

# Lifting the Fog of Fatigue

Gregory Belenky, M.D.

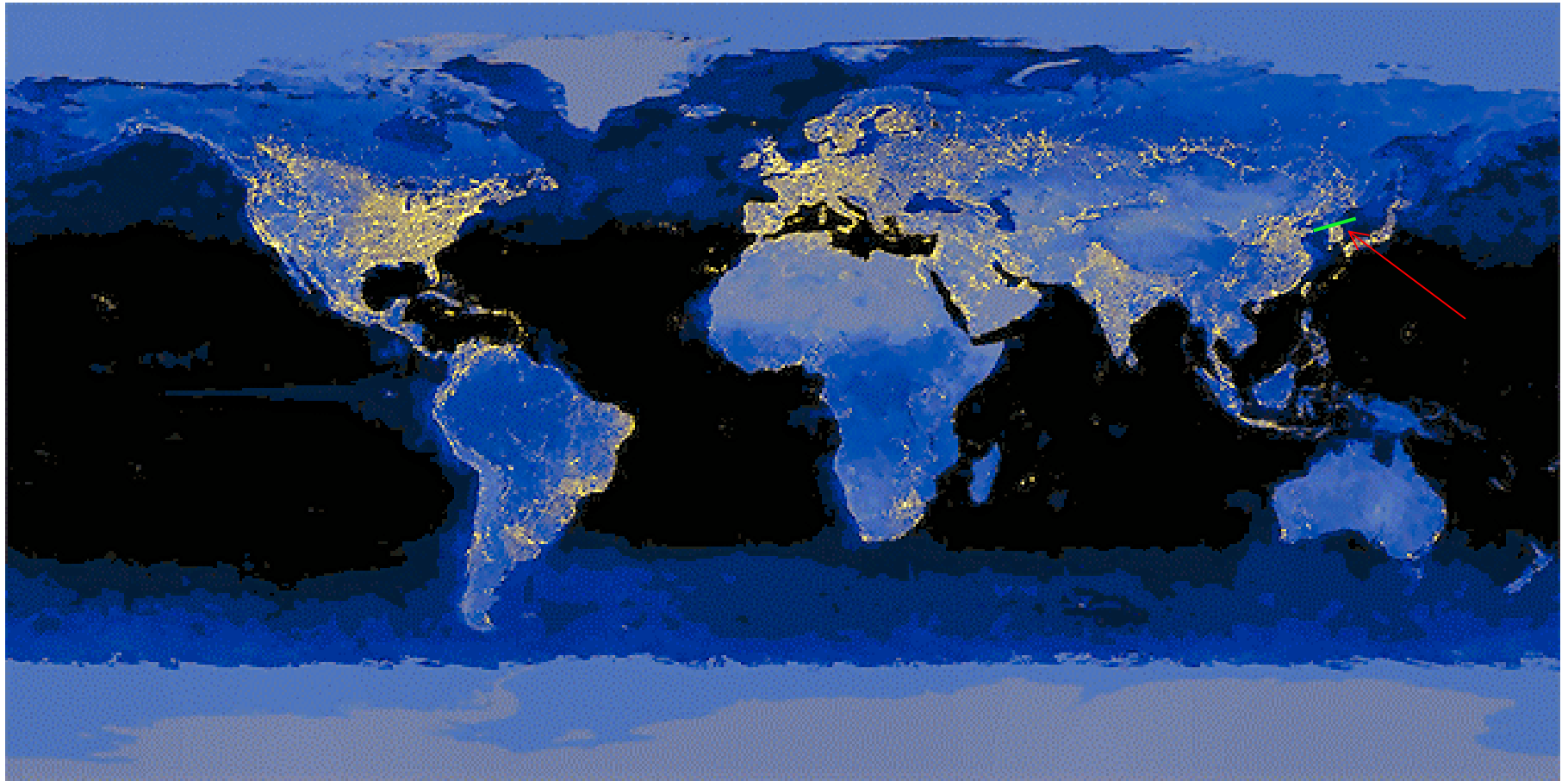
Research Professor and Director  
Sleep and Performance Research Center  
Spokane, WA

# The Operational Environment Defined

- Operational Environment
  - Human performance critical to correct outcome of the system – the outcome itself is critical
  - There a temporal envelope within which the correct decision must be made or the system fails
  - John Boyd and the Observe, Orient, Decide, Act (OODA) Loop
- Most operational settings are complex and tightly-coupled
- Many operational settings involve 24x7 operations, extended work hours and shift work
- High reliability organizations maintain
  - Mindfulness in day-to-day operations
  - Presence of mind in emergencies

Coram – John Boyd: The Fighter Pilot Who Revolutionized War

# The Earth at Night: The Problem of 24/7 Operations



# Sleep:

## A Fundamental Mystery in Neurobiology

- Sleep is found humans, mammals, birds, reptiles, fish, insects, and (perhaps) jellyfish – in any animal with one or more assemblies of nerve cells (neuronal assemblies)
- After over 100 years of experimental work, we know:
  - Adequate sleep sustains performance
  - Inadequate sleep degrades performance
- We do not know:
  - Why extended waking degrades performance?
  - How sleep restores performance?

