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14. ABSTRACT

This report discusses resarch in progress on human performance and stress, fatigue, inattention, task complexity. The approach involves using neuroergonomic models and control systems to model, estimate and control cognitive states.

15. SUBJECT TERMS

fatigue mental workload cognitive status EEG machine learning algorithms

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Report Title

Advanced Physiological Estimation of Cognitive Status

ABSTRACT

This report discusses resarch in progress on human performance and stress, fatigue, inattention, task complexity. The approach involves using neuroergonomic models and control systems to model, estimate and control cognitive states.

Advanced Physiological Estimation of Cognitive Status

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Presentation to ARL
24 May 2011

Sponsored by
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Contract No. W911NF-11-C-0081
01 April 2011 – 31 March 2012

About PDT

- Research and Development Services
  - Technologies
    - Multimodal Integrated Bio-Sensing
    - Biomedical Signal Processing and Analysis
    - Custom Algorithm Development
  - Applications
    - Human Performance Optimization
    - Human-System Integration
    - Direct Neuro- Control and Biofeedback Systems

About this Contract

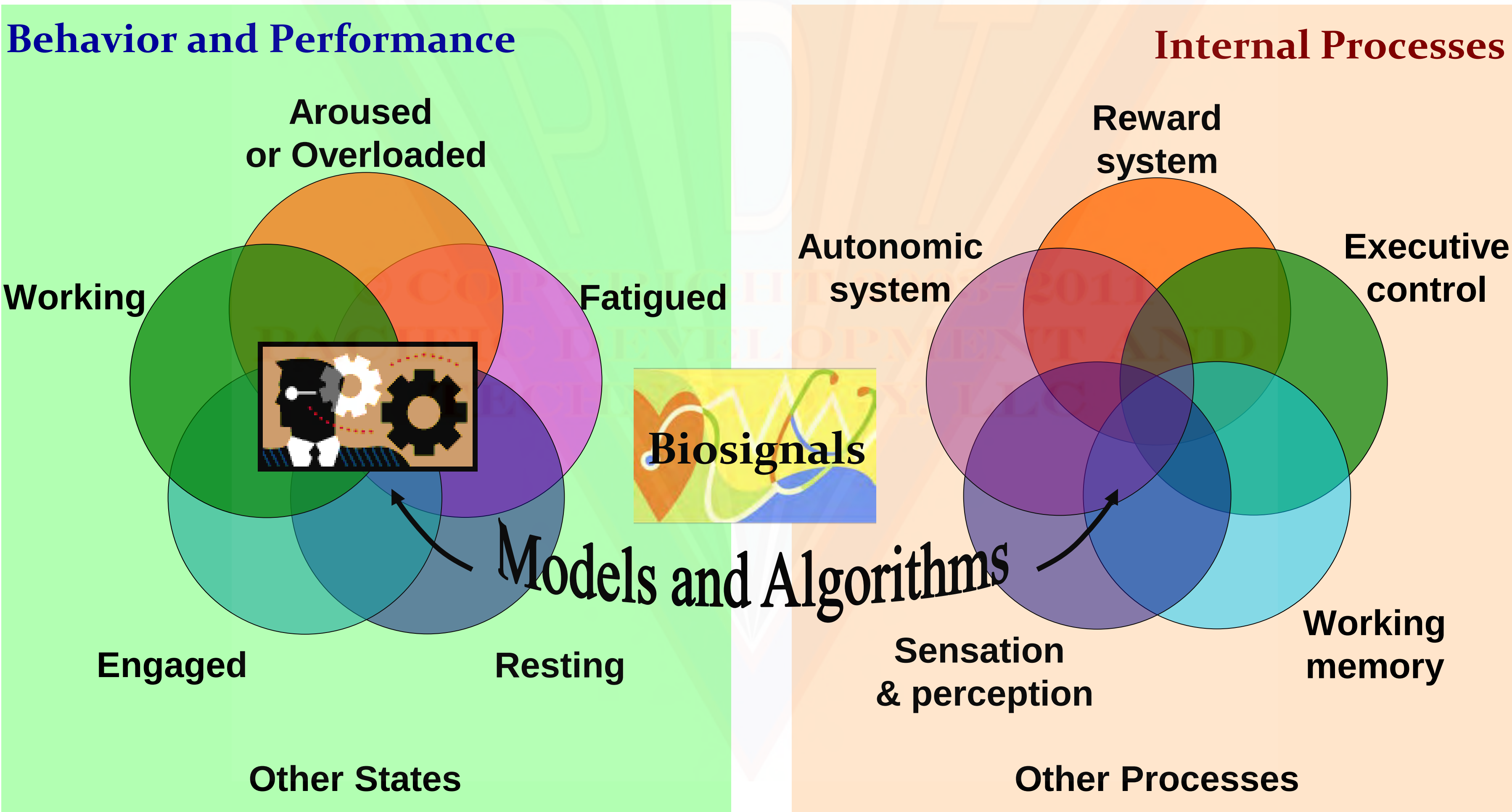
Two Related Proposals & Projects

1. “Neurosensory Optimization of Information Transfer (NOIT)”
   - ARO Proposal No. 56469-LS
   - Three-year basic research with UCLA team
2. “EEG-guided Input Lateralization and Hemispheric Activation with Neurofeedback for Display Data Control and Apprehension.”
   - ARO Proposal No. 59502-LS
   - One-year Infrastructure technology transfer to ARL

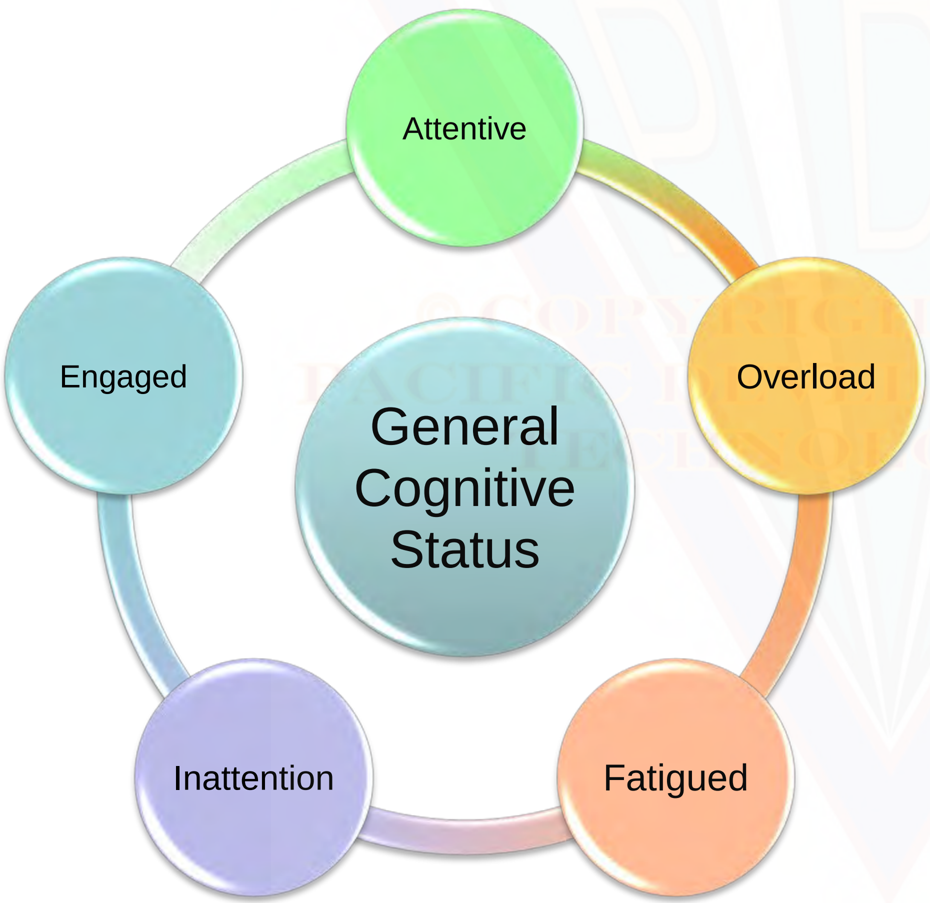
Outline

- Problems: stress, fatigue, inattention, task complexity
- Response: Neuroergonomic models and control systems
  - Create useful definitions of cognitive states
  - Model, estimate and control cognitive states
- Background (2003-2009)
  - Multimodal sensor-state models using PLS, KPLS, KPLS-SVC
  - Successful applications: **BCI, Fatigue, Engagement, Overload**
- New directions (2009-2011)
  - Truly multidimensional sensor-process models
  - Application of Multi-way methods (PARAFAC)
- Summary

