

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To) -	
4. TITLE AND SUBTITLE Advanced Physiological Estimation of Cognitive Status			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER W911NF-11-C-0081		
			5c. PROGRAM ELEMENT NUMBER 622120		
6. AUTHORS Leonard J. Trejo			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Pacific Development and Technology LLC 999 Commercial St. Palo Alto, CA 94303 -			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 59502-LS.2		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT This report discusses research 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					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Leonard Trejo
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 650-248-3318

Report Title

Advanced Physiological Estimation of Cognitive Status

ABSTRACT

This report discusses research 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

Leonard J. Trejo

Pacific Development and Technology, LLC
Palo Alto, CA 94303, USA

Presentation to ARL
24 May 2011

Sponsored by
US Army Research Office

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
-



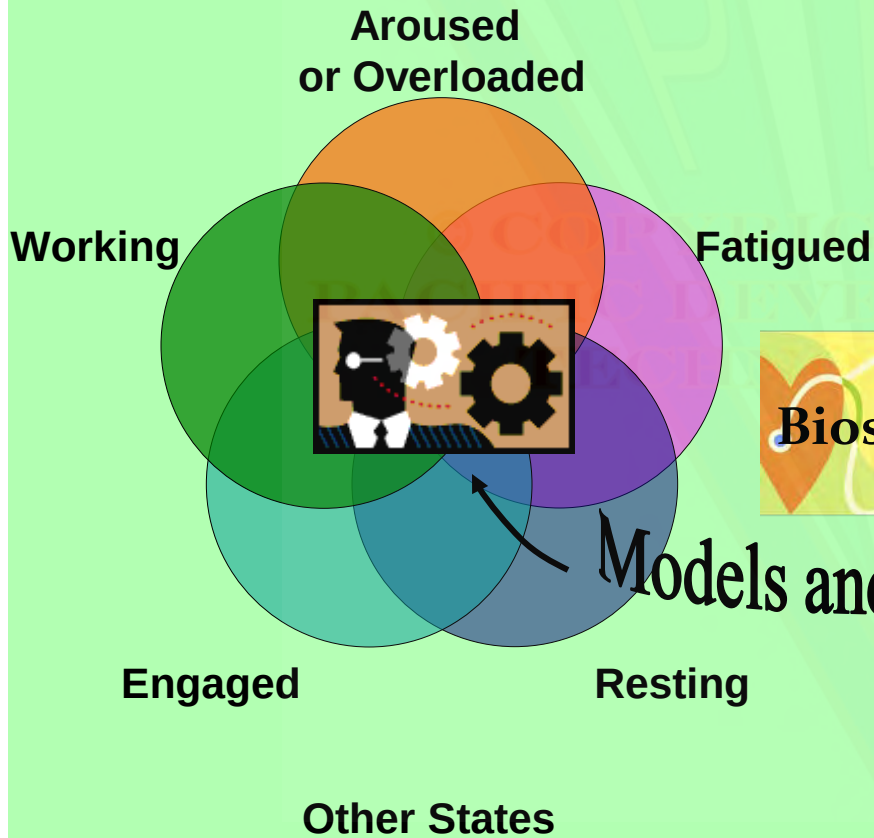
Outline

- 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

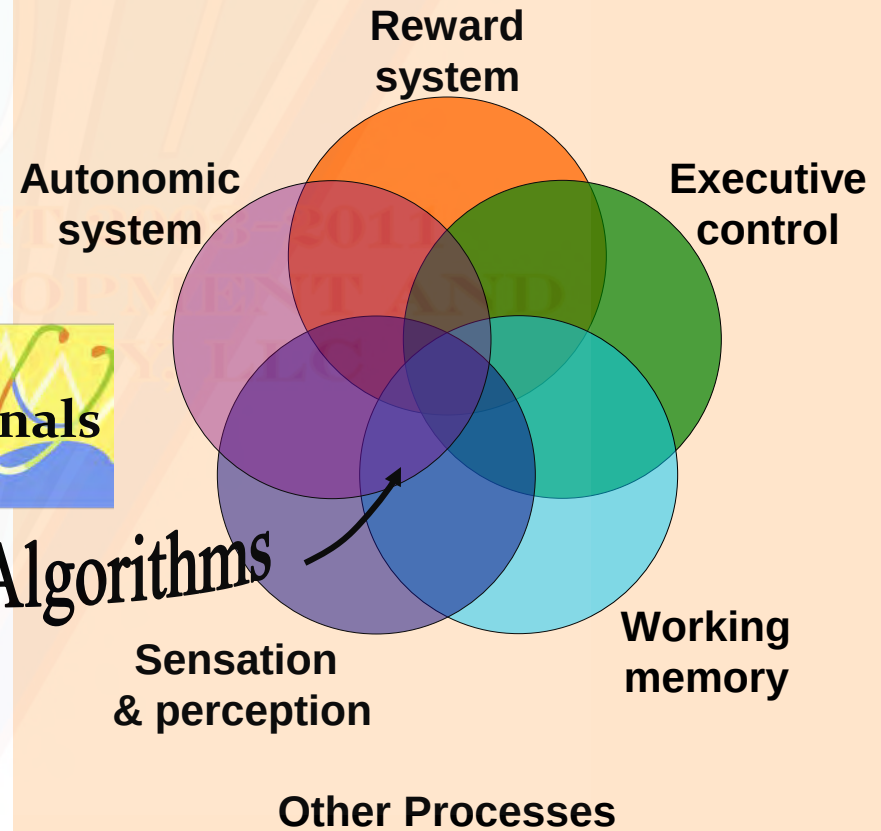


Estimation of Cognitive States

Behavior and Performance



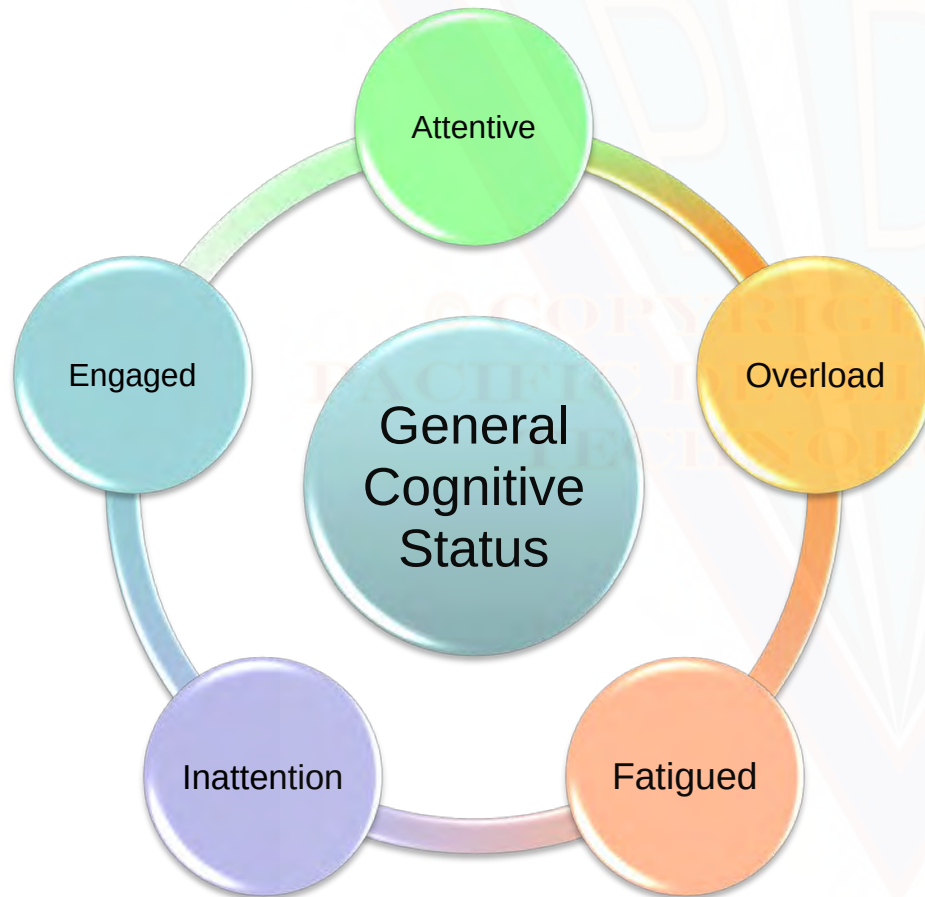
Internal Processes



Biosignals



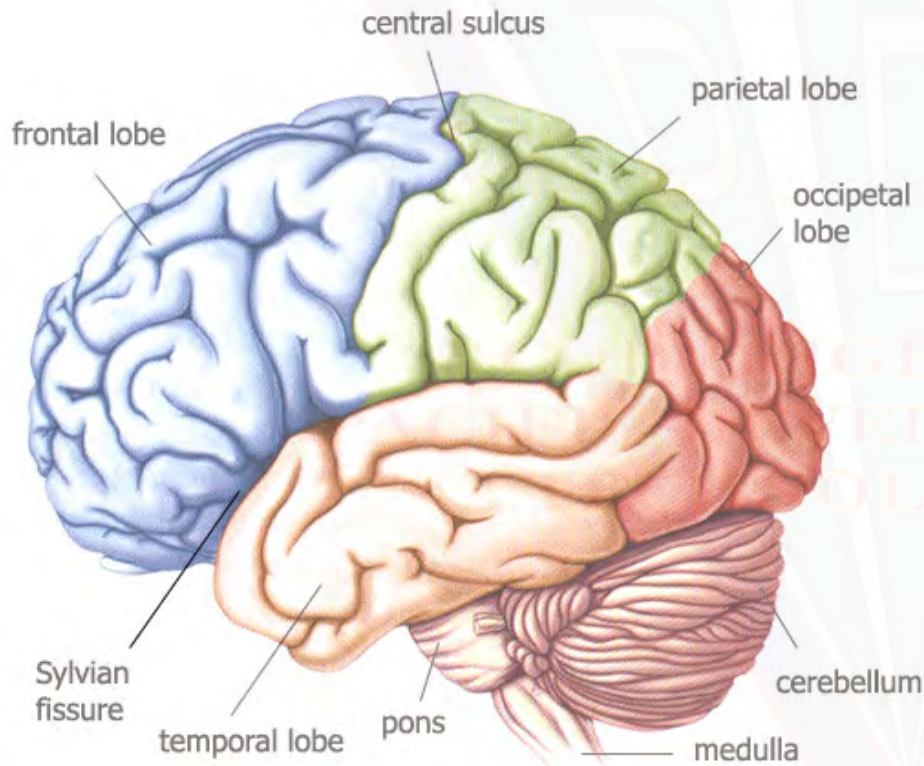
Cognitive State Constructs



- **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



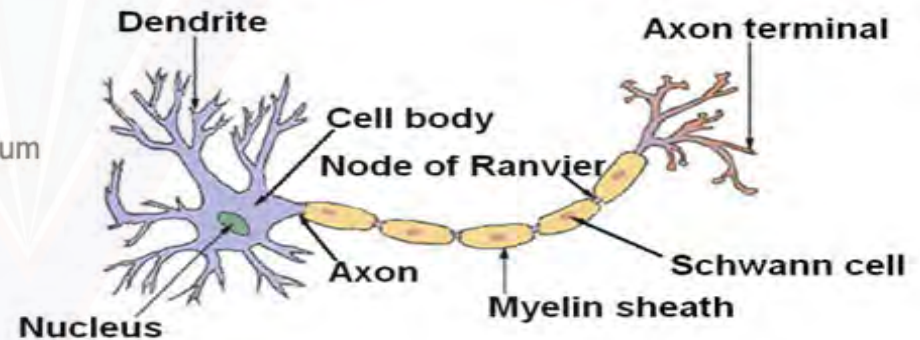
Electroencephalogram



Cerebral Cortex

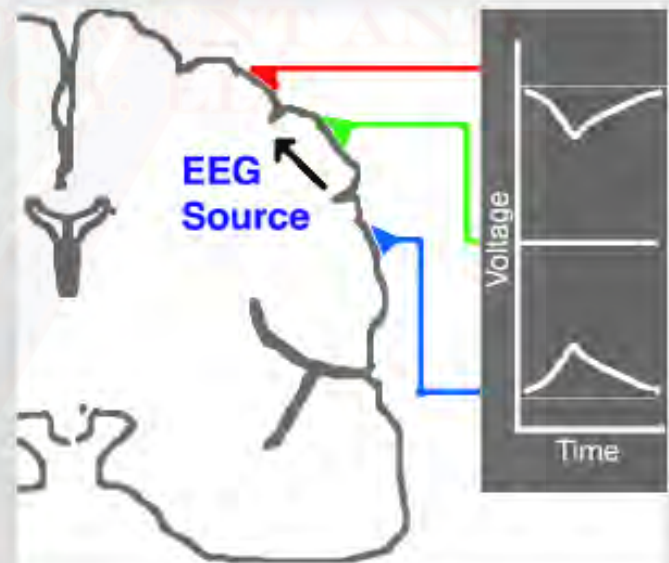
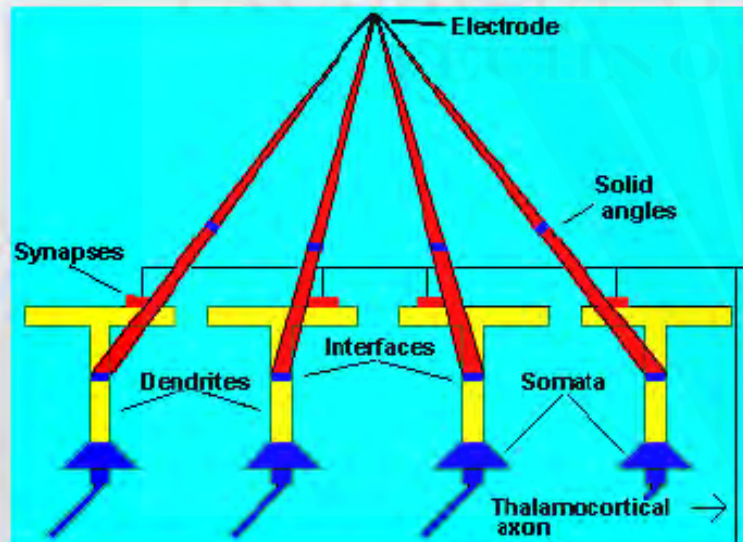
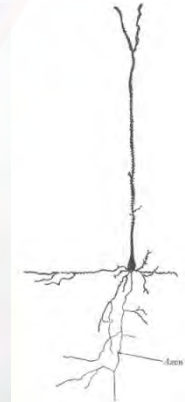
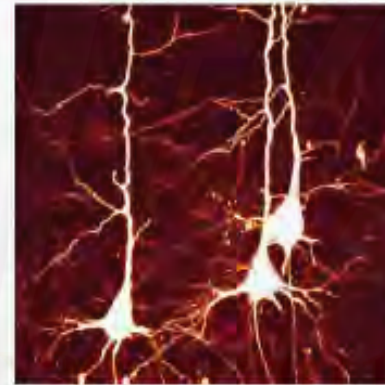
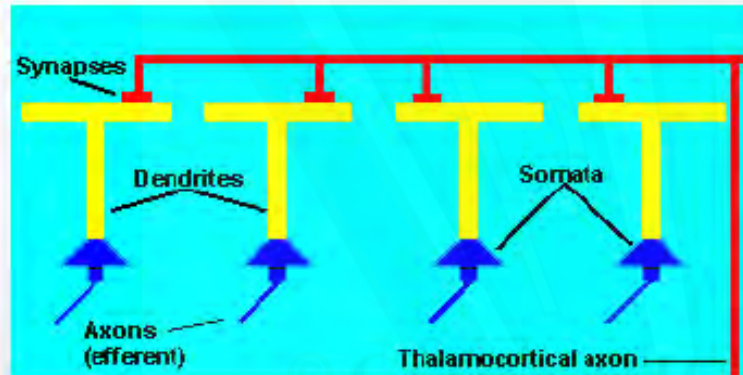
- the outermost layers of brain
- 2-4 mm thick (human)