# Why Sleep?

- Productivity

- Personal
- Corporate

*“I do not care how much they sleep; I want to know how well they perform.”*

*General Max Thurman*

- Safety

- Personal
- Corporate
- Public

*Disasters spring from “not a major blunder, but reasoned calculations that slip just a little.”*

- Health

- Well-being

*Brigadier General  
S.L.A. Marshall*

# Risks of Sleep Restriction and Sleep Deprivation

- Short term (operational environment)
  - Minutes, hours
  - Error, accident, catastrophe
- Mid-term
  - Weeks, months, years
  - Bad planning, inadequate strategizing, poor life decisions
- Long-term
  - Years
  - Overweight/obesity, Type II Diabetes, Metabolic Syndrome, Cardiovascular Disease, etc.
- Triad of factors supporting health, productivity, and well-being
  - Diet
  - Exercise
  - Sleep

# Fatigue: Operationally Defined

- Fatigue is subjectively defined by
  - Verbal self-report – “I am tired.”
  - Endorsing the high end of a fatigue scale, e.g., Samn-Perelli
  - Observation by co-workers of fatigue behaviors or degraded performance
- Fatigue is objectively defined by degraded performance
  - Added metrics
  - Psychomotor vigilance task (PVT)
  - Embedded metrics
    - Lane deviation – driving
    - FOQA – flying
    - etc....

# Field Measurement of Sleep and Performance

- Objective Measurement of Sleep
  - Electrophysiological recording (PSG)
  - Activity Monitoring (Actigraph)
- Objective Measurement of Performance (PVT)