Estimation of Cognitive States

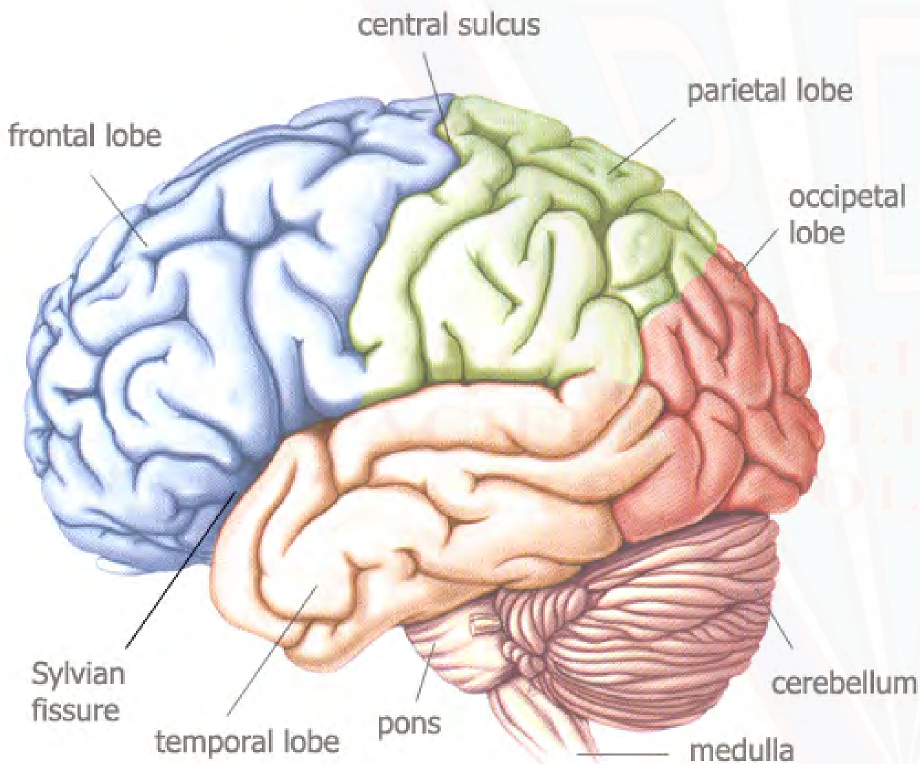


Cognitive State Constructs



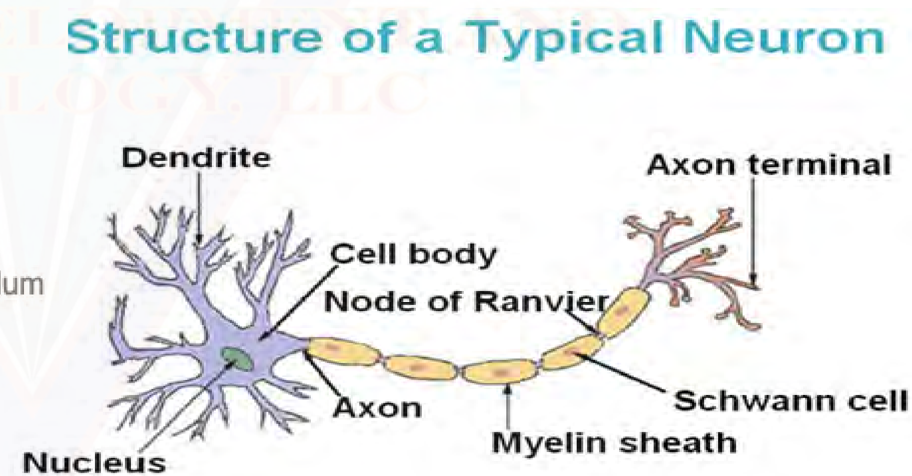
- **Inattentive:** resting, distracted, complacent, bored
- **Engaged:** attending to primary task with minimal effort (waiting)
- **Attentive:** attention and effort committed to primary task
- **Overload:** task demands exceed mental speed or skill level
- **Fatigued:** desire to with-draw attention and effort from a task; reduced executive control

Electroencaphalogram

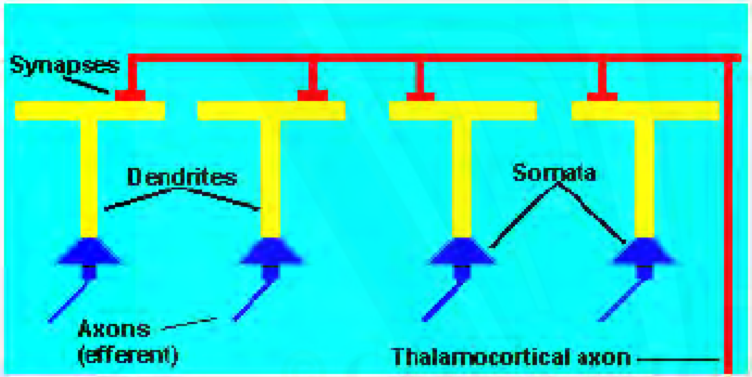


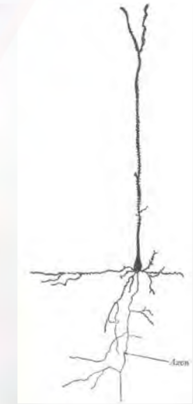
Cerebral Cortex

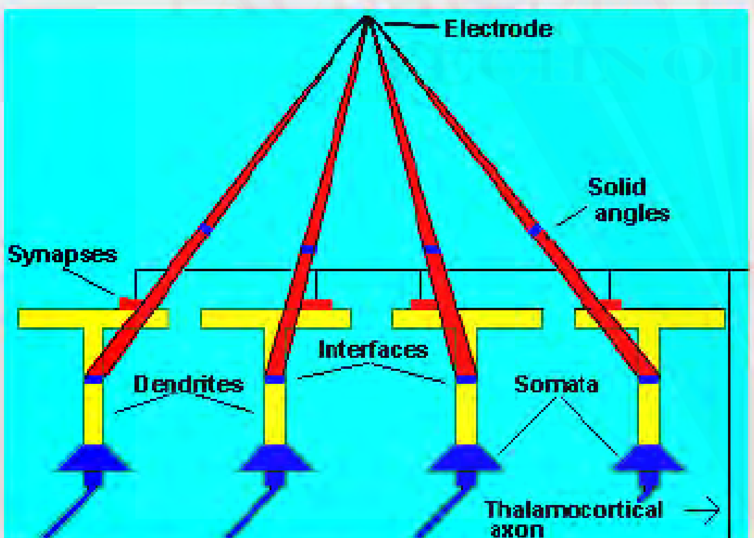
- the outermost layers of brain
- 2-4 mm thick (human)

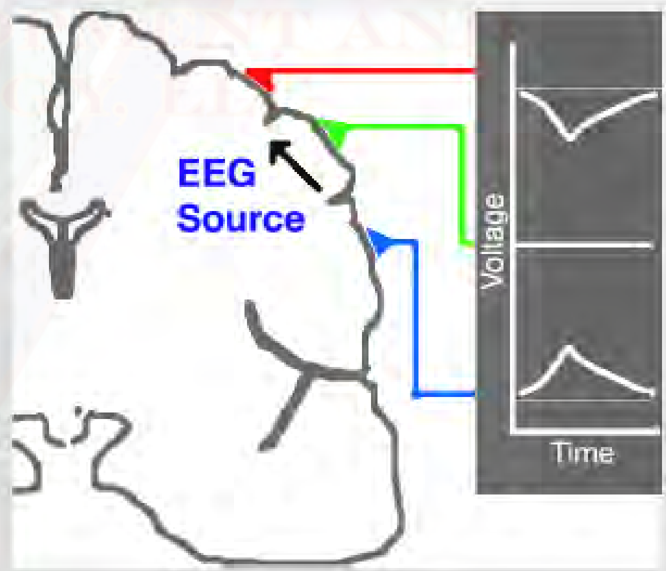


EEG Sources

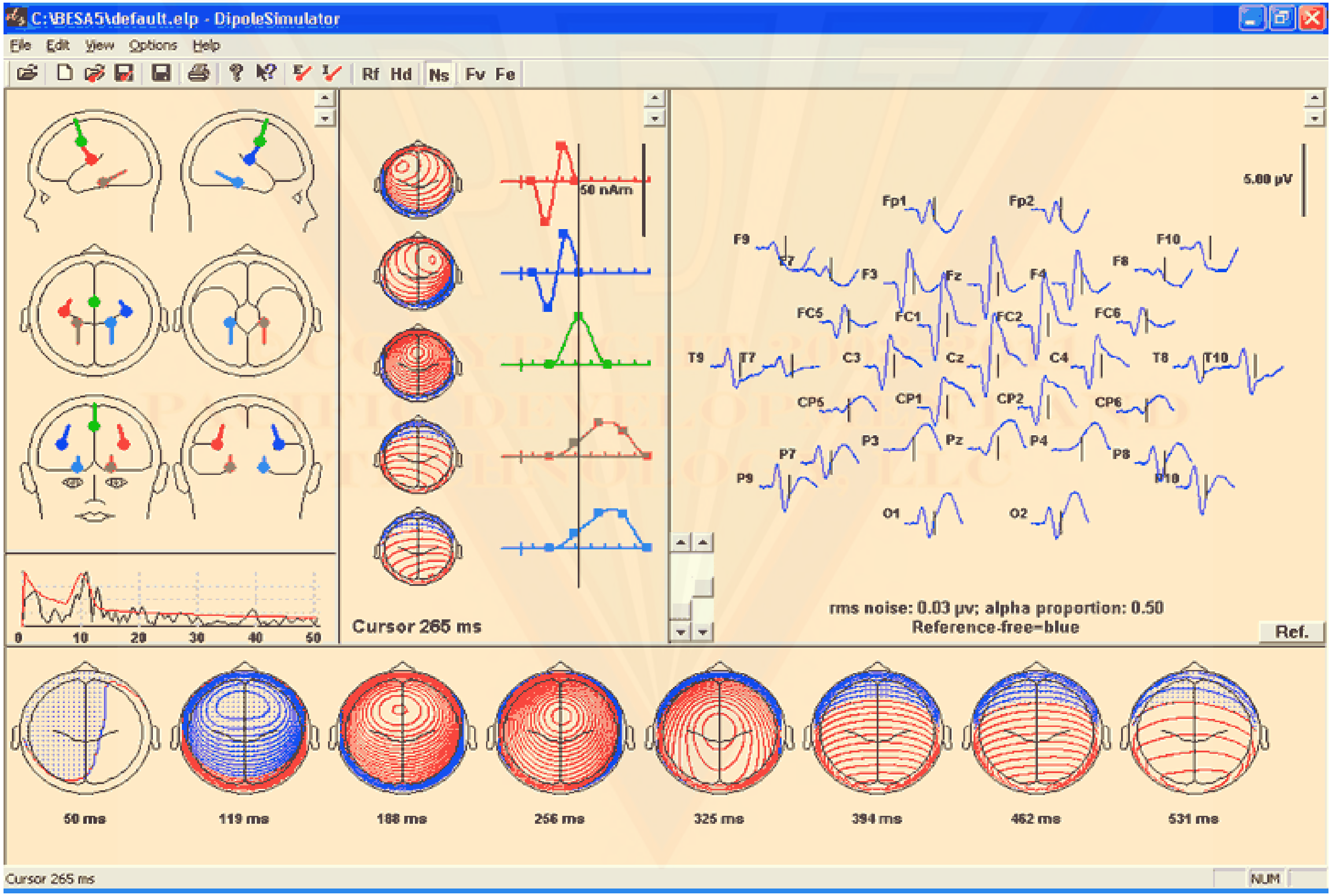

Synapses
Dendrites
Somata
Axons
(efferent)
Thalamocortical axon




Electrode
Solid
angles
Synapses
Interfaces
Dendrites
Somata
Thalamocortical
axon


EEG
Source
Voltage
Time

EEG Sources

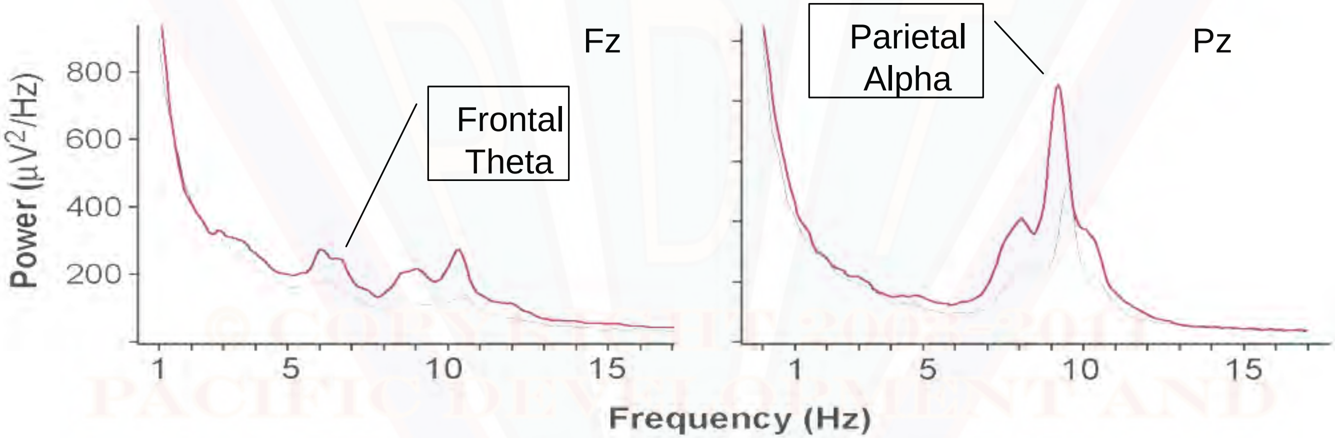

C:\BESA5\default.elp - DipoleSimulator
File Edit View Options Help
Rf Hd Ns Fv Fe
50 nAm
Cursor 265 ms
5.00 µV
Fp1 Fp2
F9 F7 F3 Fz F4 F8 F10
FC5 FC1 FC2 FC6
T9 T7 C3 Cz C4 T8 T10
CP5 CP1 CP2 CP6
P7 P3 Pz P4 P8
P9 P10
O1 O2
rms noise: 0.03 µv; alpha proportion: 0.50
Reference-free-blue
Ref.
50 ms
119 ms
188 ms
256 ms
325 ms
394 ms
462 ms
531 ms
Cursor 265 ms
NUM