Structure of a Typical Neuron



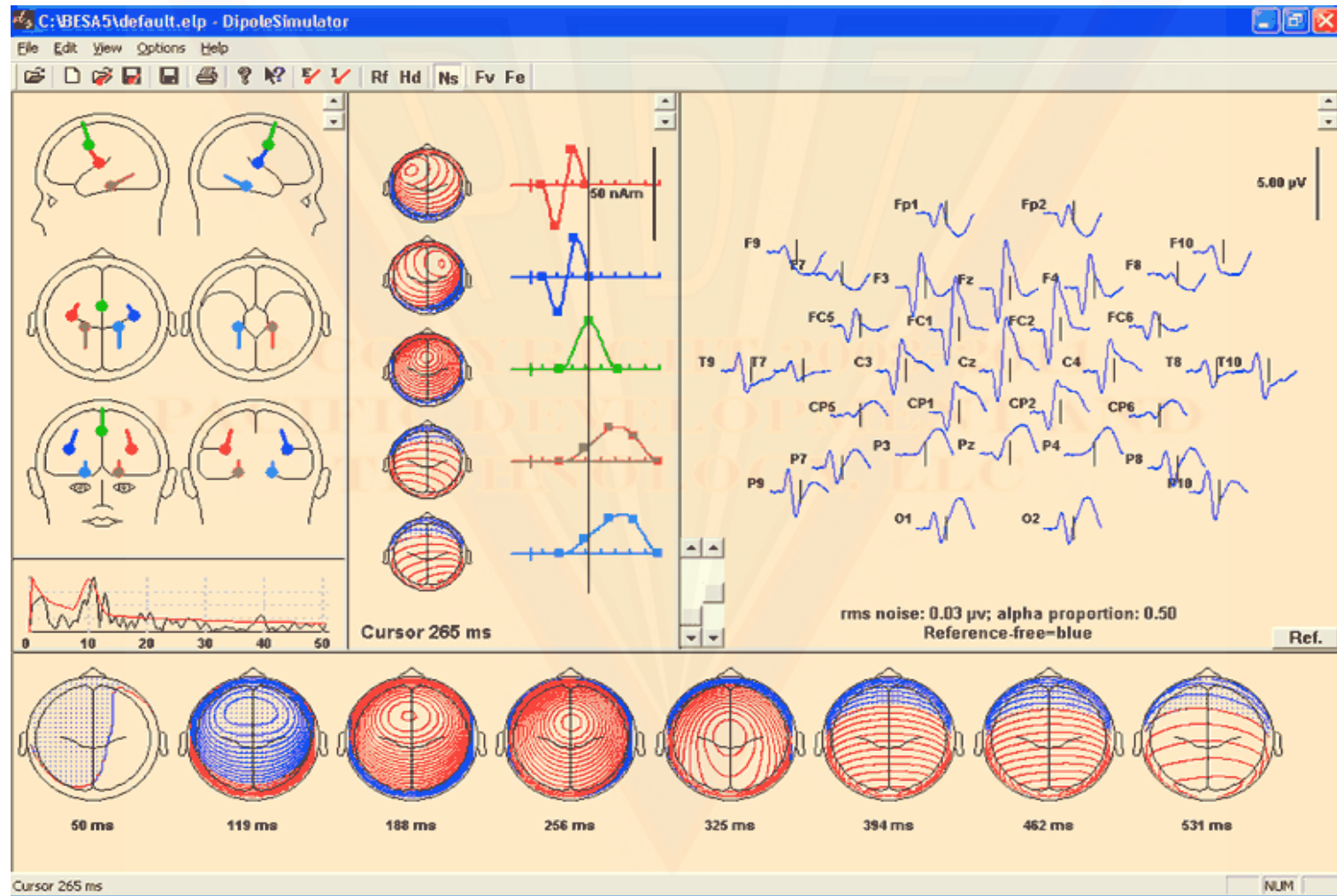


EEG Sources





EEG Sources



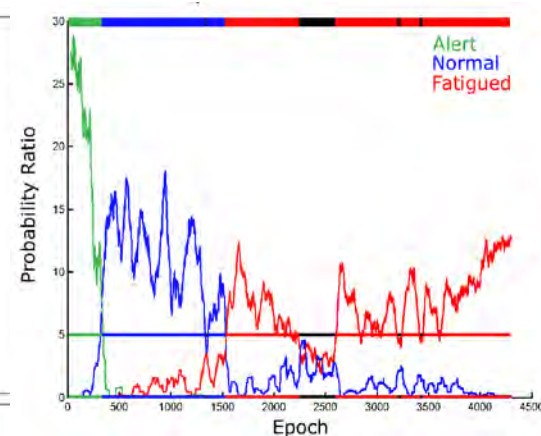
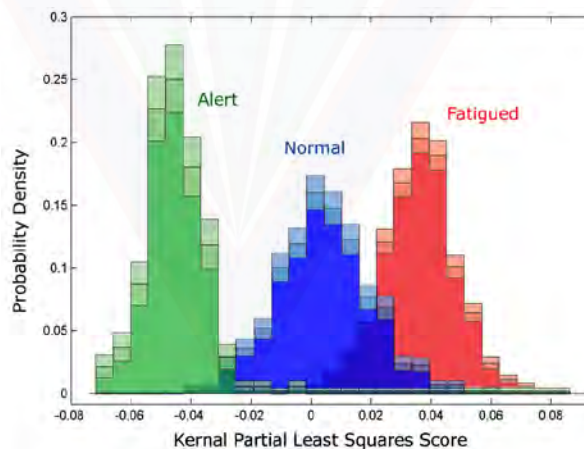
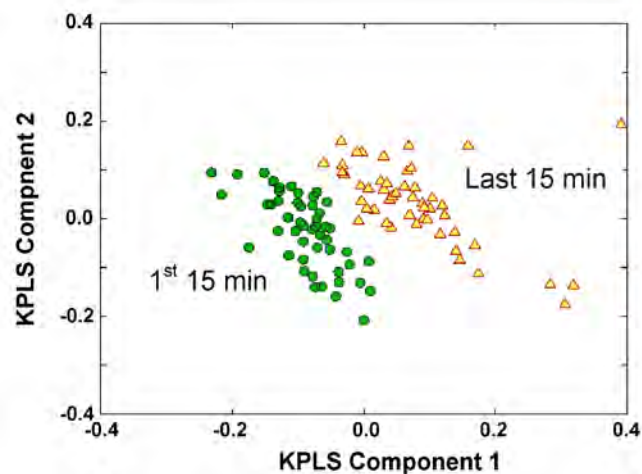
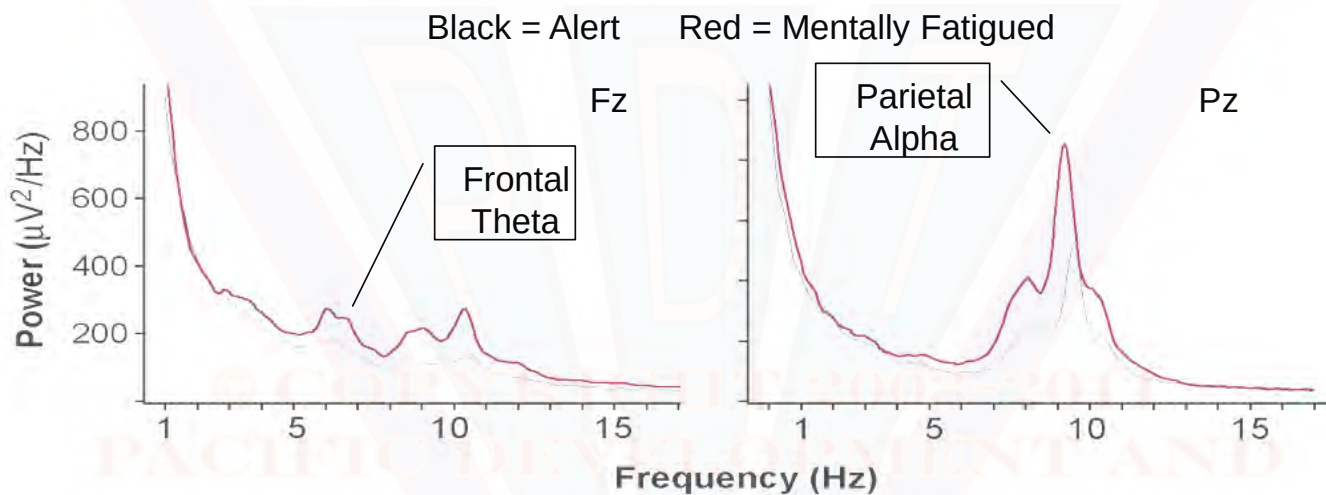