*“I do not care how much they sleep; I want to know how well they perform.”*

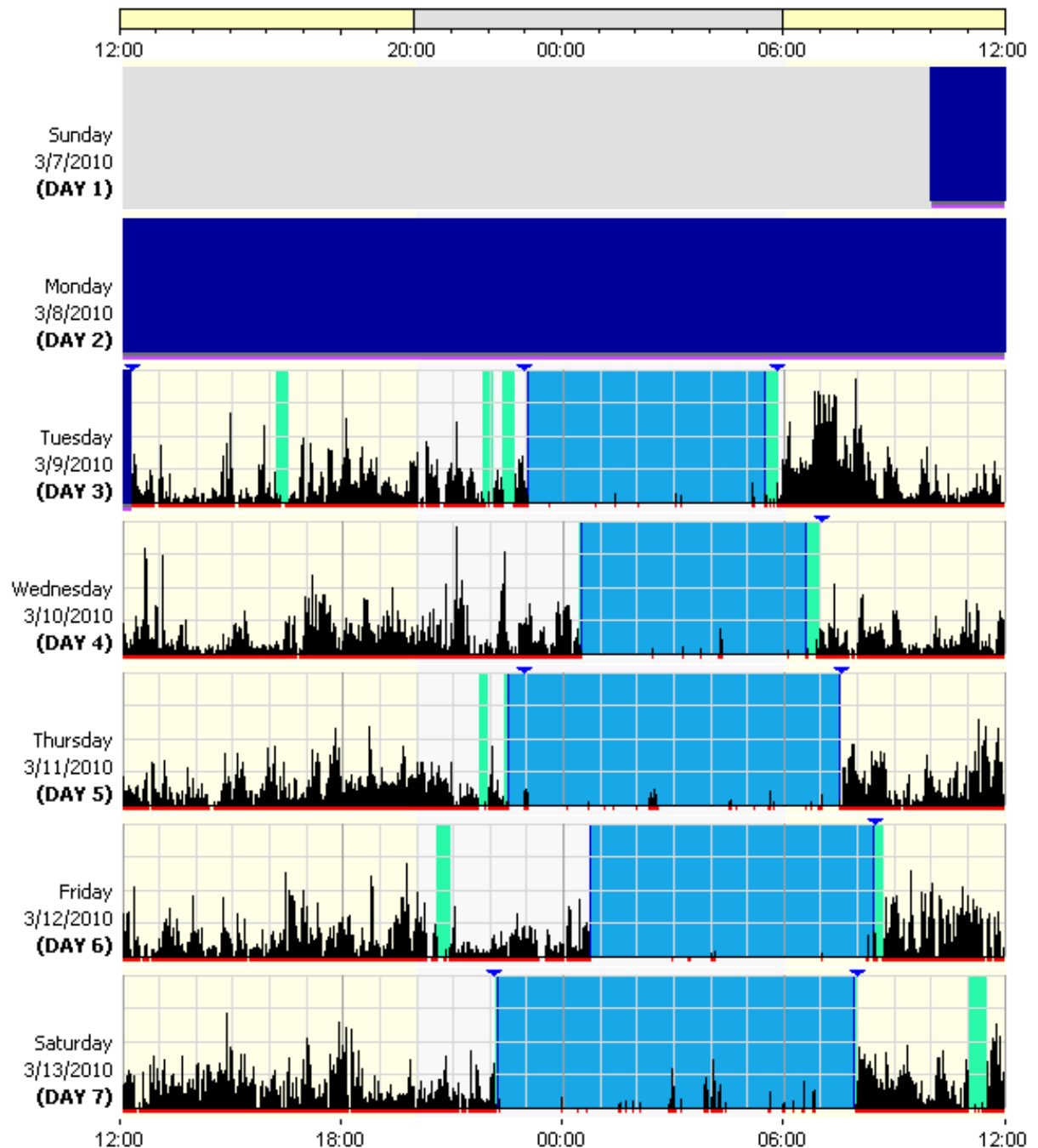
*General Max Thurman*





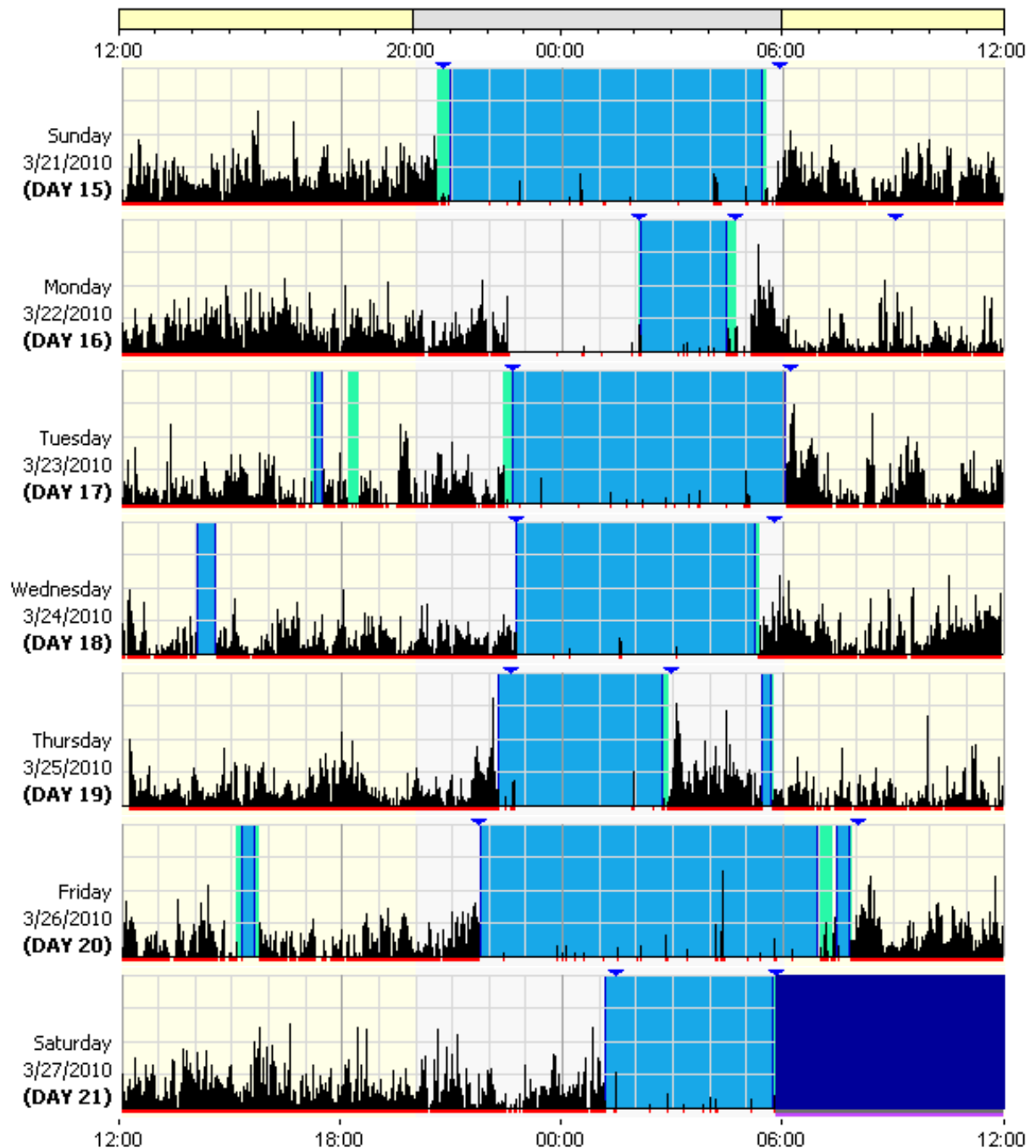
# Actigraph Data

- Blue boxes indicate sleep intervals
- Teal boxes indicate periods of rest
- Purple black out indicates excluded data due to off-wrist detection



# Actigraph Data

- Blue boxes indicate sleep intervals
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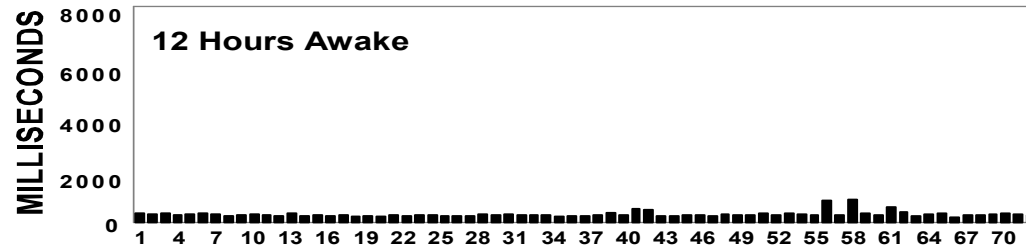