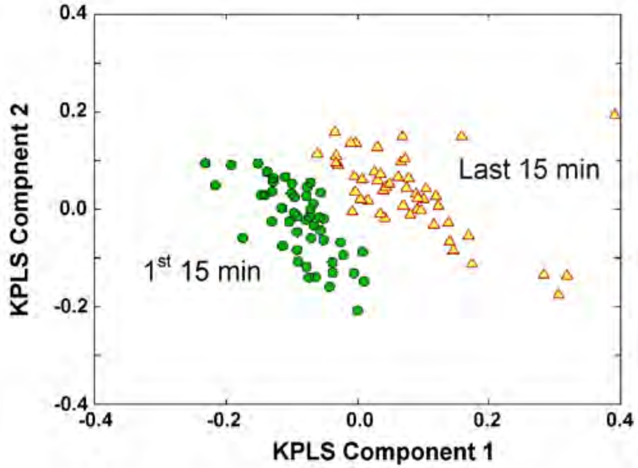
Other Elements of Sensor-State Models

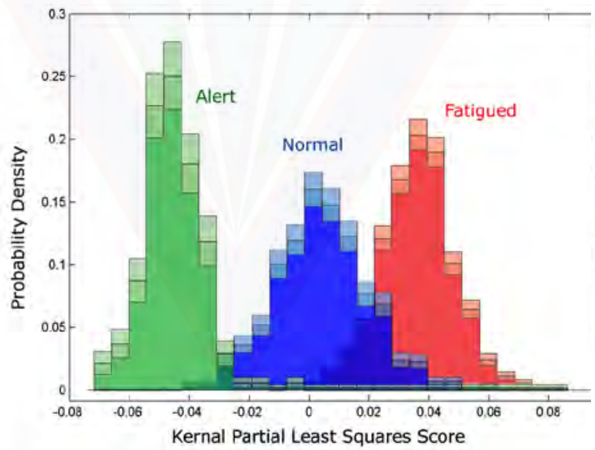
Modality	Effect of Workload
Heart rate	Increase
Heart rate variability (and HFQRS)	Decrease
Vertical and horizontal EOG (eye movements)	Increase
Blinks	May decrease for intake
Pupil diameter	Increase
Skin conductance, SCR, GSR	Increase
EMG (frontalis, temporalis, trapezius)	Increase

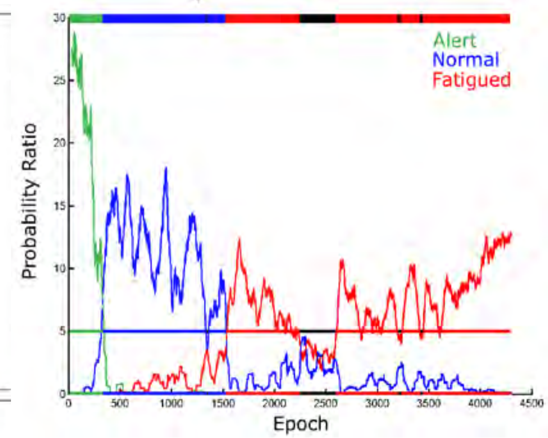
Application 1: Mental Fatigue

Black = Alert   Red = Mentally Fatigued



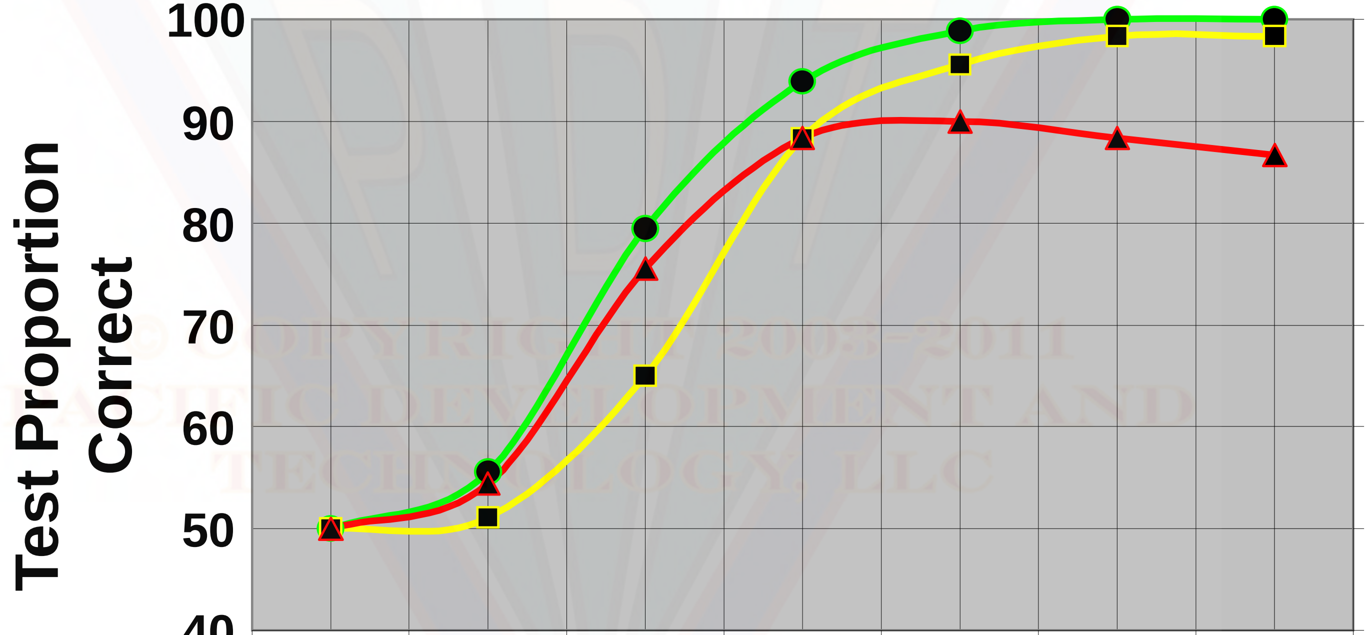






Robust EEG-Based Classification of Mental Fatigue

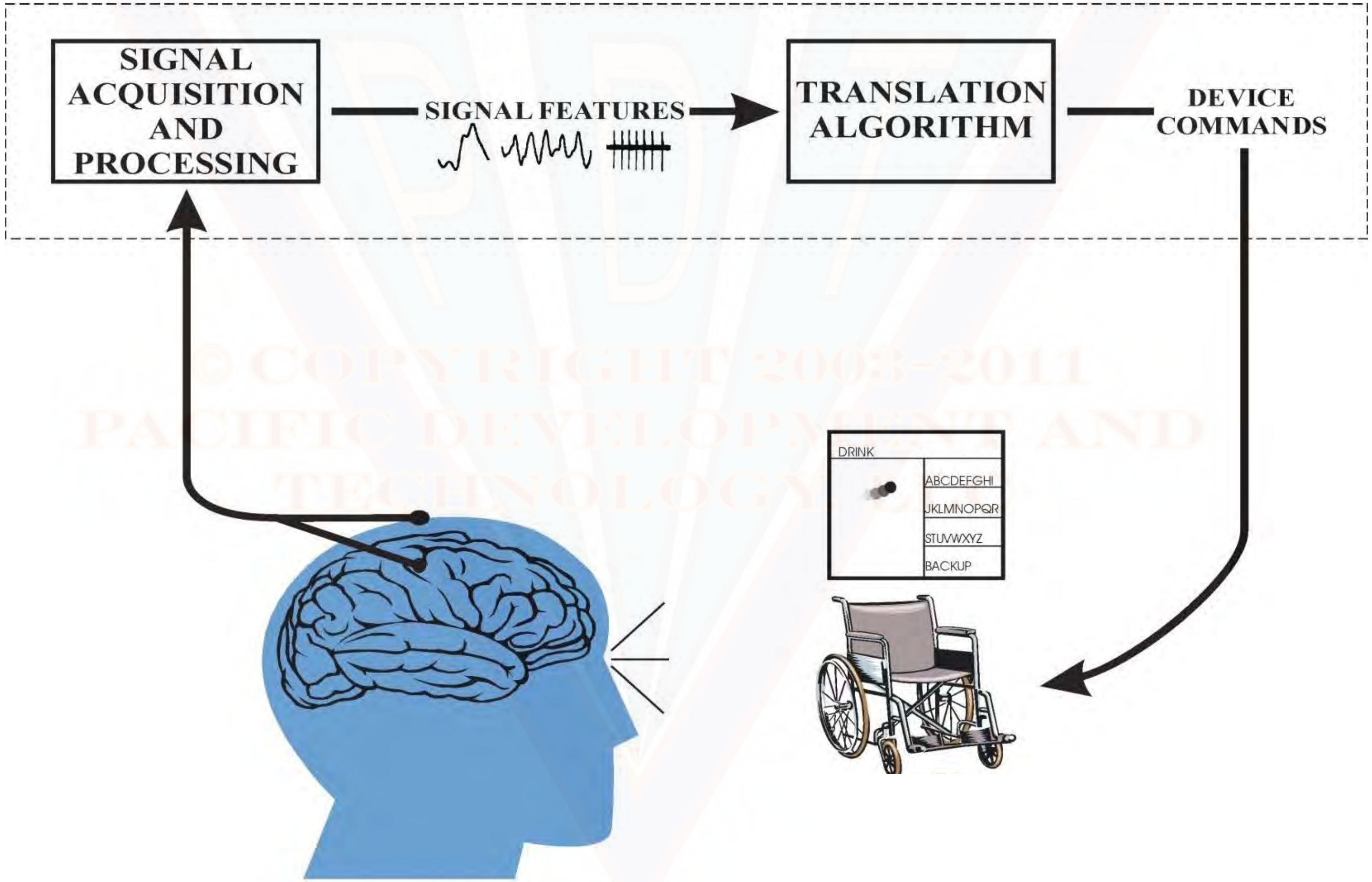
2300 (Day 1) vs. 1900 Hrs (Day 2)