Other Elements of Sensor-State Models

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



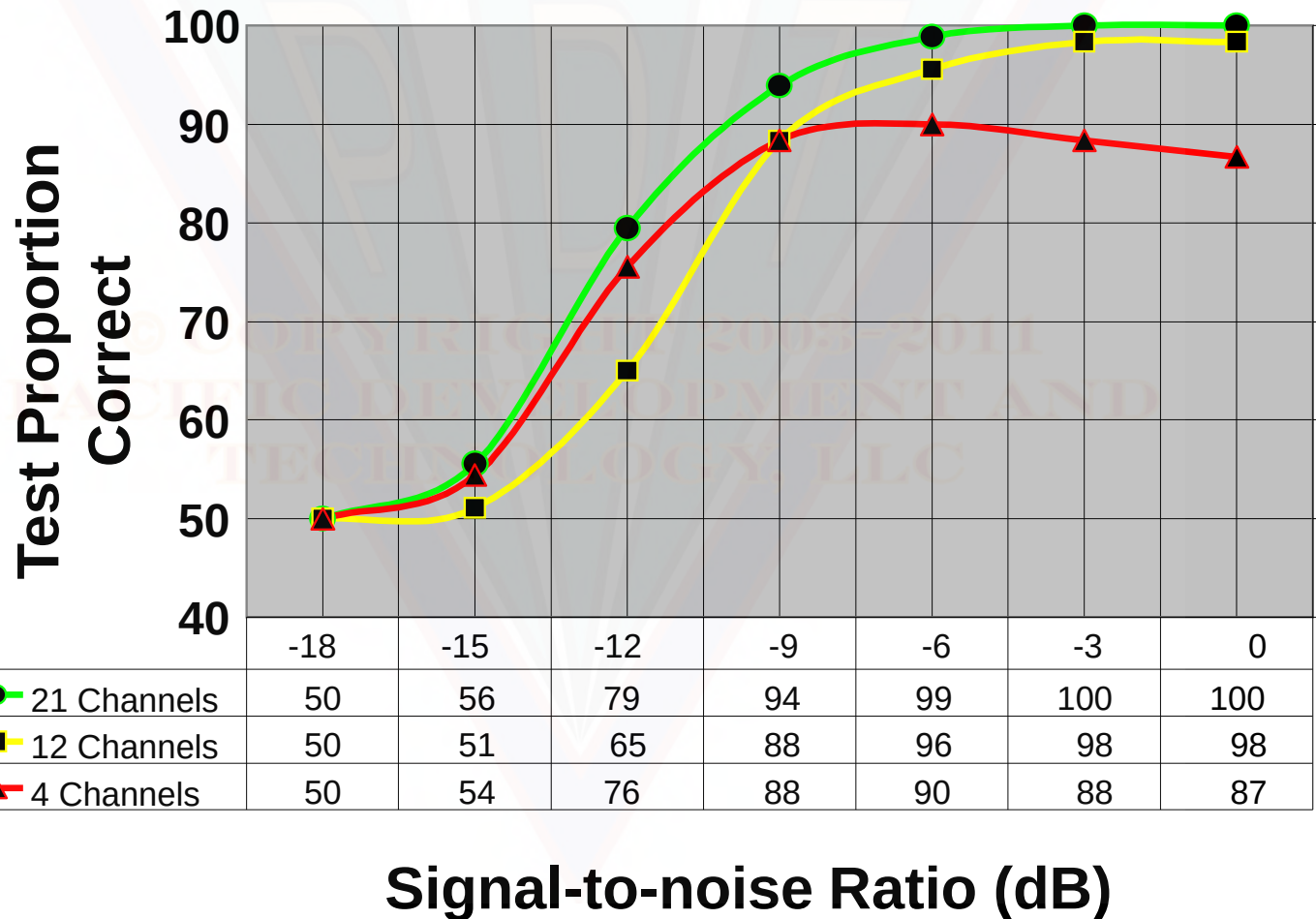
Application 1: Mental Fatigue





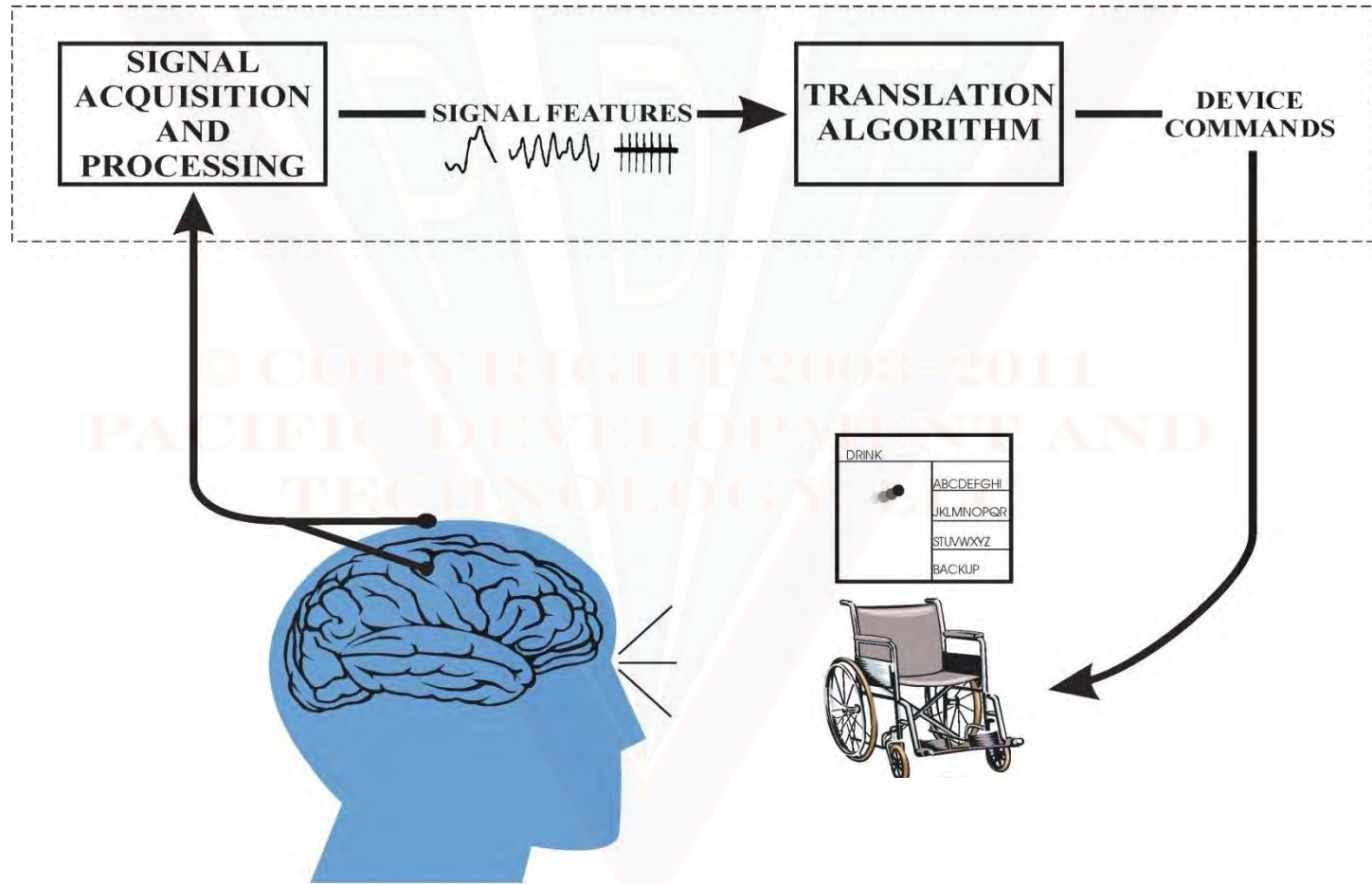
Robust EEG-Based Classification of Mental Fatigue