# The Psychomotor Vigilance Task (PVT): A Sensitive Metric of Vigilance

- A reaction time test
- Administered by PC or Smartphone
- ~10 stimuli present/min for 10 min
  - Sensitive to sleep deprivation and sleep restriction
  - Sensitive to circadian periodicity
  - Sensitive to time on task (workload)
- Good psychometric properties
  - IQ independent
  - Virtually no learning involved
  - Unforgiving of attentional lapses

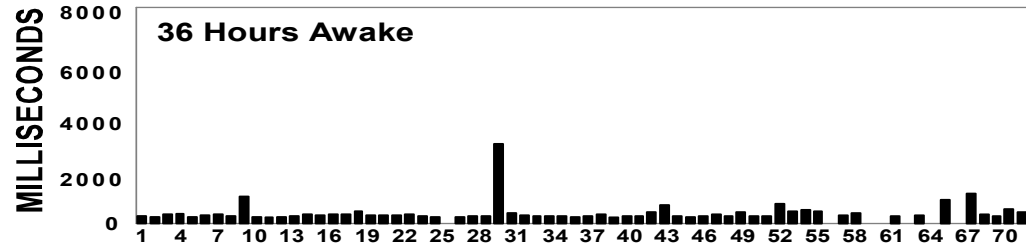
# Response by Response:

## Attentional Lapses during Sleep Deprivation

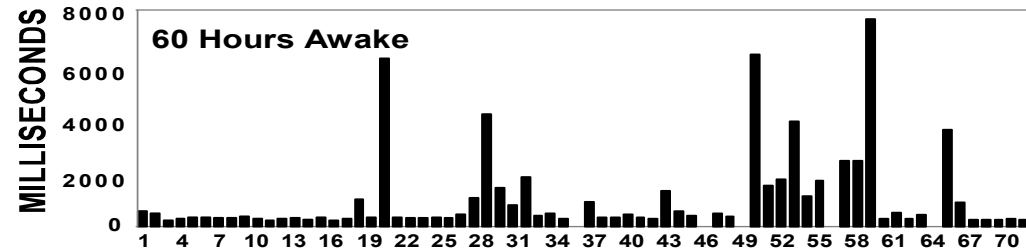
12 Hours  
Awake



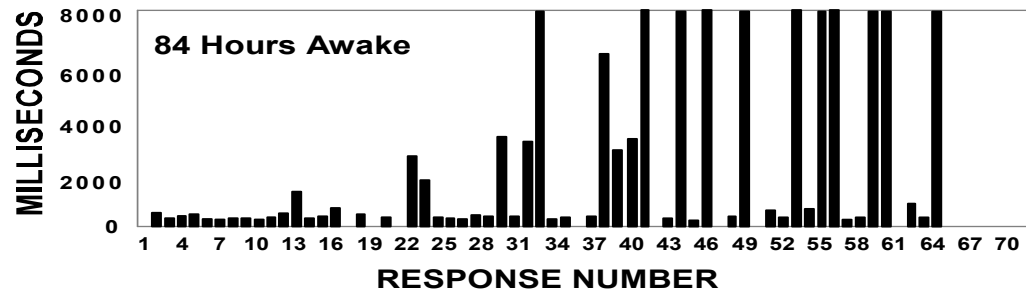
36 Hours  
Awake



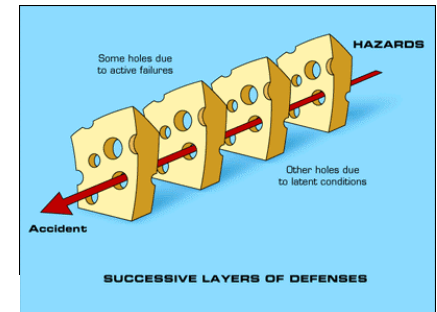
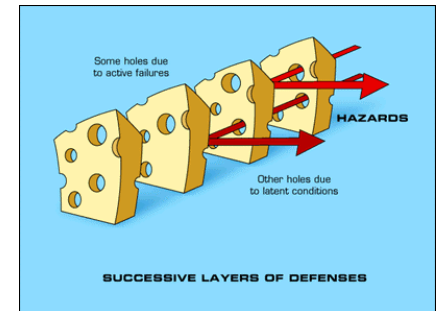
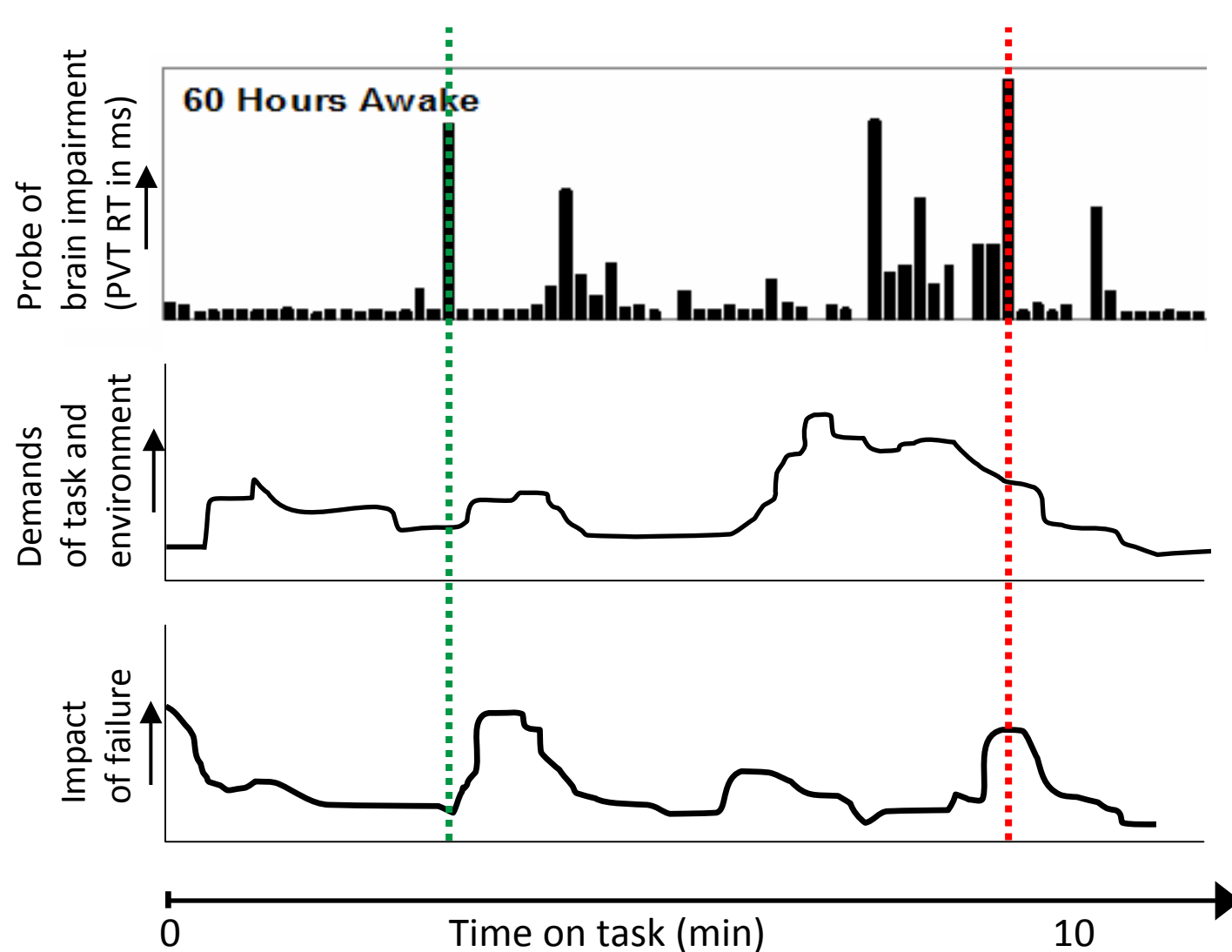
60 Hours  
Awake