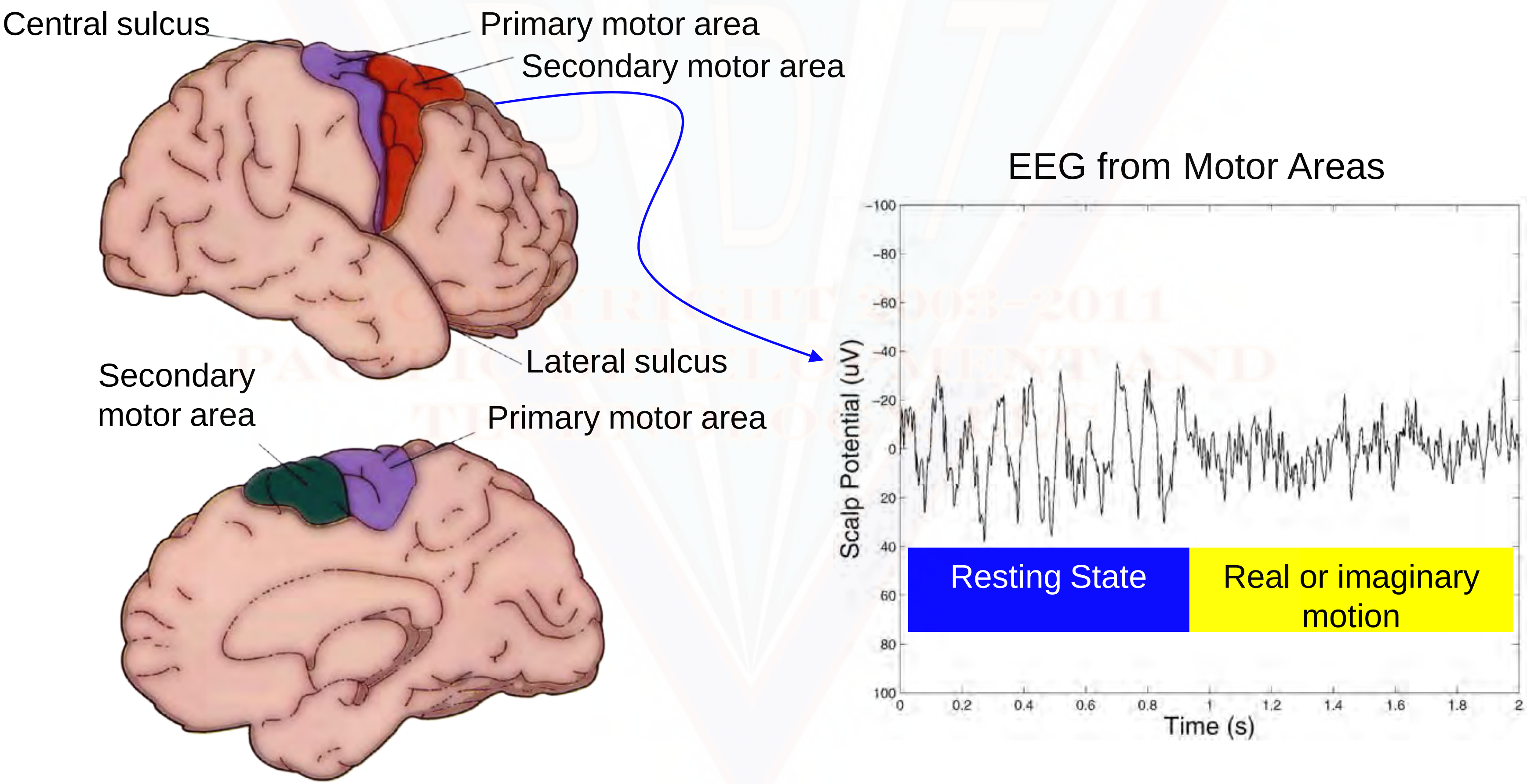
	-18	-15	-12	-9	-6	-3	0
21 Channels	50	56	79	94	99	100	100
12 Channels	50	51	65	88	96	98	98
4 Channels	50	54	76	88	90	88	87

Signal-to-noise Ratio (dB)

Application 2: BCI

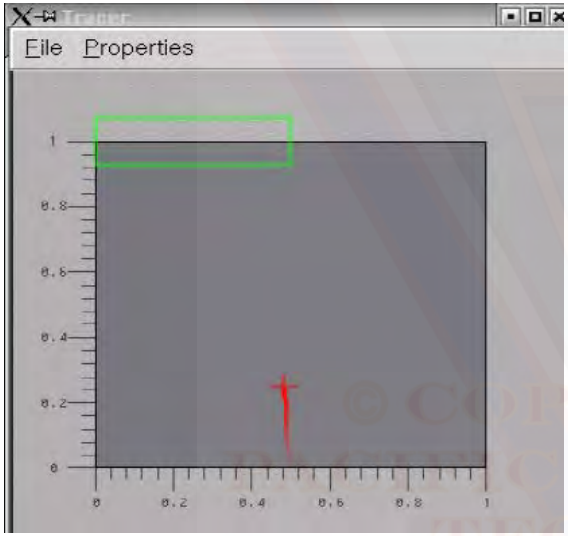


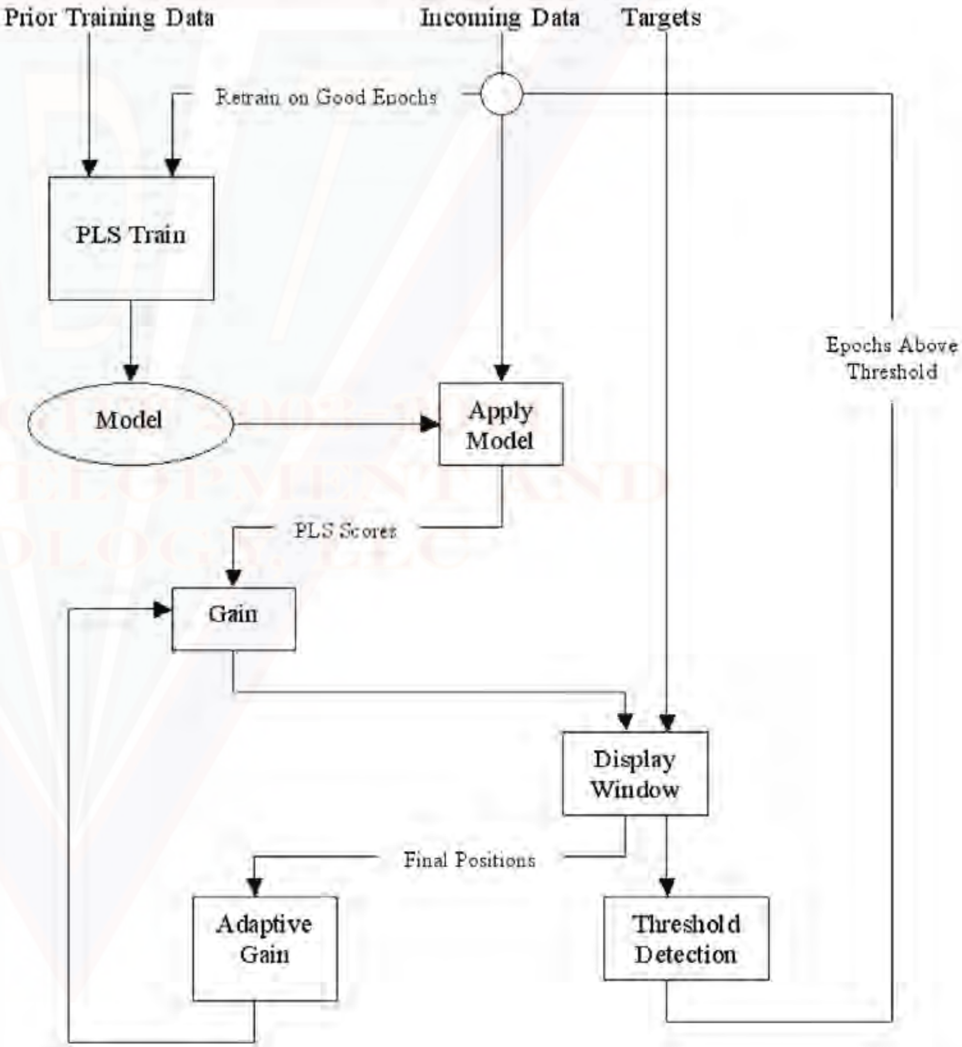
Application 2: BCI



(Adapted from Beatty, 1995)