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



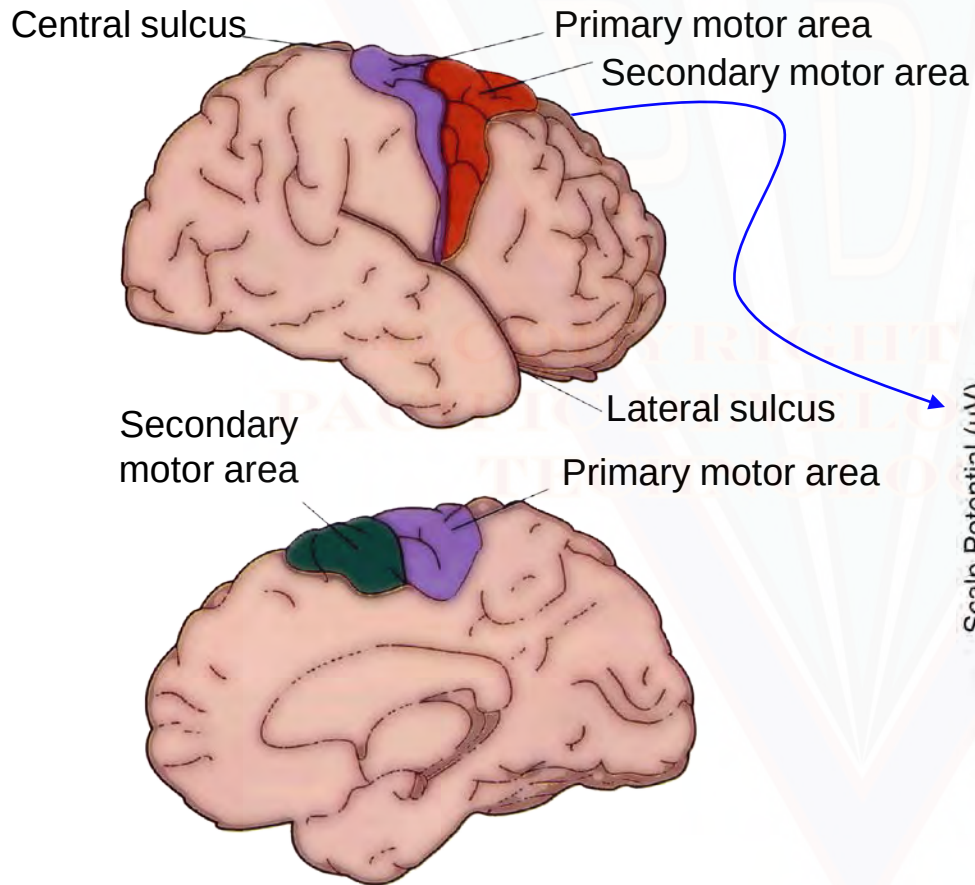


Application 2: BCI

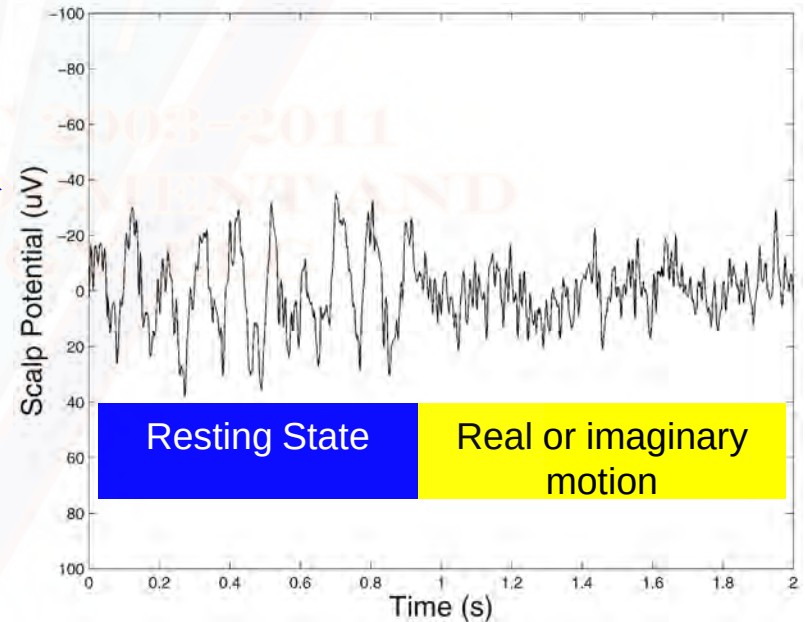




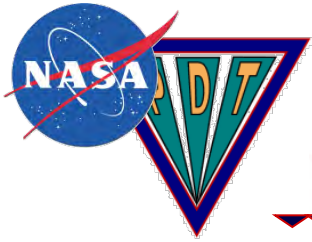
Application 2: BCI



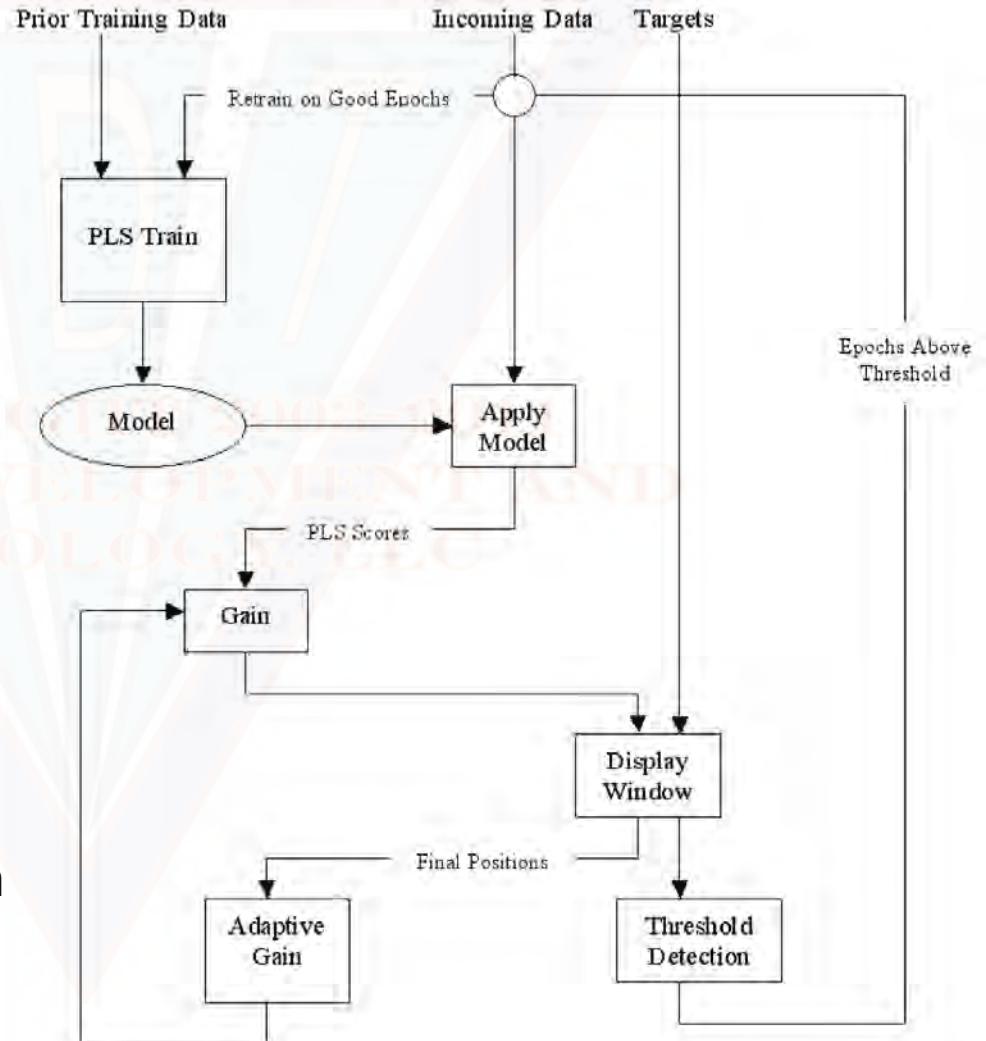
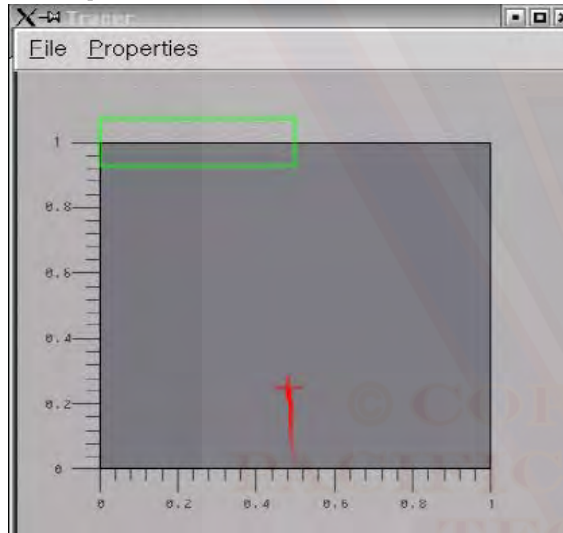
EEG from Motor Areas



(Adapted from Beatty, 1995)



Application 2: BCI



Control System for Target Practice

Trial-by-trial classification (left, right)