84 Hours  
Awake



# From Wake State Instability to Accidents: Performance Lapses Predict Risk (Not Errors)



Swiss Cheese Model of  
Accident Causation  
(Reason, 2001)

From Van Dongen  
and Hursh (2010)  
*PPSM 5e*

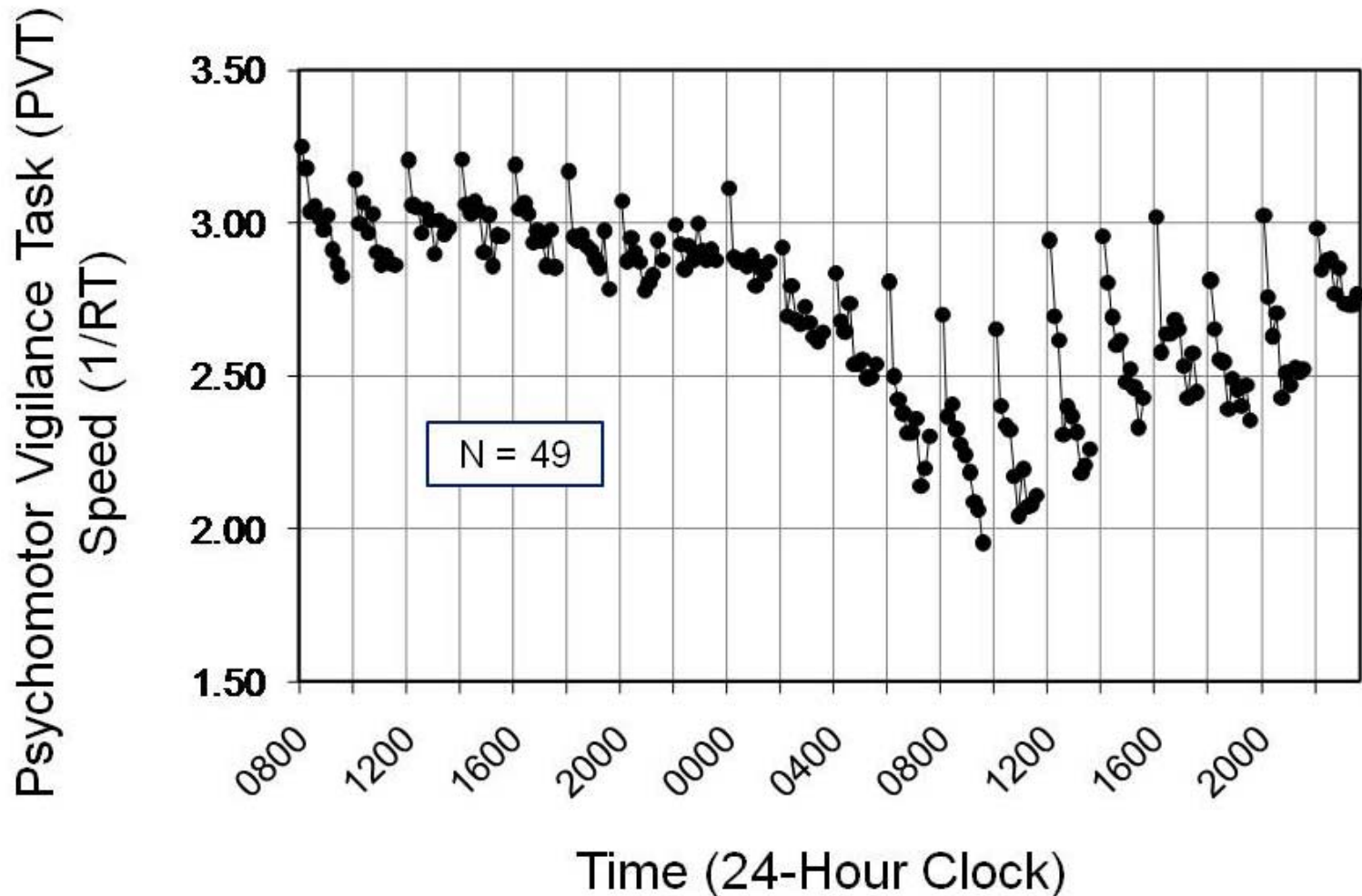
# Fatigue and its Components

- Fatigue operationally defined
  - Subjectively by self-report
  - Objectively by degraded performance
- Fatigue is the final common pathway integrating
  - Sleep/wake history (time awake and sleep loss)
  - Circadian rhythm (time of day)