Application 2: BCI





Control System for Target Practice

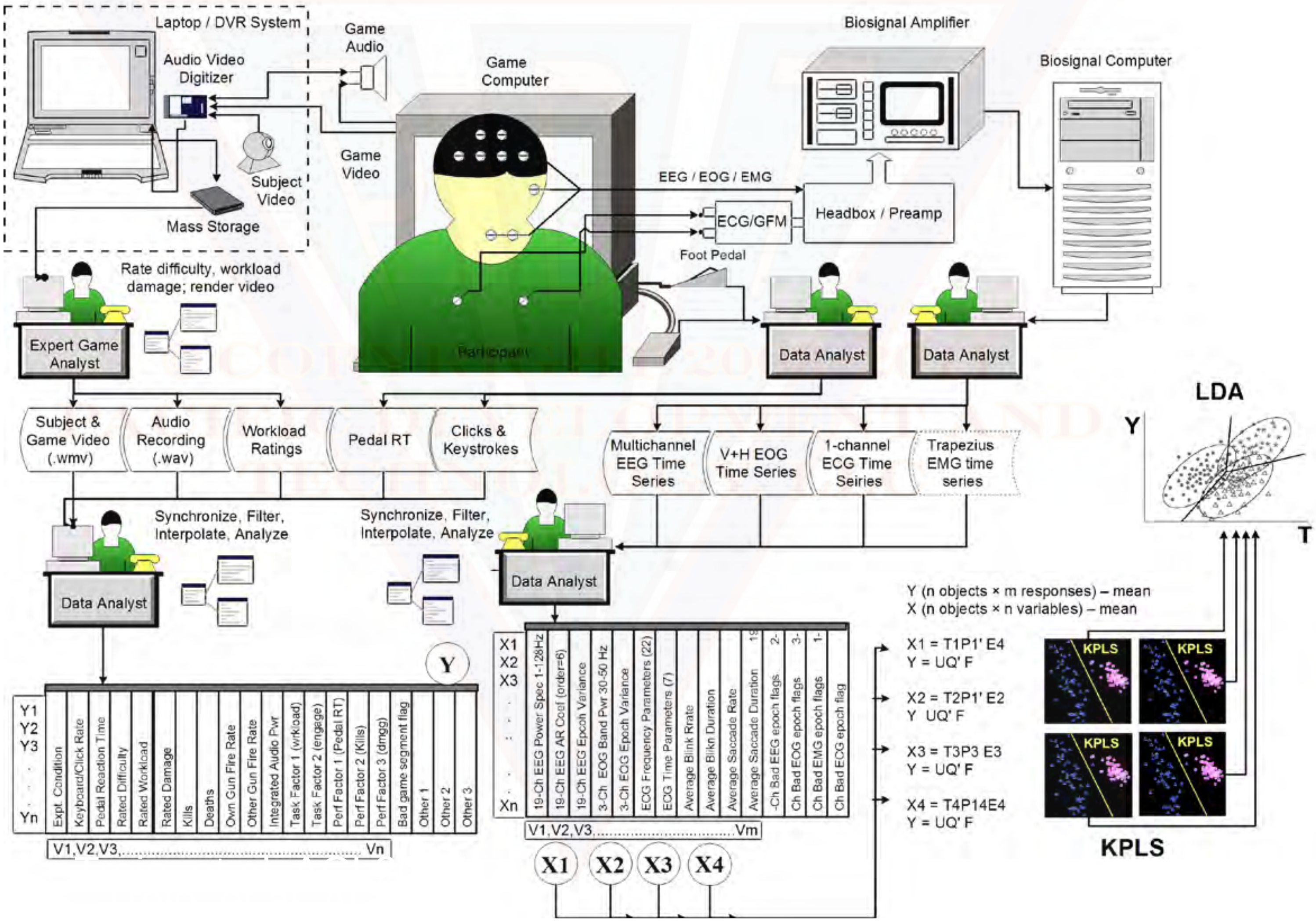
Trial-by-trial classification (left, right)

- 250 ms display update

Dual adaptive controller design

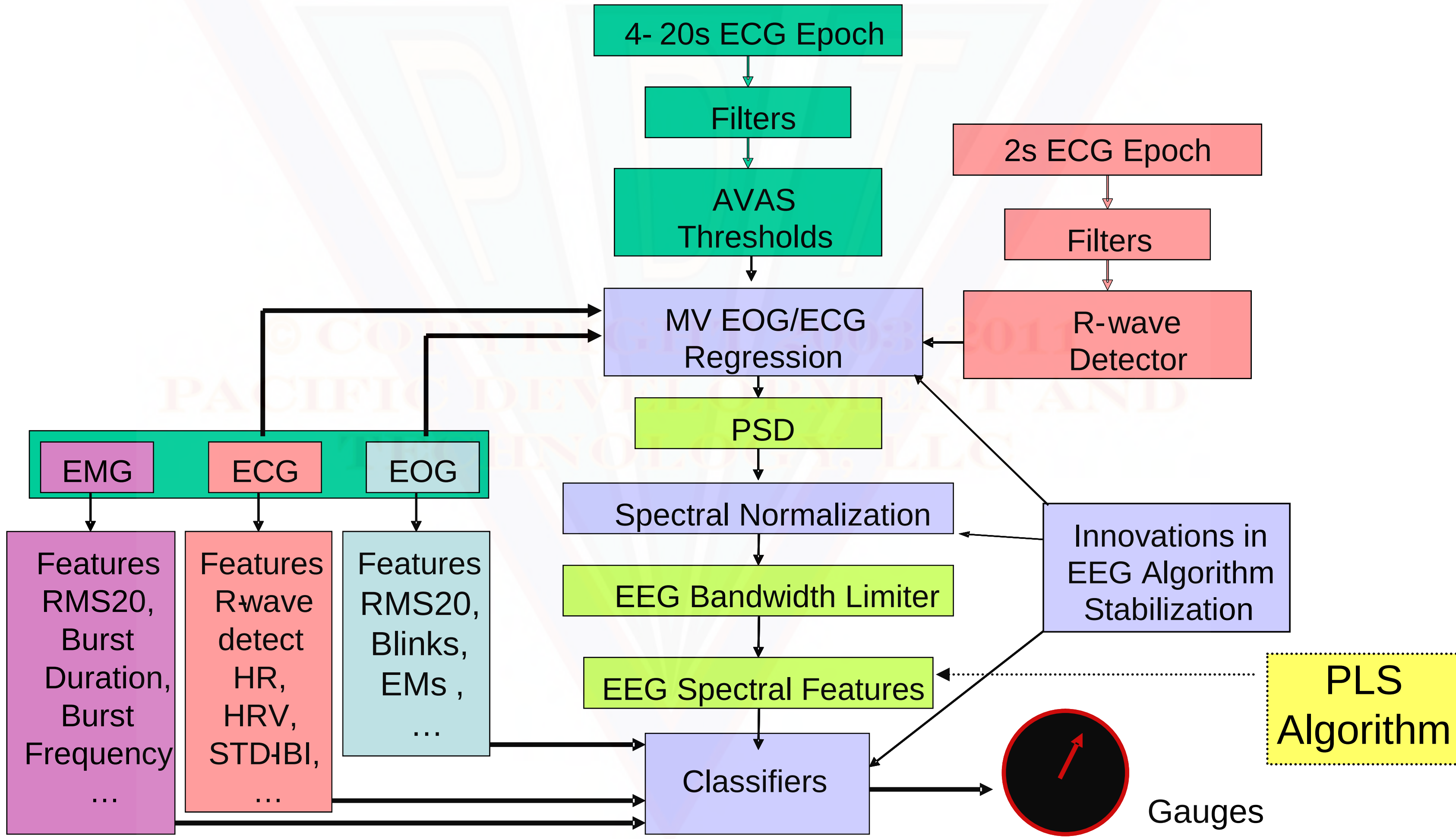
- Adaptive PLS pattern recognition
- Adaptive gain control for motion