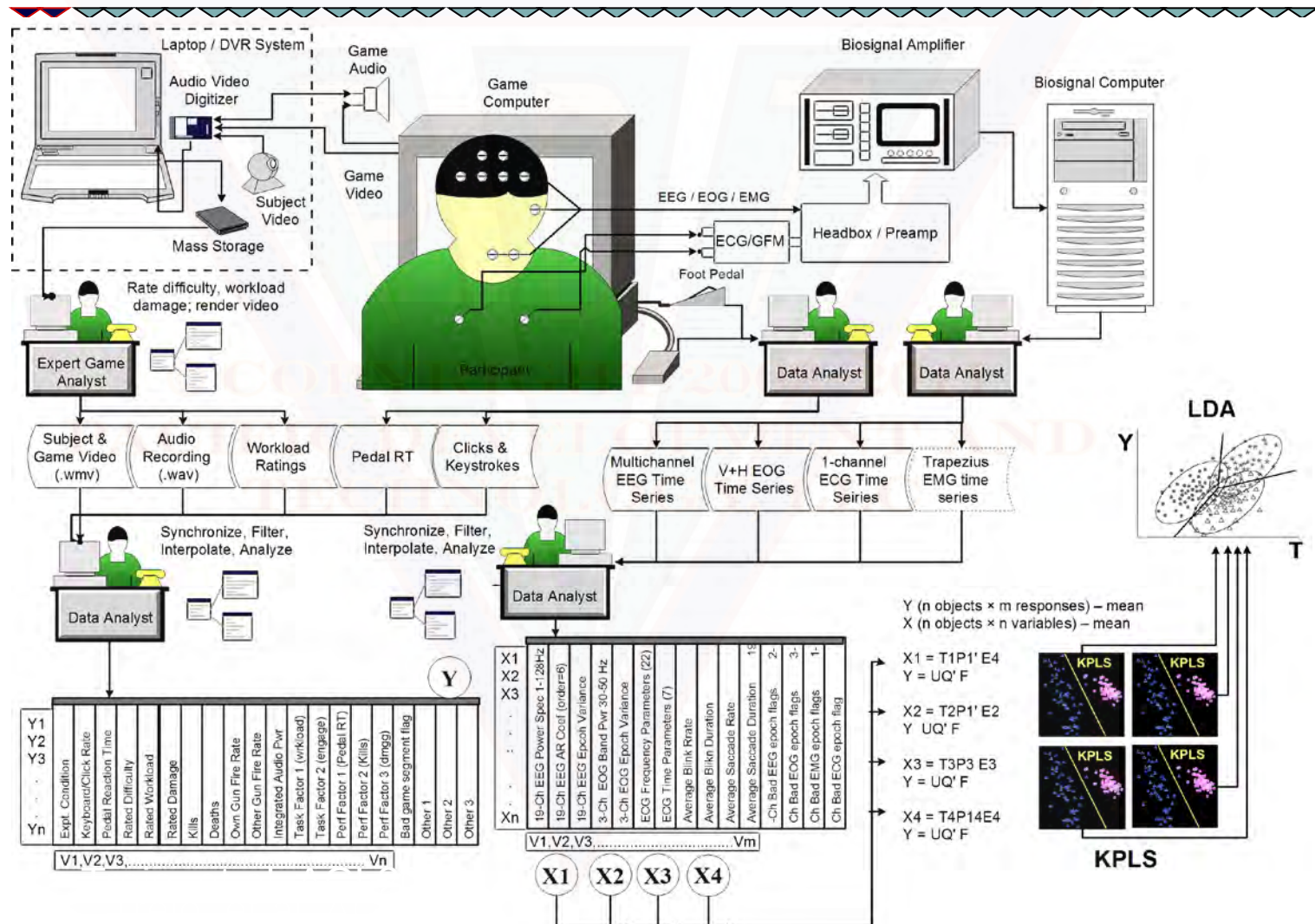
- 250 ms display update

Dual adaptive controller design

- Adaptive PLS pattern recognition
- Adaptive gain control for motion

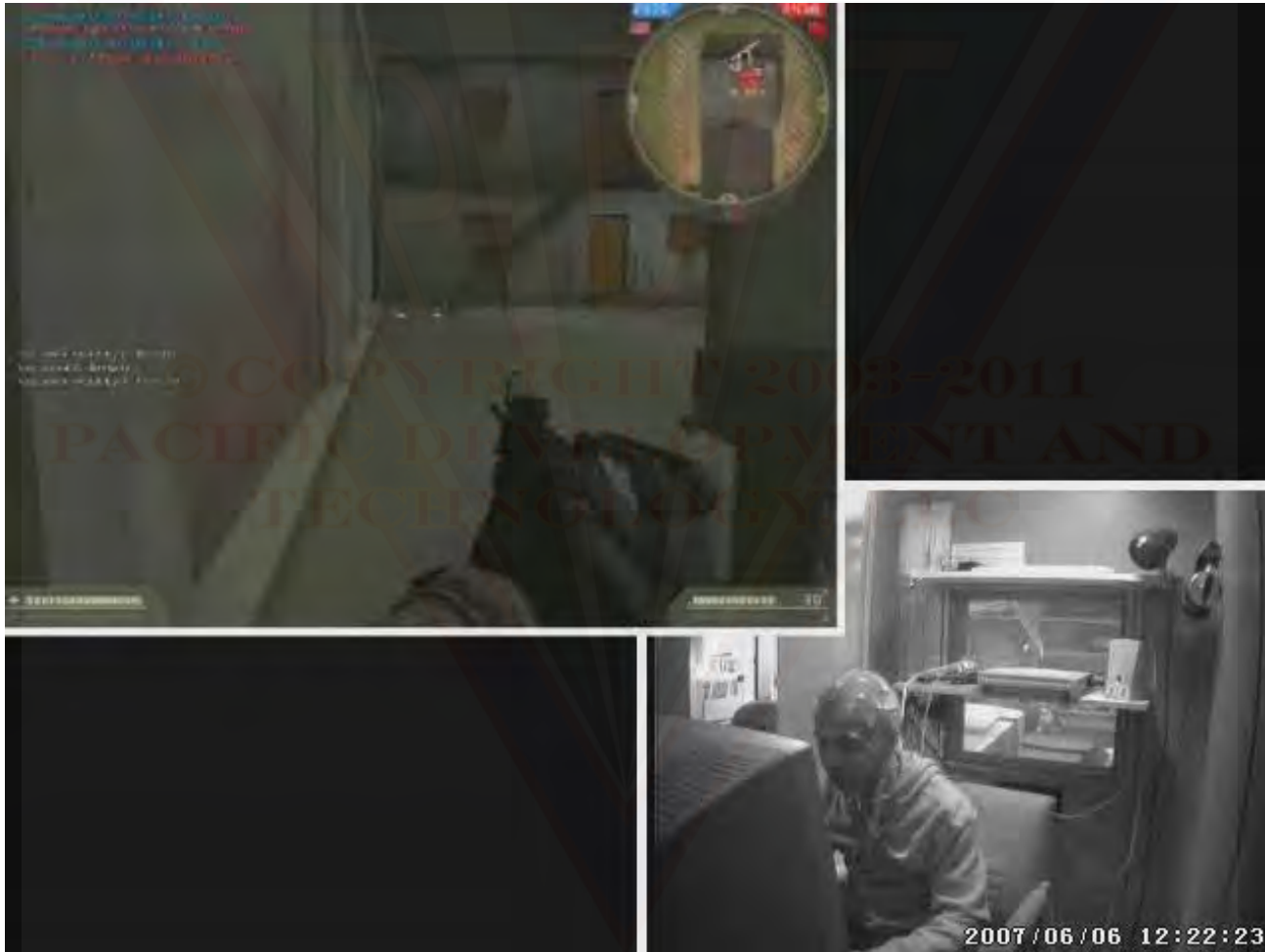


Application 3: Detection of Cognitive Overload



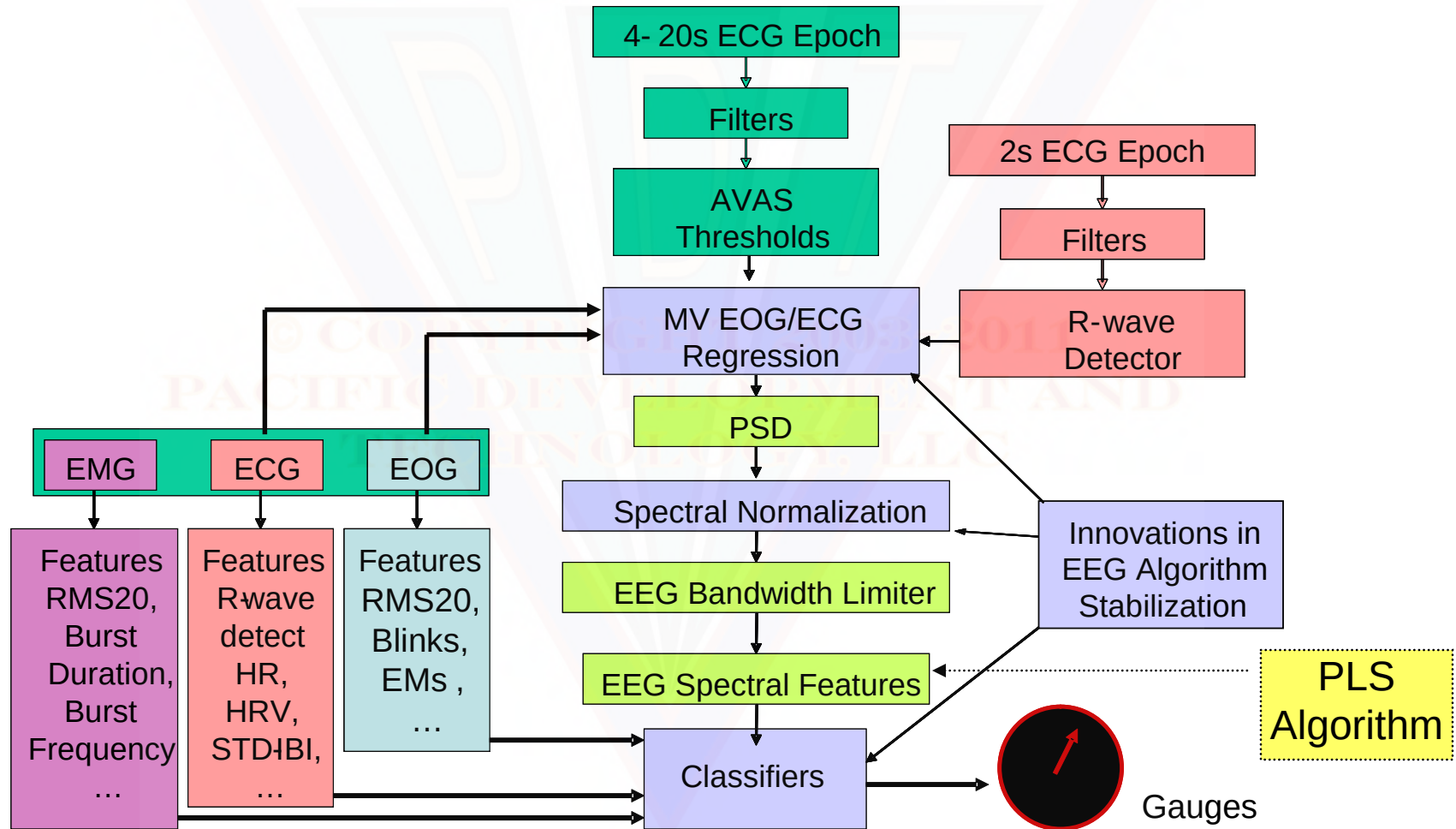


Experiment for Overload Detection



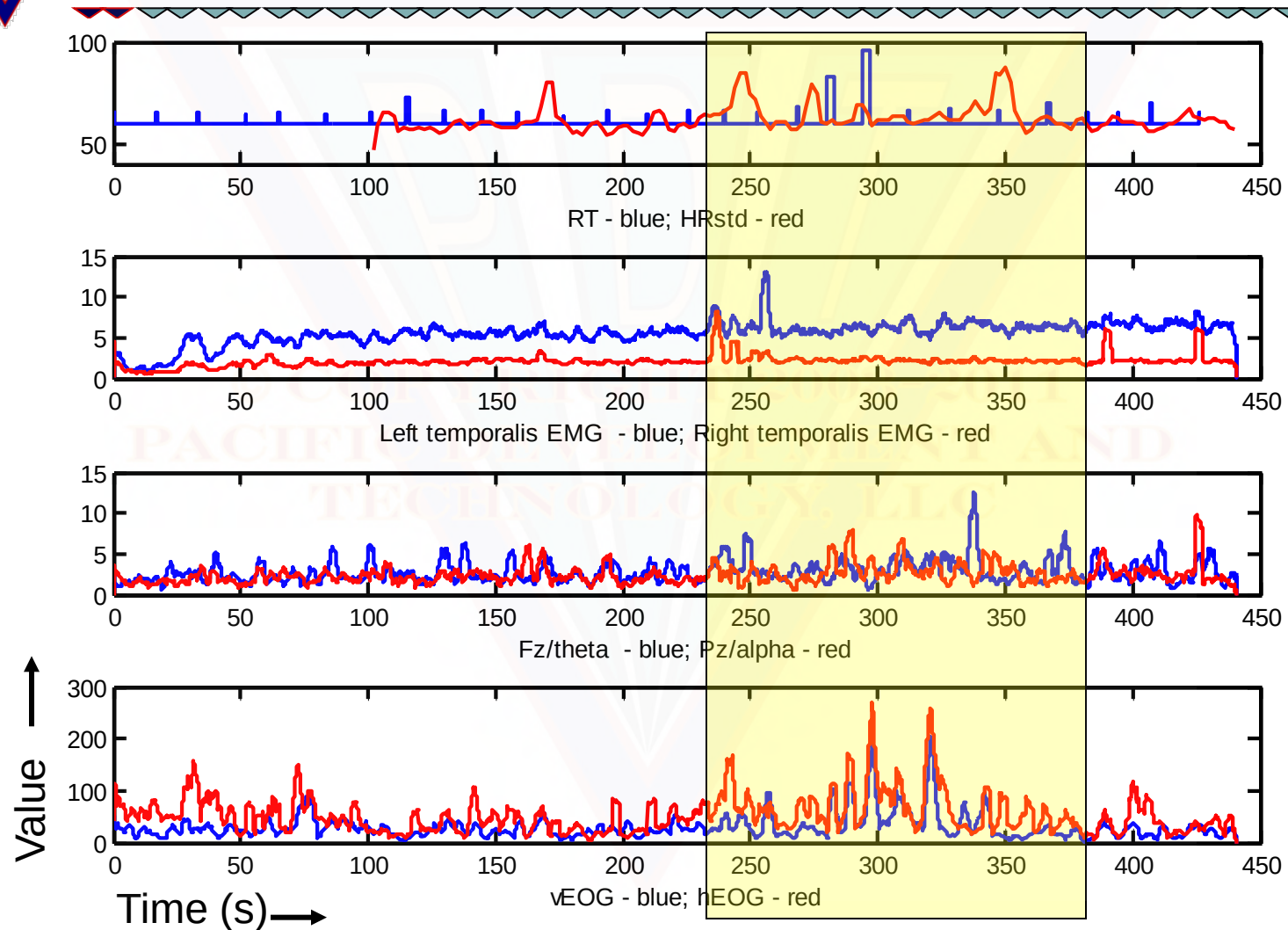


Stabilizing Classifiers





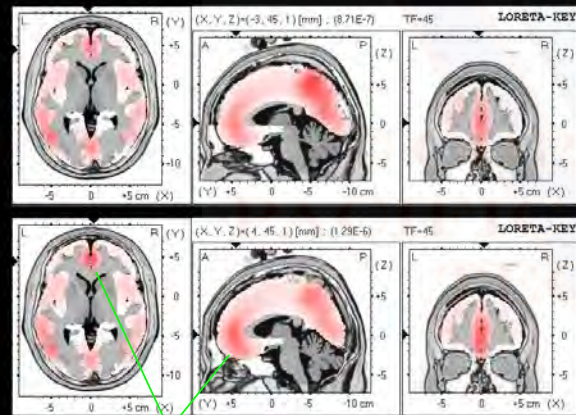
Multimodal Overload Patterns





Attention-related EEG Sources

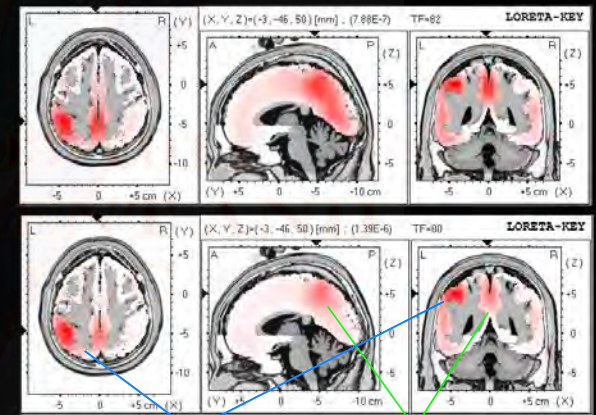
Passive viewing: theta



Anterior Cingulate

Engaged 5: theta