  - Workload (time on task, task intensity, and task complexity)
  - Individual differences in response to time awake, time of day, and time on task

# Sleep, Fatigue, and Predicting Performance and Fatigue Risk

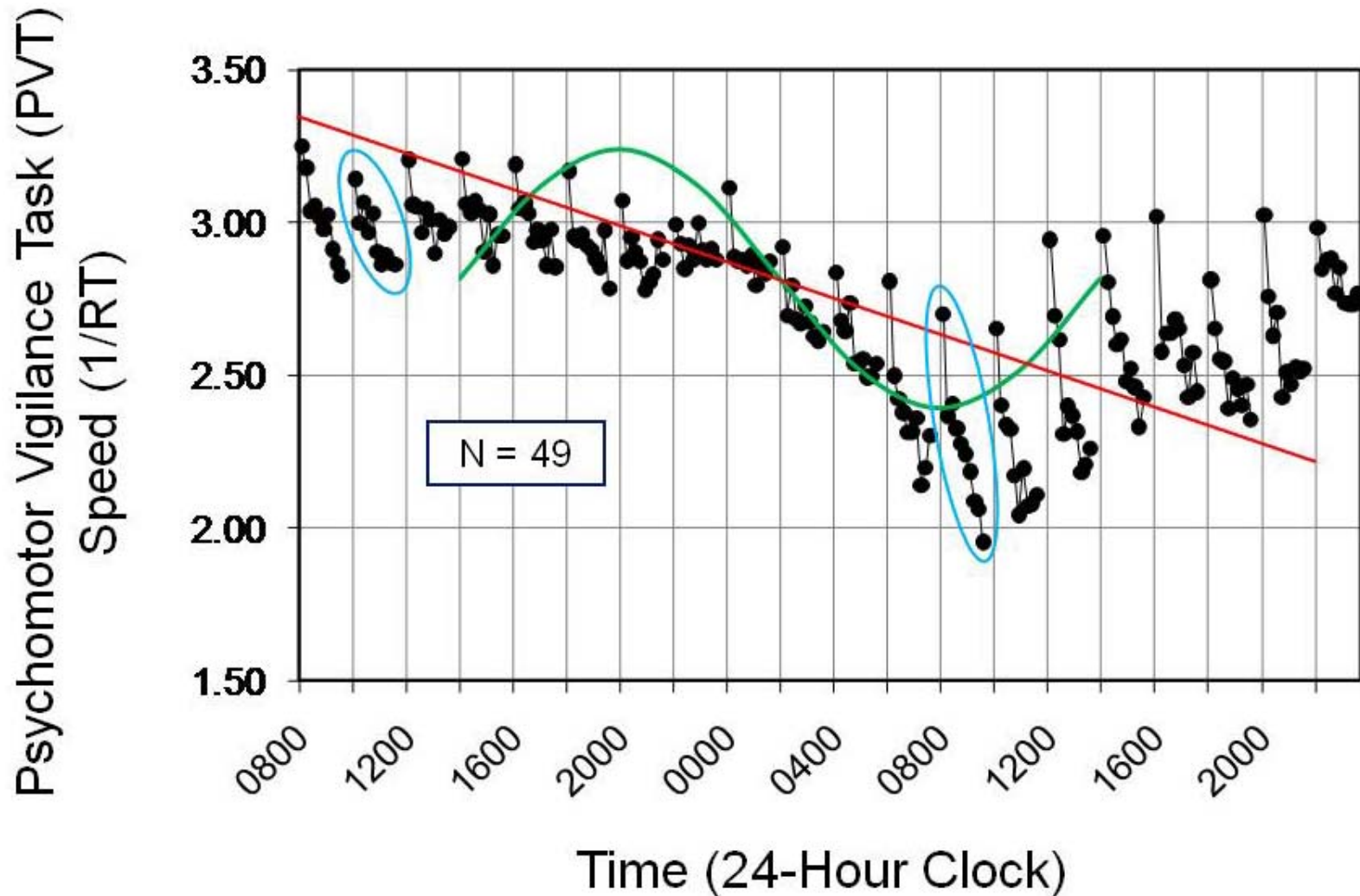
- Epidemiological studies associate sleep/wake history, circadian phase, and workload with accident risk
- Mathematical models have are being developed to integrate sleep/wake history, circadian rhythm, and workload to predict individual performance (fatigue-risk) in real-time

