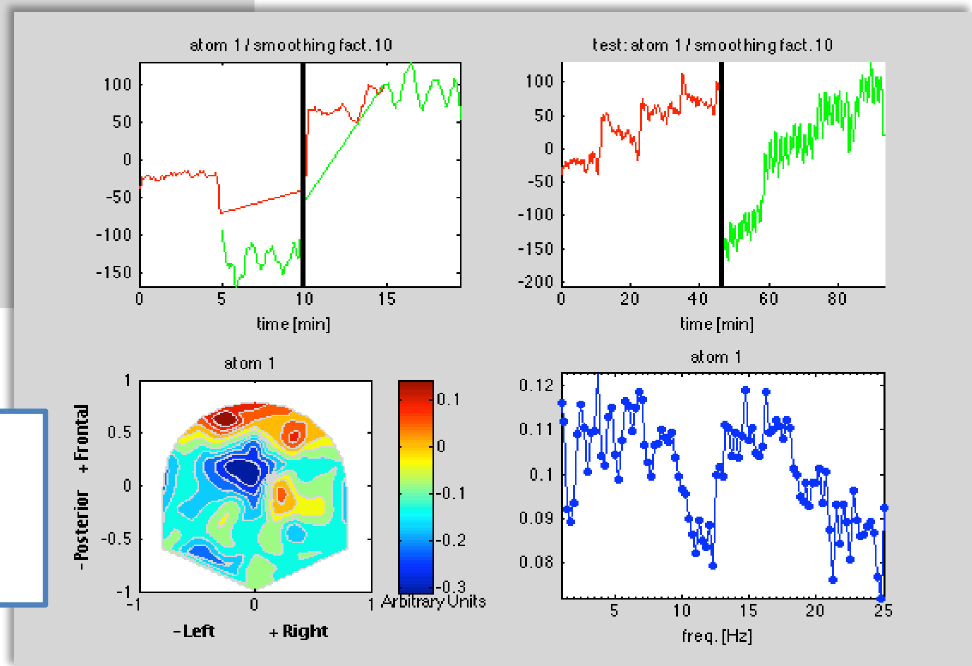


Space-time-frequency loadings and classifier performance for first atom

NPLS Classification of Mental Fatigue in eLANT Task: S103 2 Days

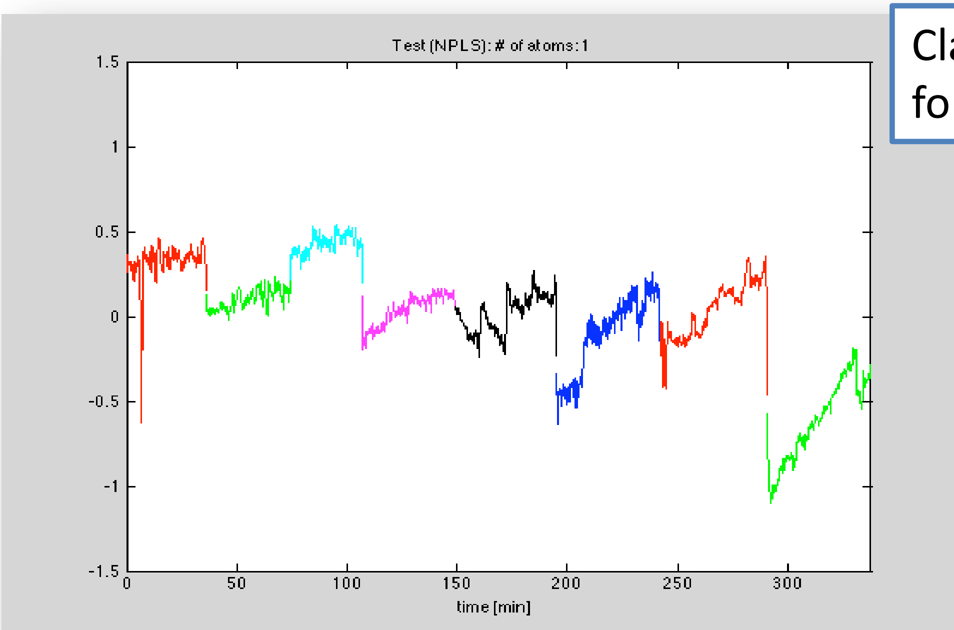


Classifier output over time on task on two separate days for increasing numbers of atoms

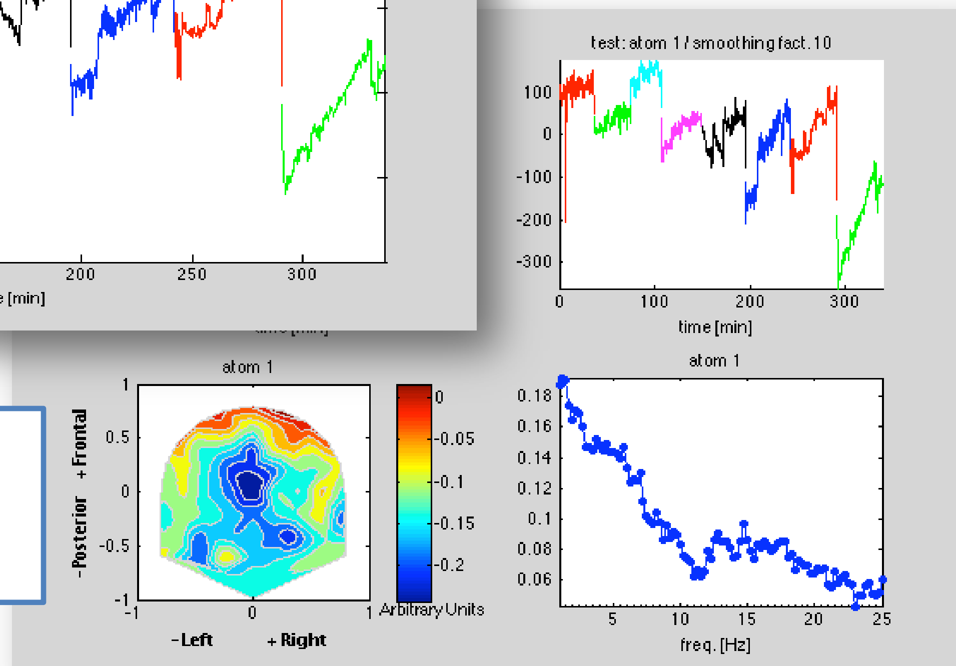


Space-time-frequency loadings and classifier performance for first atom

NPLS Classification of Mental Fatigue in eLANT Task: 4 Ss x 2 Days



Classifier output over time on task for 4 Ss x 2 sessions (days)



Space-time-frequency loadings and classifier performance for first atom

Summary

- EEG atoms can track mental states and may assess outcomes of NFT training
  - The baseline power level of a beta-band EEG atom increased in a group trained to increase beta amplitude at electrode C3
  - This C3 beta group significantly improved performance for conflict targets in the LVF during the LANT task
- Developed NPLS classifiers of mental fatigue based on EEG power atoms with dimensions of time, electrode and frequency
  - NPLS classifiers tracked the development of mental fatigue in individuals during eLANT task sessions
  - Demonstrated a multi-subject, multi-session NPLS classifier

Future Directions

- Continued work on interpreting the physiological and network significance of EEG atoms
- Normative multi-resolution "Atomic" databases for quantitative EEG (QEEG) diagnosis of disorders
- "Atomic" neurofeedback methods for
  - Treatment of attention/learning/neurological disorders including traumatic brain injury
  - Optimizing human performance
- Adaptive interfaces and human systems engineering using EEG atoms to dynamically track operator functional state