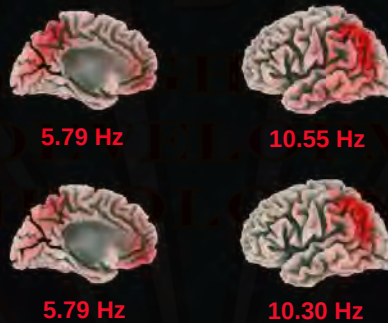
alpha



Inferior Parietal

Precuneus

alpha

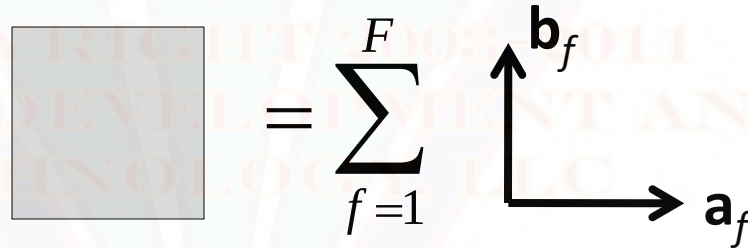




Familiar (bilinear) Mapping Algorithms

Factor Analysis

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


$$\text{[Matrix]} = \sum_{f=1}^F \begin{matrix} \uparrow b_f \\ \rightarrow a_f \end{matrix}$$

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

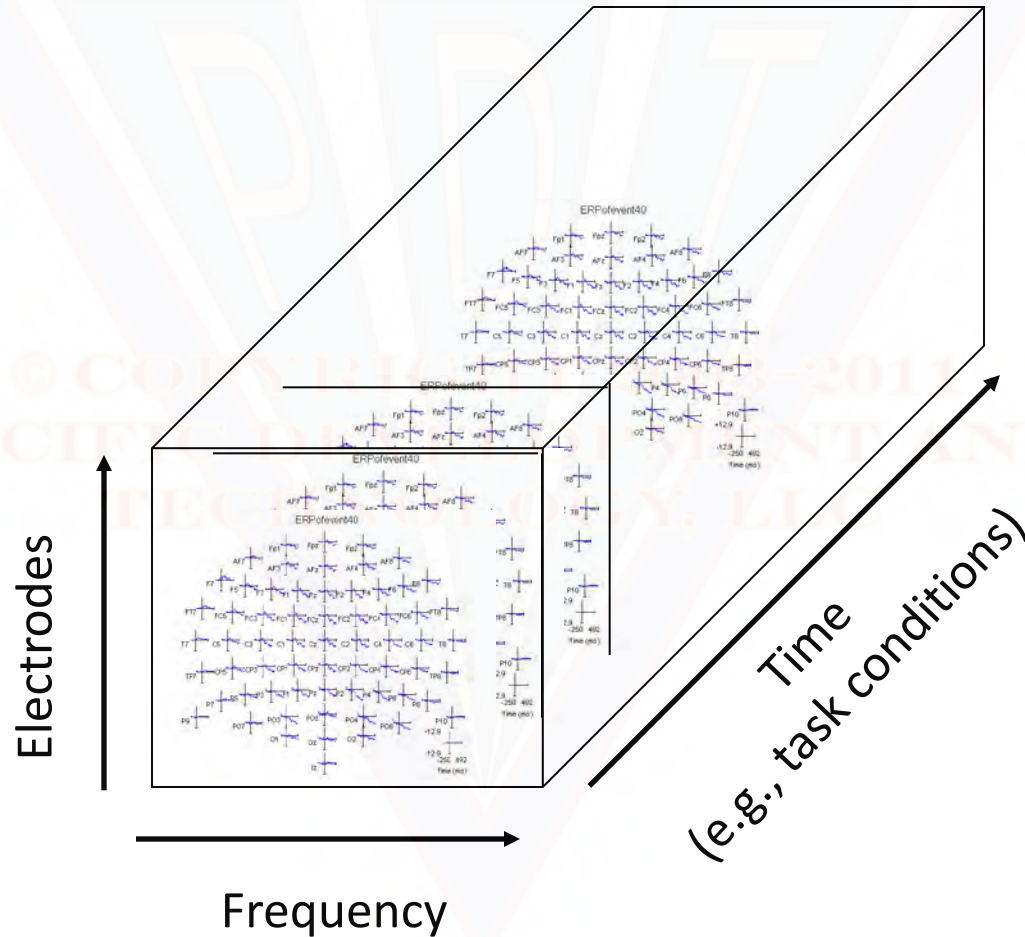
- a. Assume orthogonal factors: PARAFAC
- b. Allow interacting factors: Tucker 3

3. Modeling approach

- a. Unsupervised extraction: PARAFAC, CANDECOMP, Tucker 3
- b. Supervised extraction: N-PLS