Application 3: Detection of Cognitive Overload

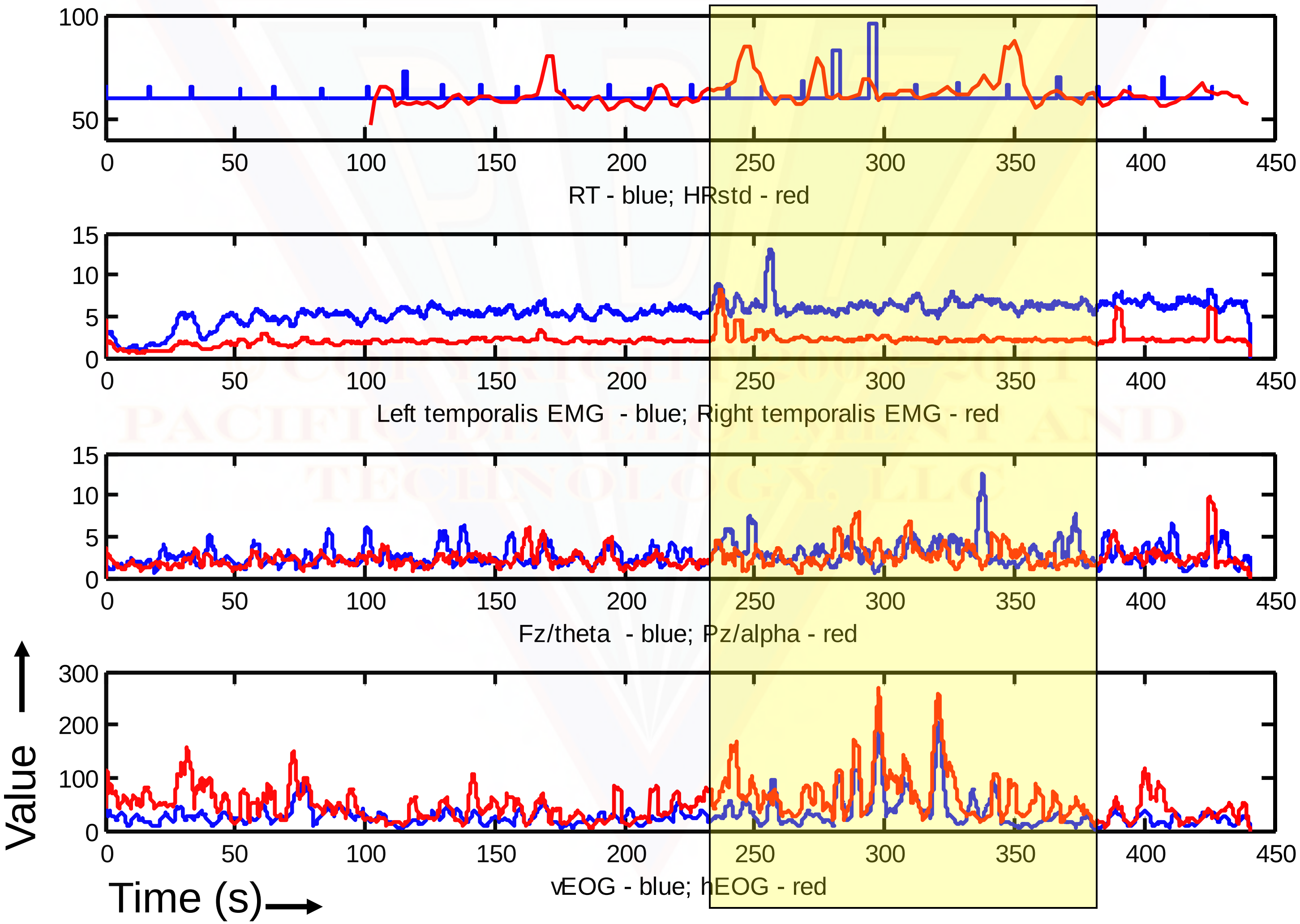


Experiment for Overload Detection

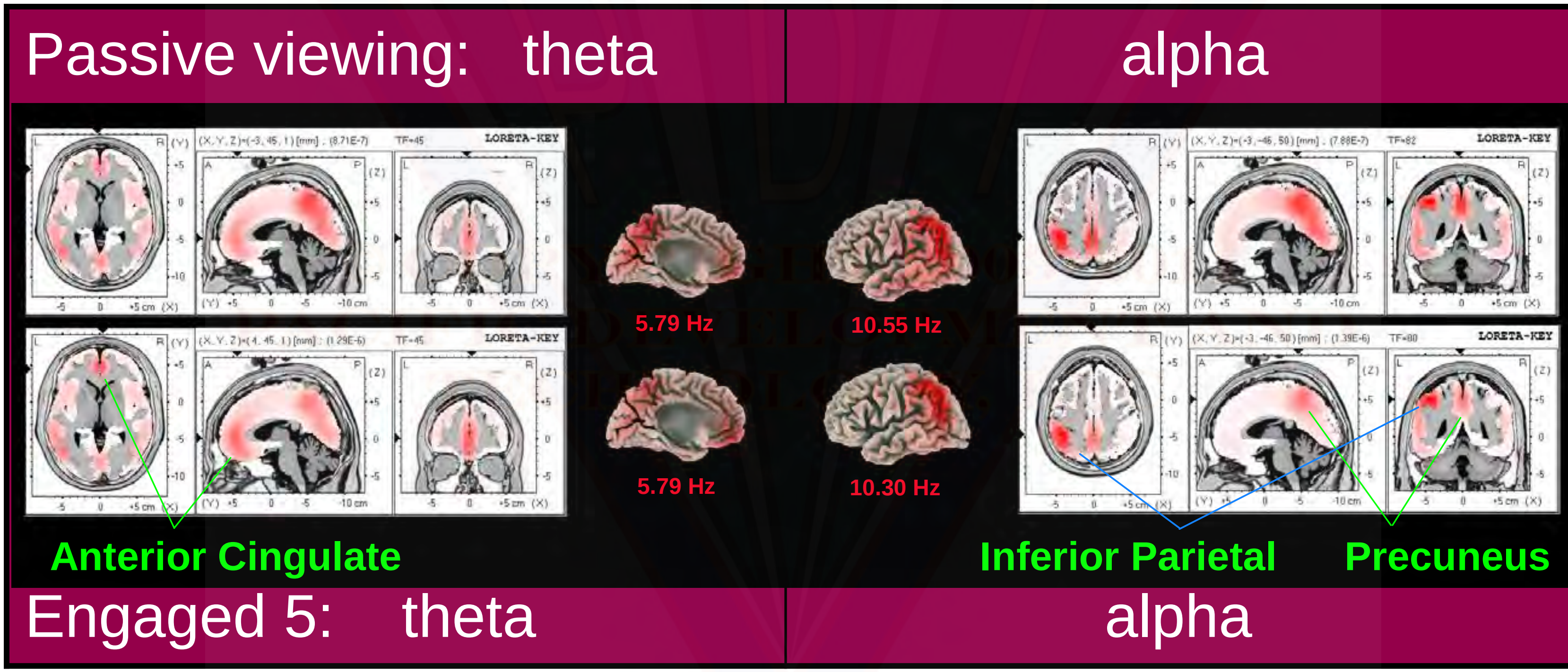
Stabilizing Classifiers



Multimodal Overload Patterns



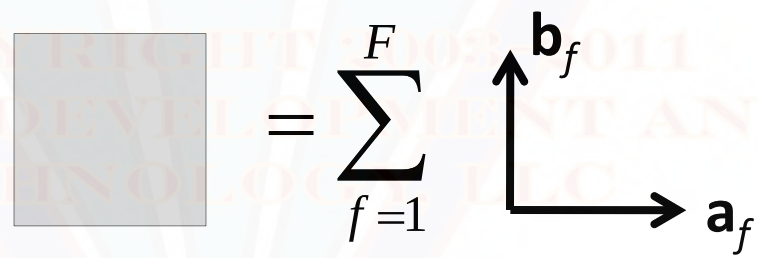
Attention-related EEG Sources



Familiar (bilinear) Mapping Algorithms

Factor Analysis

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



Principal Component Analysis (PCA)

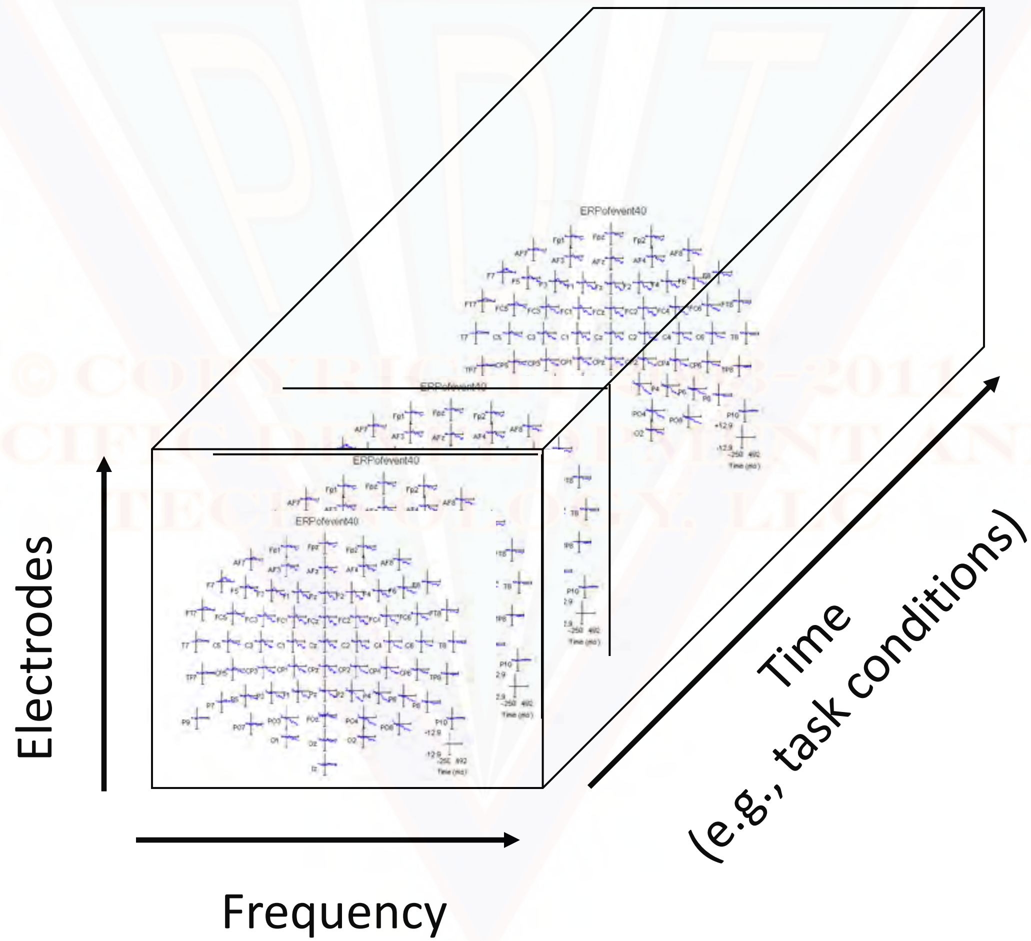
$$e_{ij} = 0$$

Multimodal Mapping

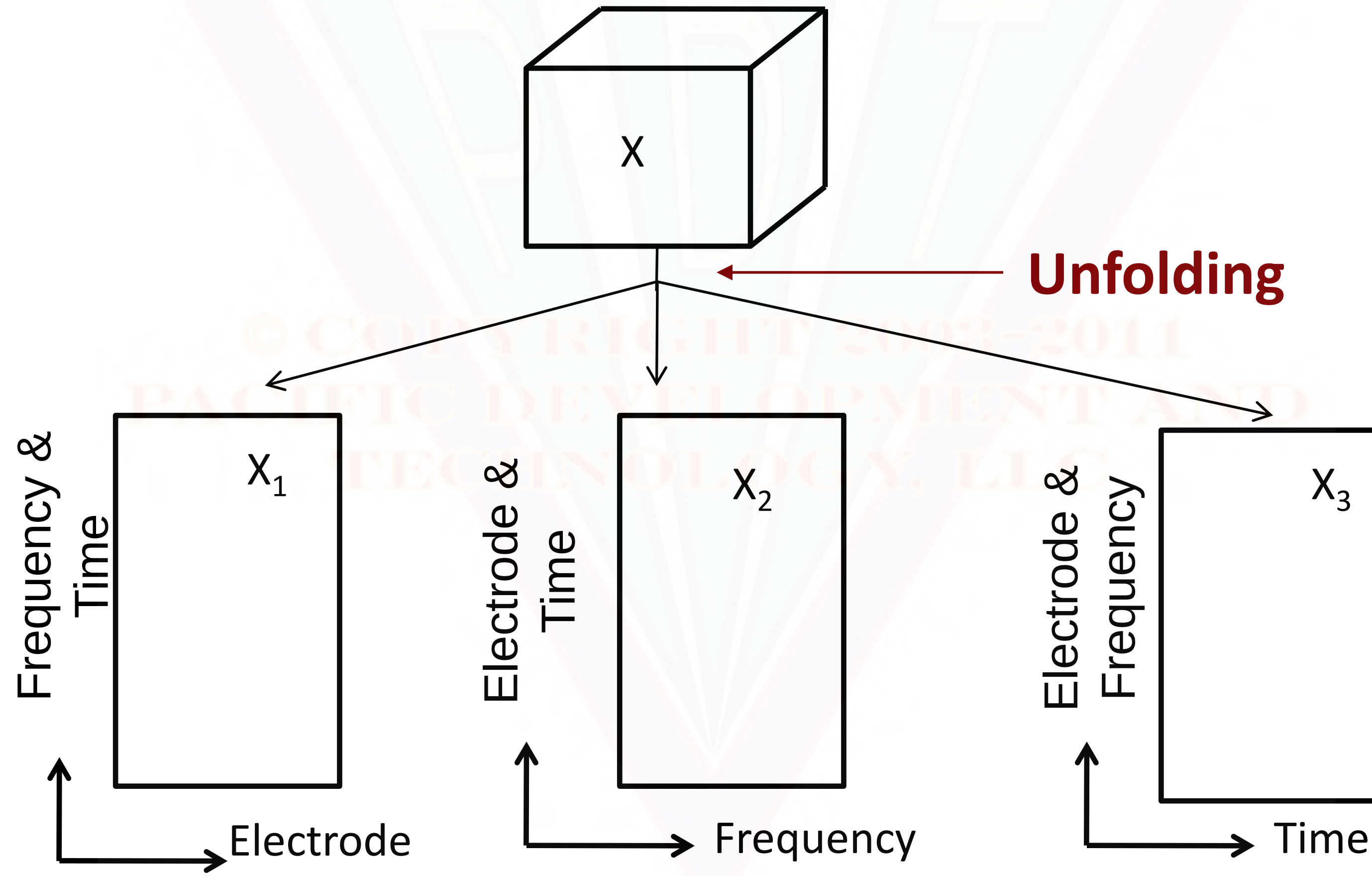
How to generalize bilinear models to systems with more dimensions?

1. **Unfolding a bilinear model**
   a. Represent all experimental factors in one dimension
   b. Observations (trials) is second dimension
   c. Contrast each dimension vs. pairs of the other two
2. **Multidimensional model**
   a. Assume orthogonal factors: PARAFAC
   b. Allow interacting factors: Tucker 3
3. **Modeling approach**
   a. Unsupervised extraction: PARAFAC, CANDECOMP, Tucker 3
   b. Supervised extraction: N-PLS

EEG-based Estimation of Task Demands



Unfolding a Bilinear Model



Multidimensional Modeling

(Tucker 3 Model, unsupervised)

$$x_{ijk} = \sum_{l=1}^{F_1} \sum_{m=1}^{F_2} \sum_{n=1}^{F_3} a_{il} b_{jm} c_{kn} g_{lmn} + e_{ijk}$$

- x_{ijk} is an element of *(l x m x n)* multidimensional array
- *F1, F2, F3* are the number of components extracted on the 1st, 2nd and 3rd mode
- *a, b, c* are elements of the **A, B, C** loadings matrices for the 1st, 2nd and 3rd mode
- *g* are the elements of the core matrix **G** which defines how individual loading vectors in different modes interact
- e_{ijk} is an error element (unexplained variance)

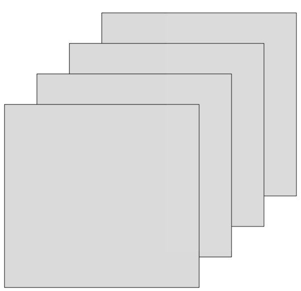
PARAFAC

(Parallel Factor Analysis, unsupervised)

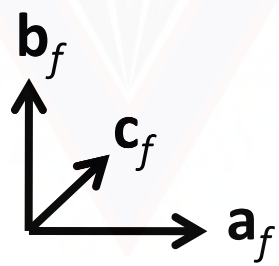
PARAFAC is a special case of the Tucker 3 model where *F1*= *F2* = *F3*=*F* and *G* = I

For a 3-way array:

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



$$= \sum_{f=1}^{F}$$



"Atoms" = $a_1 b_1 c_1$

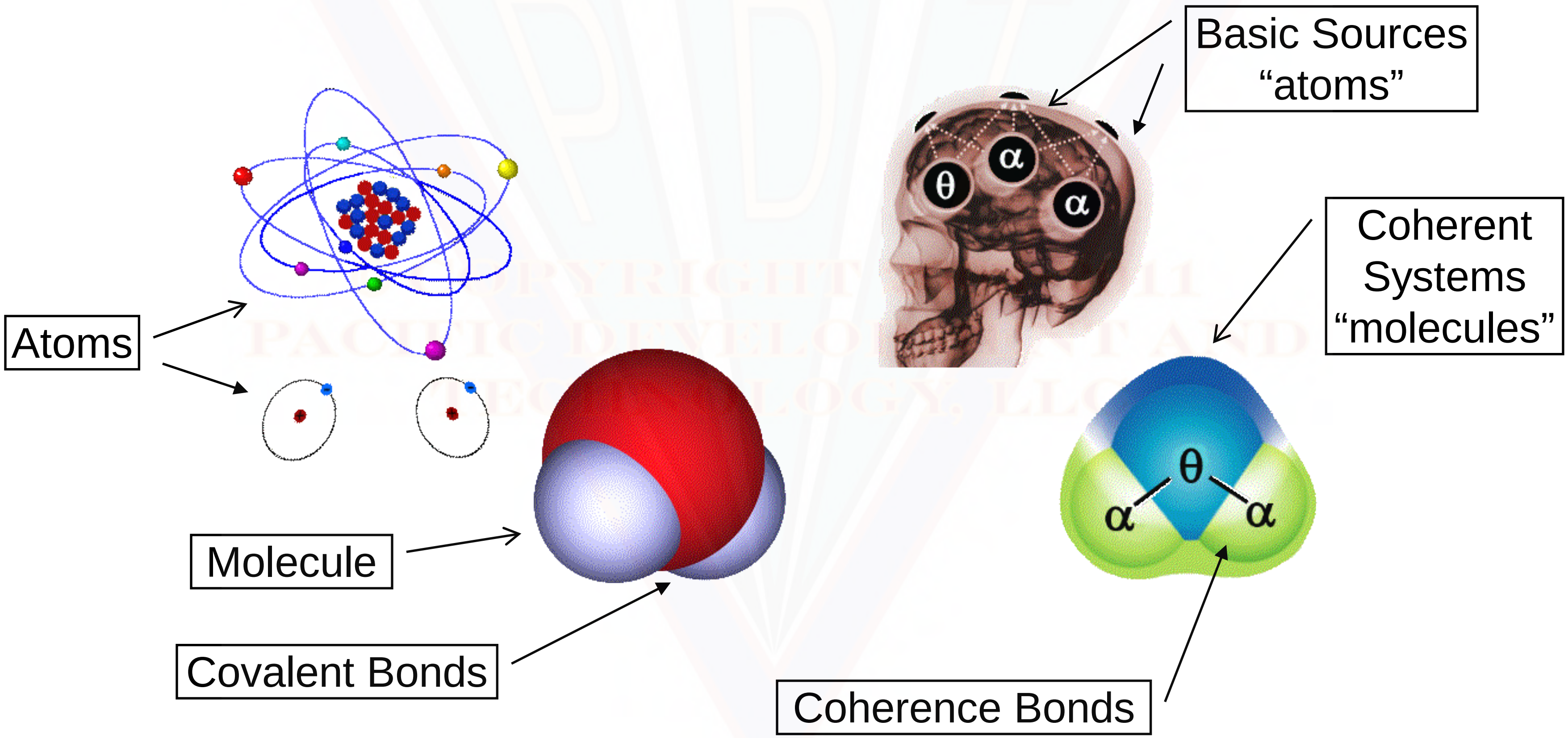
$a_2 b_2 c_2$

$a_3 b_3 c_3$

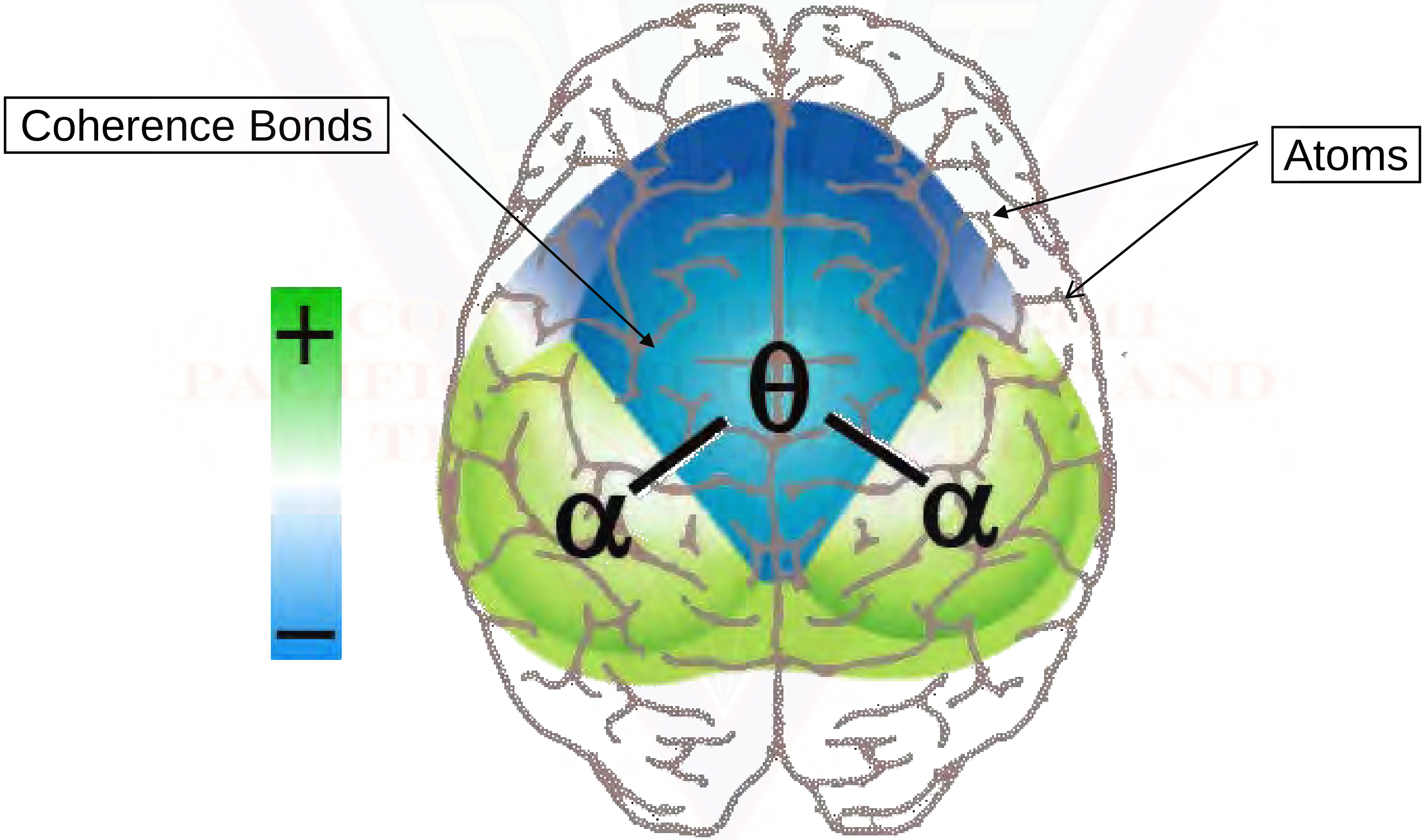
. . .