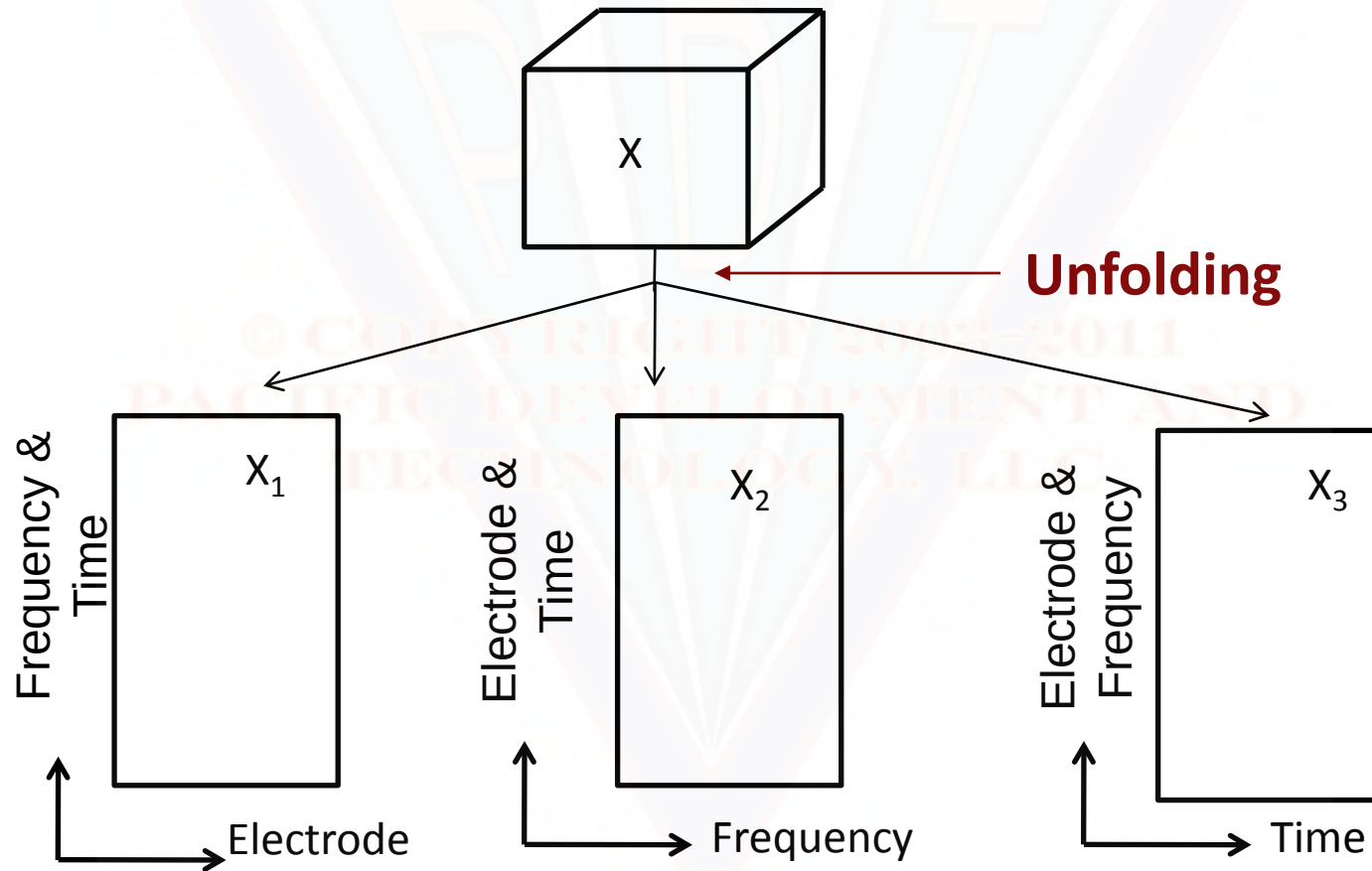


EEG-based Estimation of Task Demands





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 $(l \times m \times n)$ multidimensional array
- F_1, F_2, F_3 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)



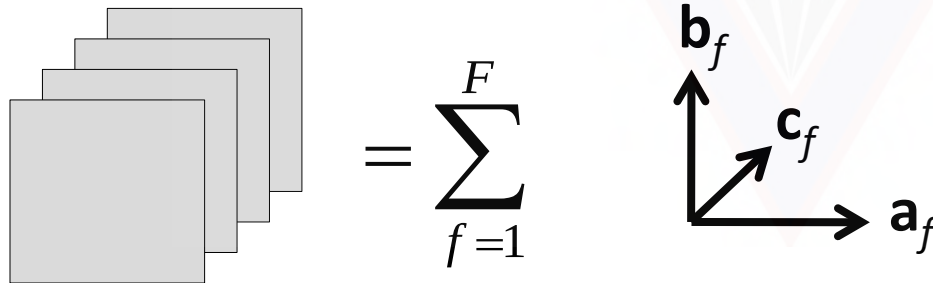
PARAFAC

(Parallel Factor Analysis, unsupervised)

PARAFAC is a special case of the Tucker 3 model
where $F_1 = F_2 = F_3 = F$ and $G = I$

For a 3-way array:

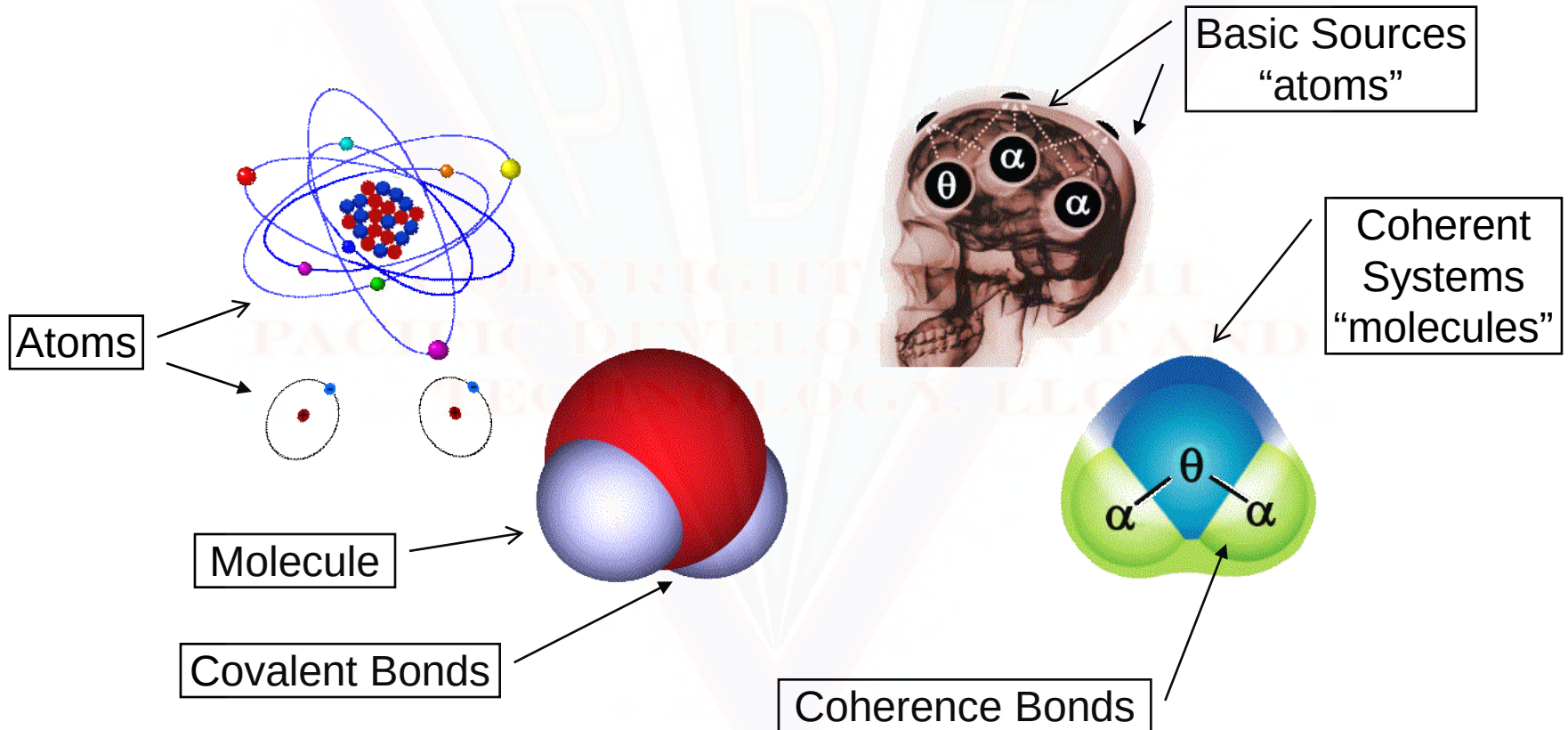
$$x_{ijk} = \sum_{f=1}^F a_{if} b_{jf} c_{kf} + e_{ijk}$$