$a_f b_f c_f$

“Atomic” EEG Elements

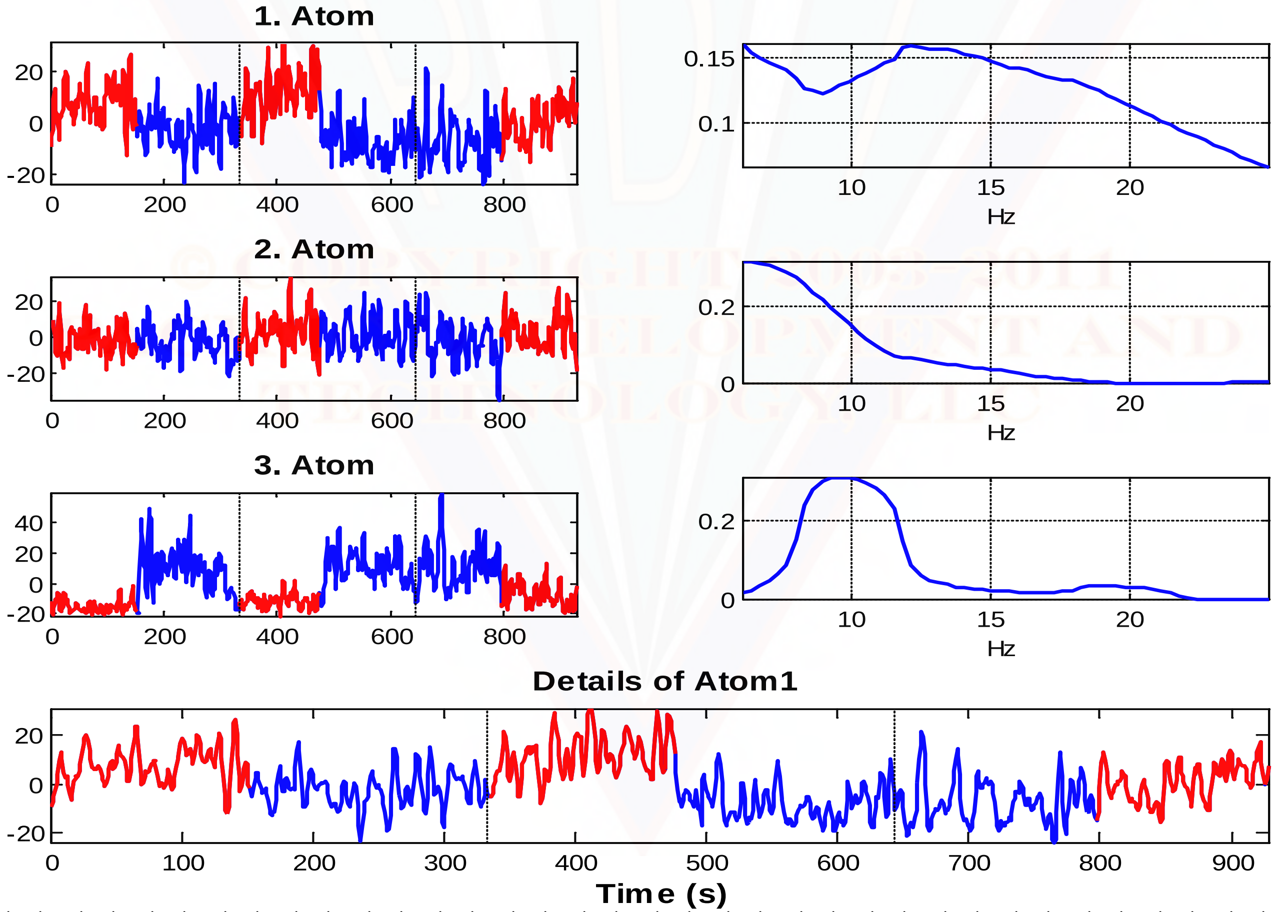


“Molecular” EEG Processes



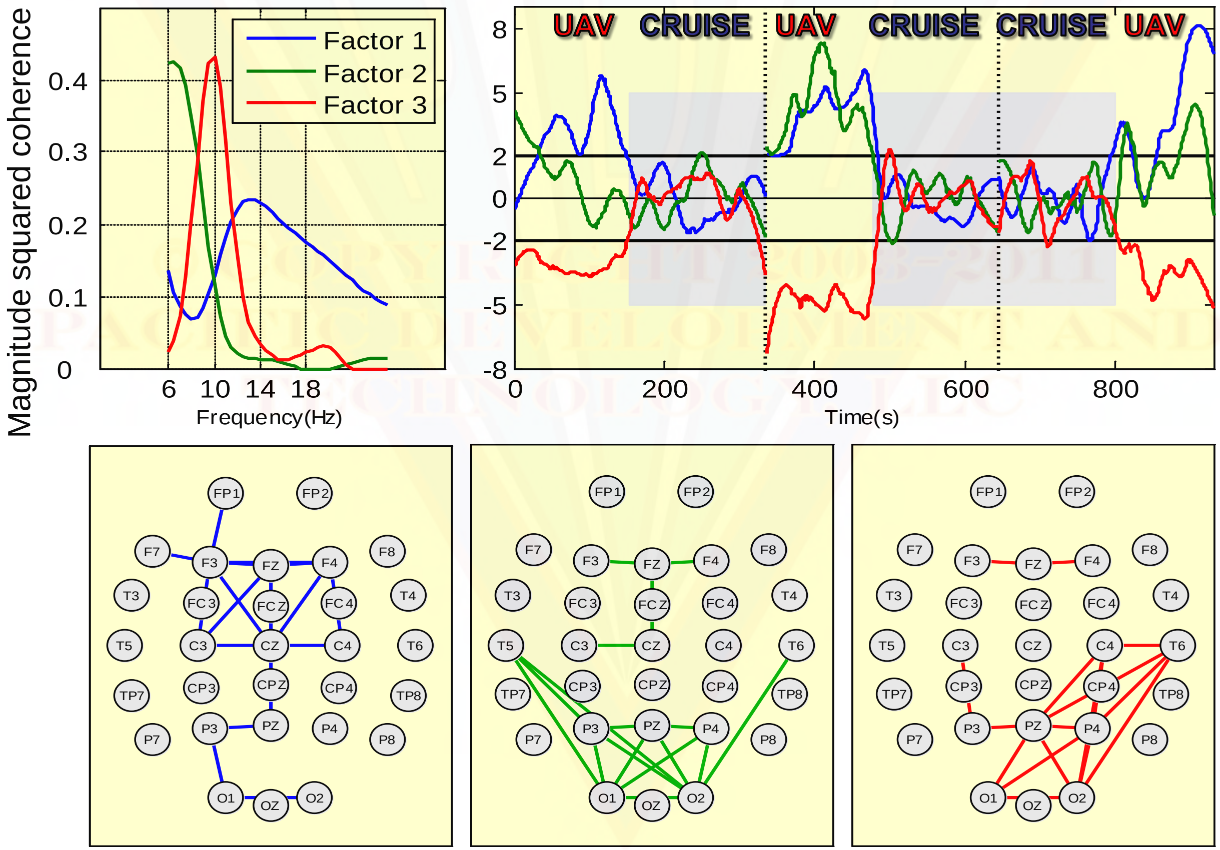
PARAFAC Applied to UAV Task

PARAFAC *EEG power* model during UAV task performance in one participant.
Blue areas = low demands (cruise); red areas = high demands (UAV control).



PARAFAC Applied to UAV Task

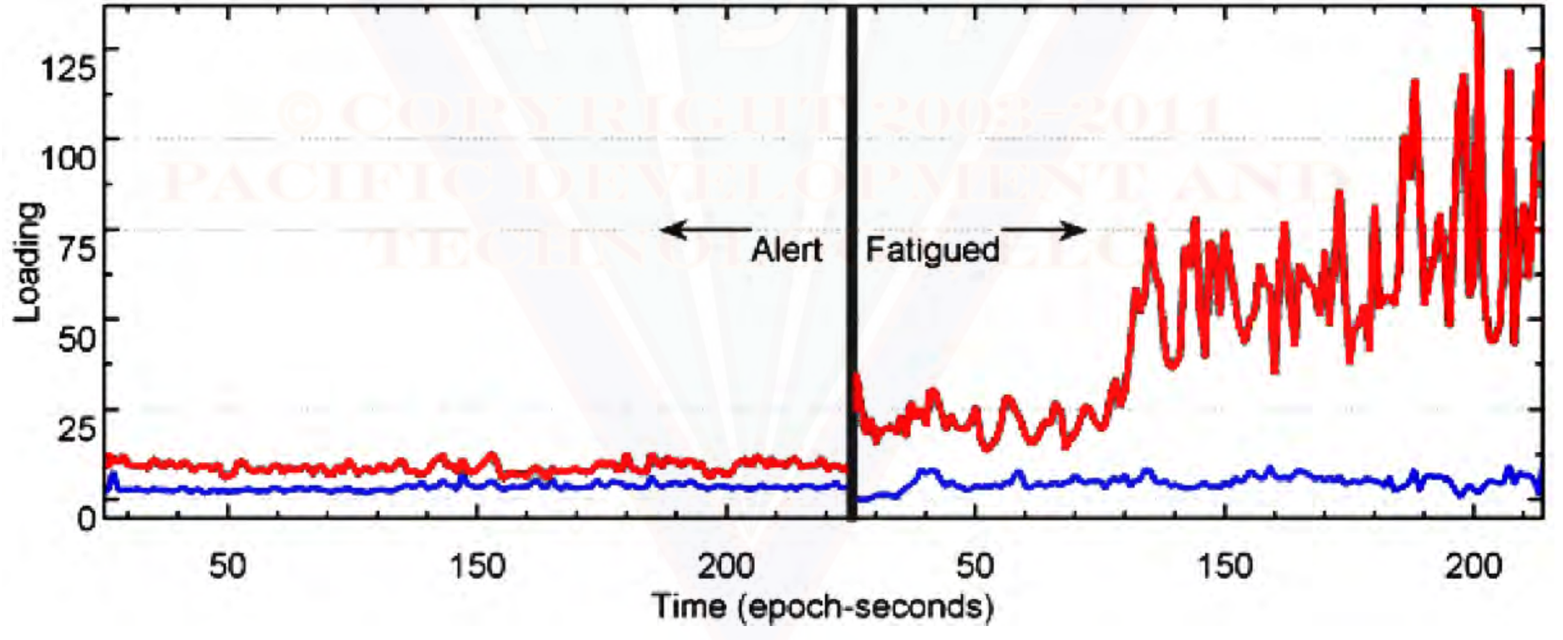
PARAFAC EEG *coherence model* during UAV task performance in one participant



Top 10% of inter-electrode coherences

PARAFAC Applied to Fatigue

PARAFAC *power model* 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.



Application Summary

- **Models of engagement, fatigue & BCI**
  - PLS models 90-100% accurate
  - Stable within a day
  - Stable from day to day
- **Detection of cognitive overload**
  - PLS models
    - 60-90% accurate
    - Unstable over time
    - Require individual models
  - PARAFAC models
    - Accurate for UAV task, fatigue
    - Stable over time
    - Evidence for normative models

Recommended Directions

1. Improved deployable multimodal **sensors** (EEG, fNIR, EOG, gaze, HRV, EMG, SCR, SpO_2, BP, core body temperature, gesture, posture, facial expression, ...)
2. Multimodal experimental designs and operational tests
3. Improved neurocognitive **process models**
4. Improved sensor-process **mapping algorithms**

Summary

- **Successes and Failures**
  - Fatigue, BCI, engagement: accurate, stable
  - Overload detection: variably accurate, stable
- **New models of state-related EEG sources**
  - “Atomic” EEG sources
  - “Molecular” EEG systems
- **New multidimensional models and algorithms**
  - Traditional bilinear methods (PCA, ICA, PLS, KPLS)
  - Truly multidimensional methods
    - Correlated factors (Tucker 3)
    - Uncorrelated factors (PARAFAC, CANDECOMP, N-PLS)
    - Supervised algorithms (N-PLS)