“Atoms” = $a_1 b_1 c_1$
 $a_2 b_2 c_2$
 $a_3 b_3 c_3$
...
 $a_f b_f c_f$

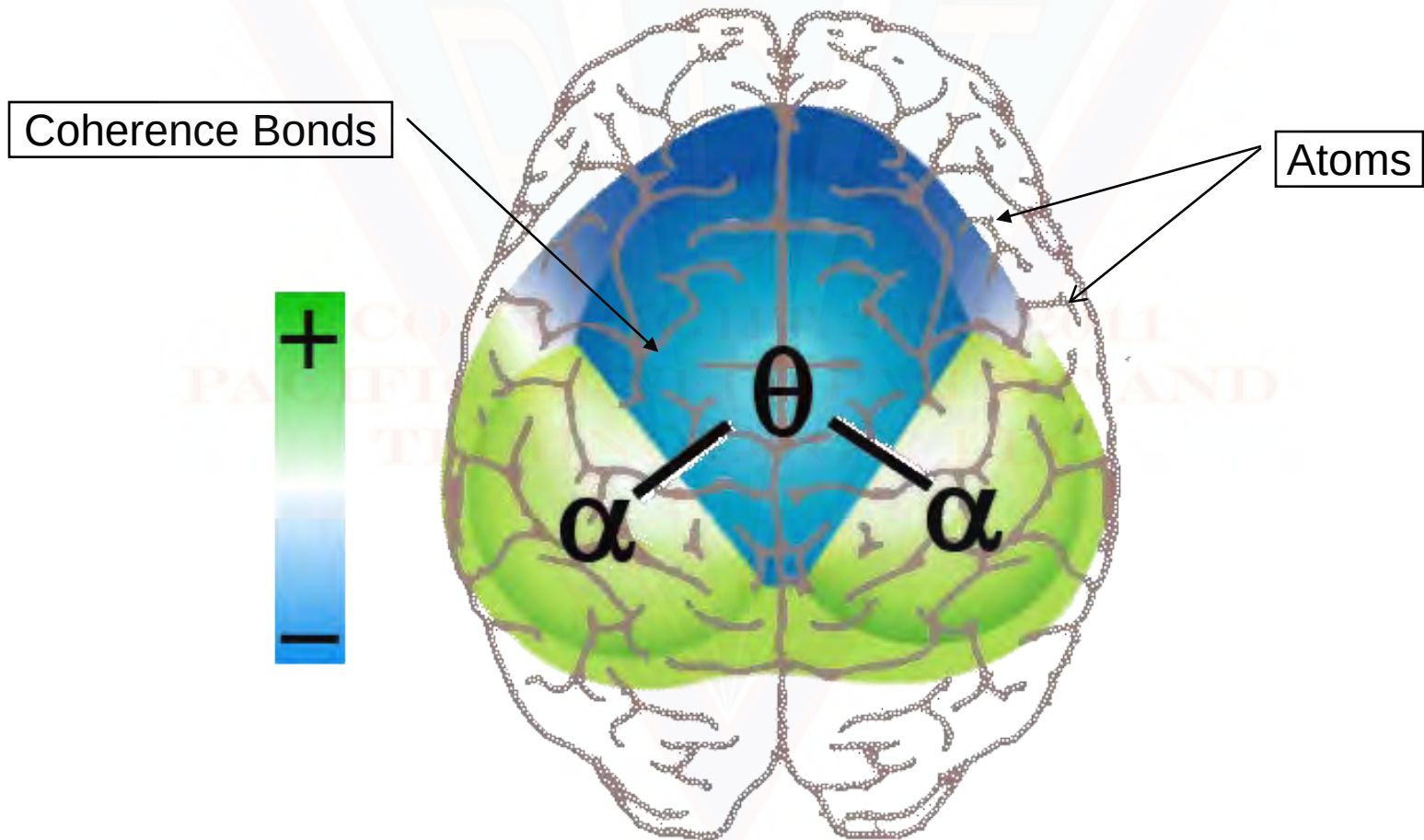


“Atomic” EEG Elements





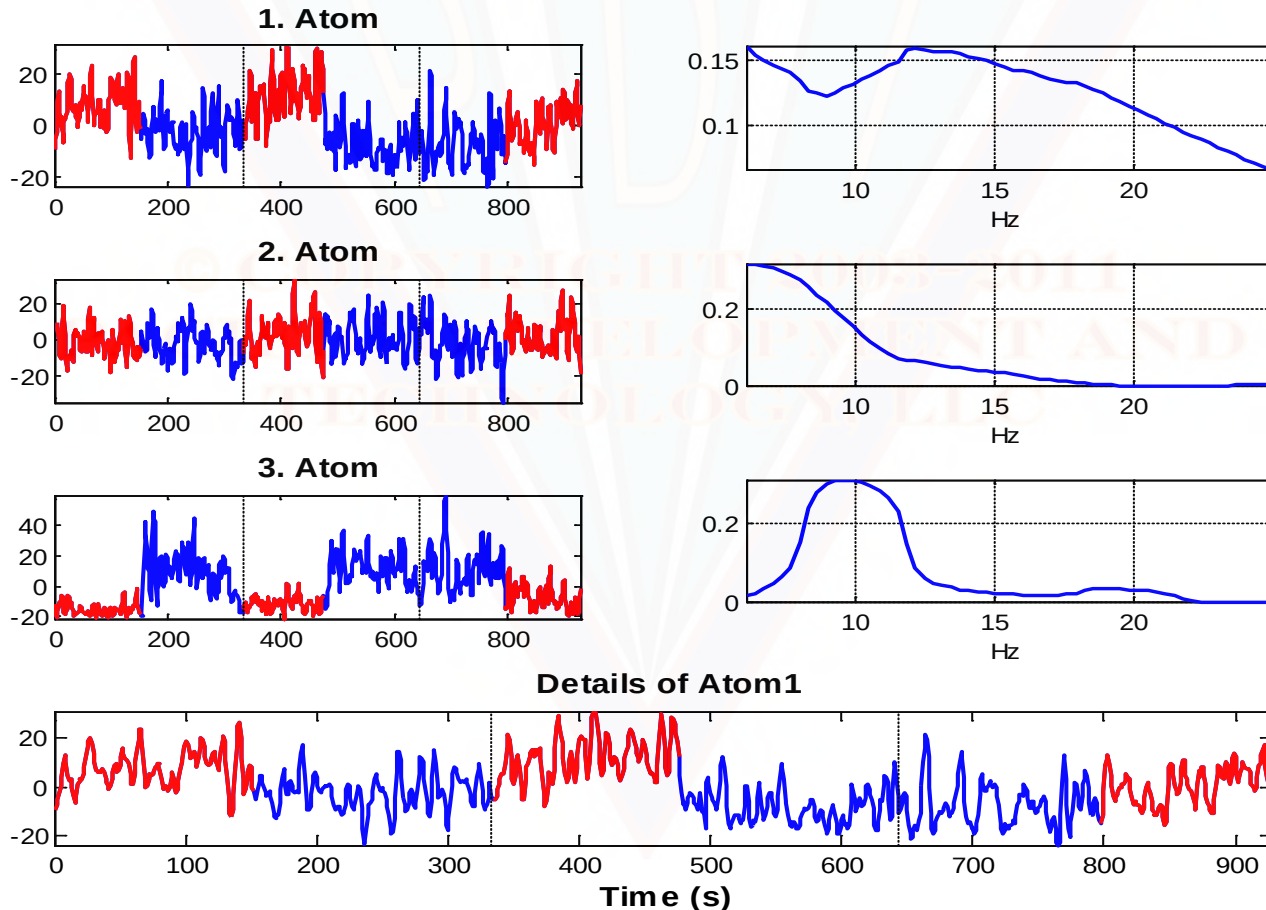
“Molecular” EEG Processes





PARAFAC Applied to UAV Task

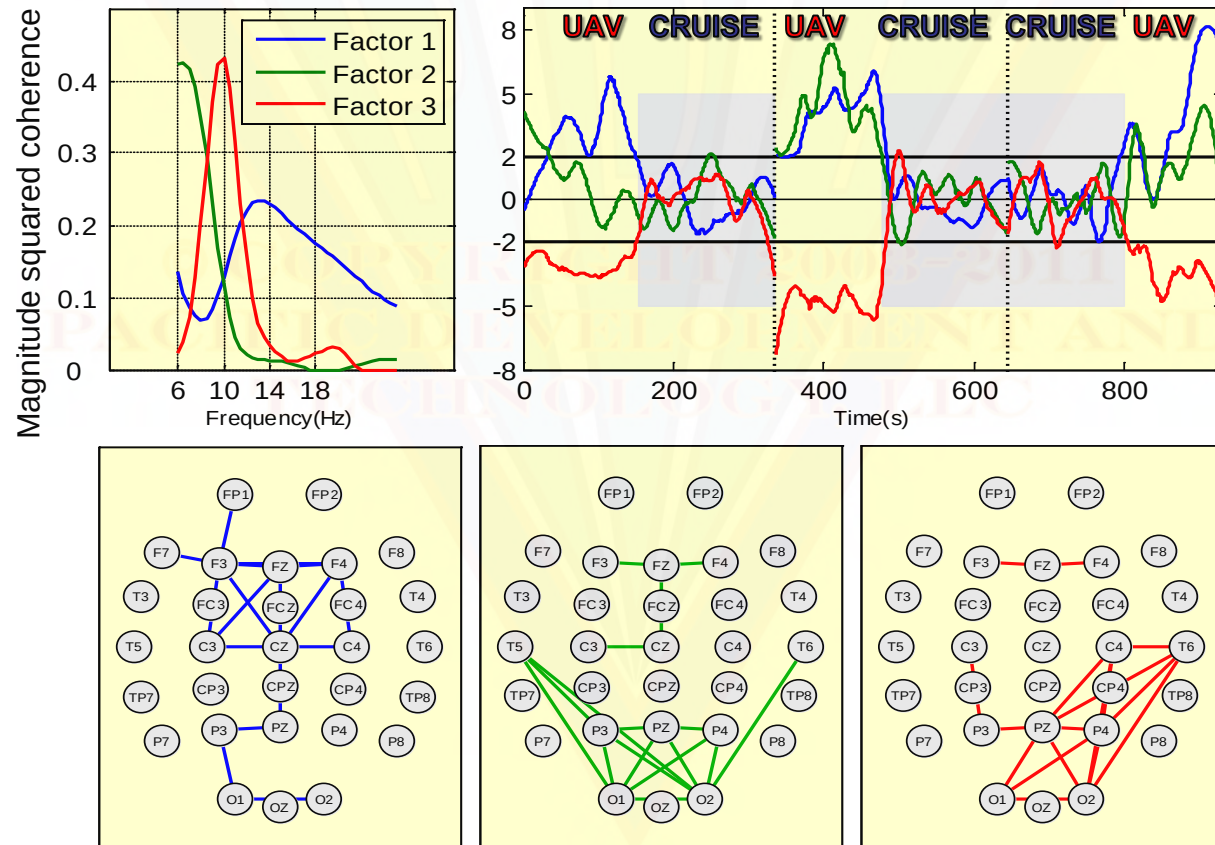
PARAFAC *EEG power* model during UAV task performance in one participant.
Blue areas = low demands (cruise); red areas = high demands (UAV control).





PARAFAC Applied to UAV Task

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

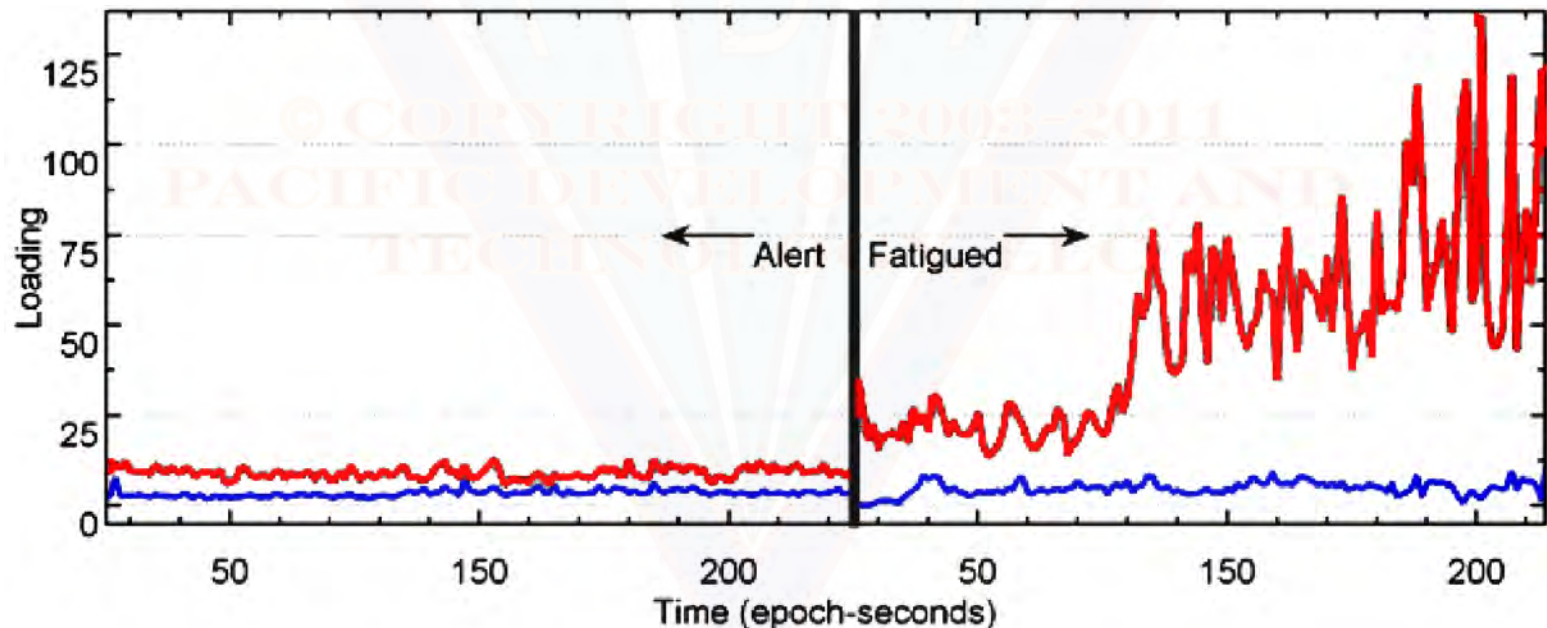


Top 10% of inter-electrode coherences



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, SpO₂, 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)