# Fatigue as the Integration of Sleep Loss, Circadian Rhythm, and Workload

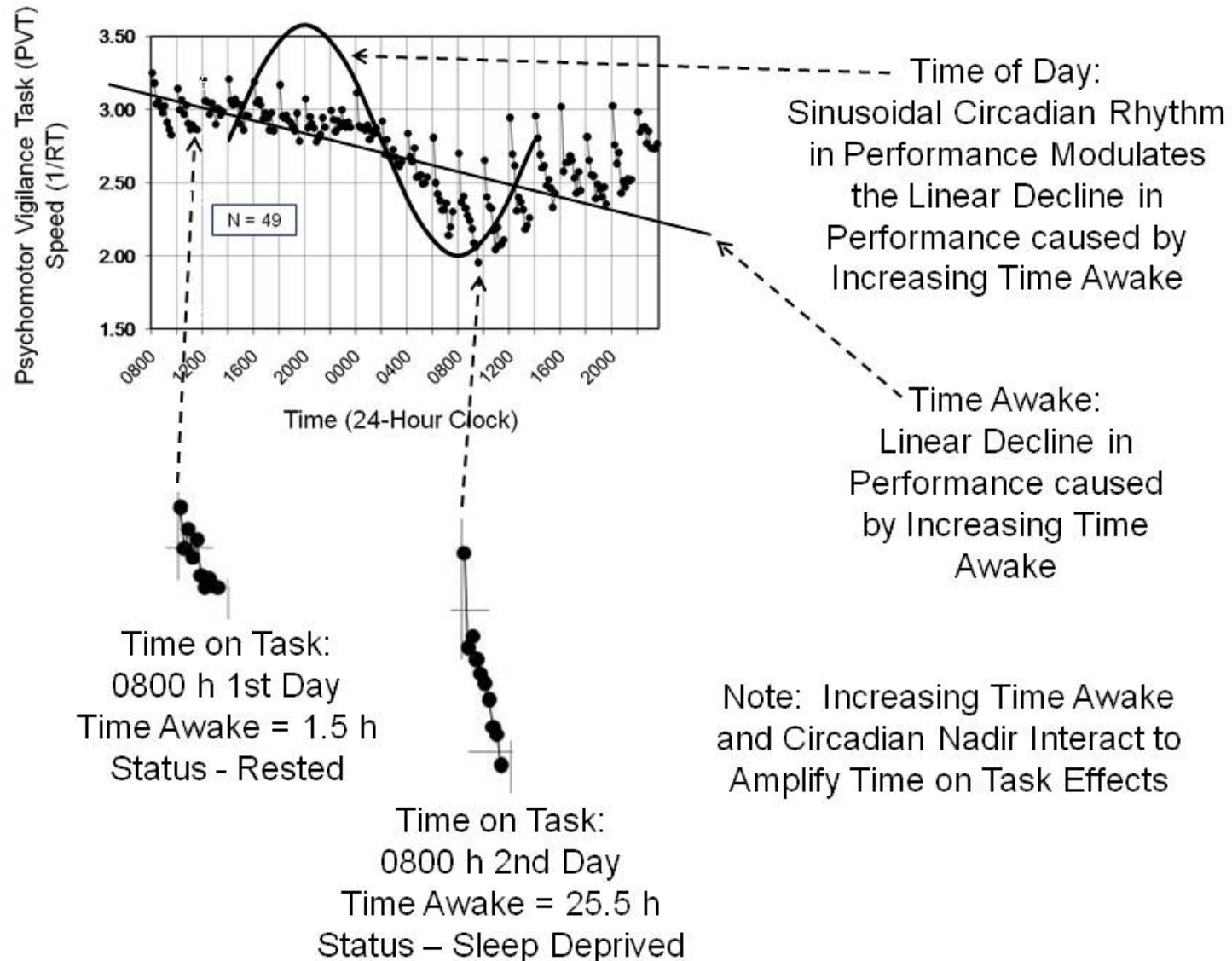




# Linear Decline with Extended Waking Modulated by Circadian Phase Amplifies Time on Task

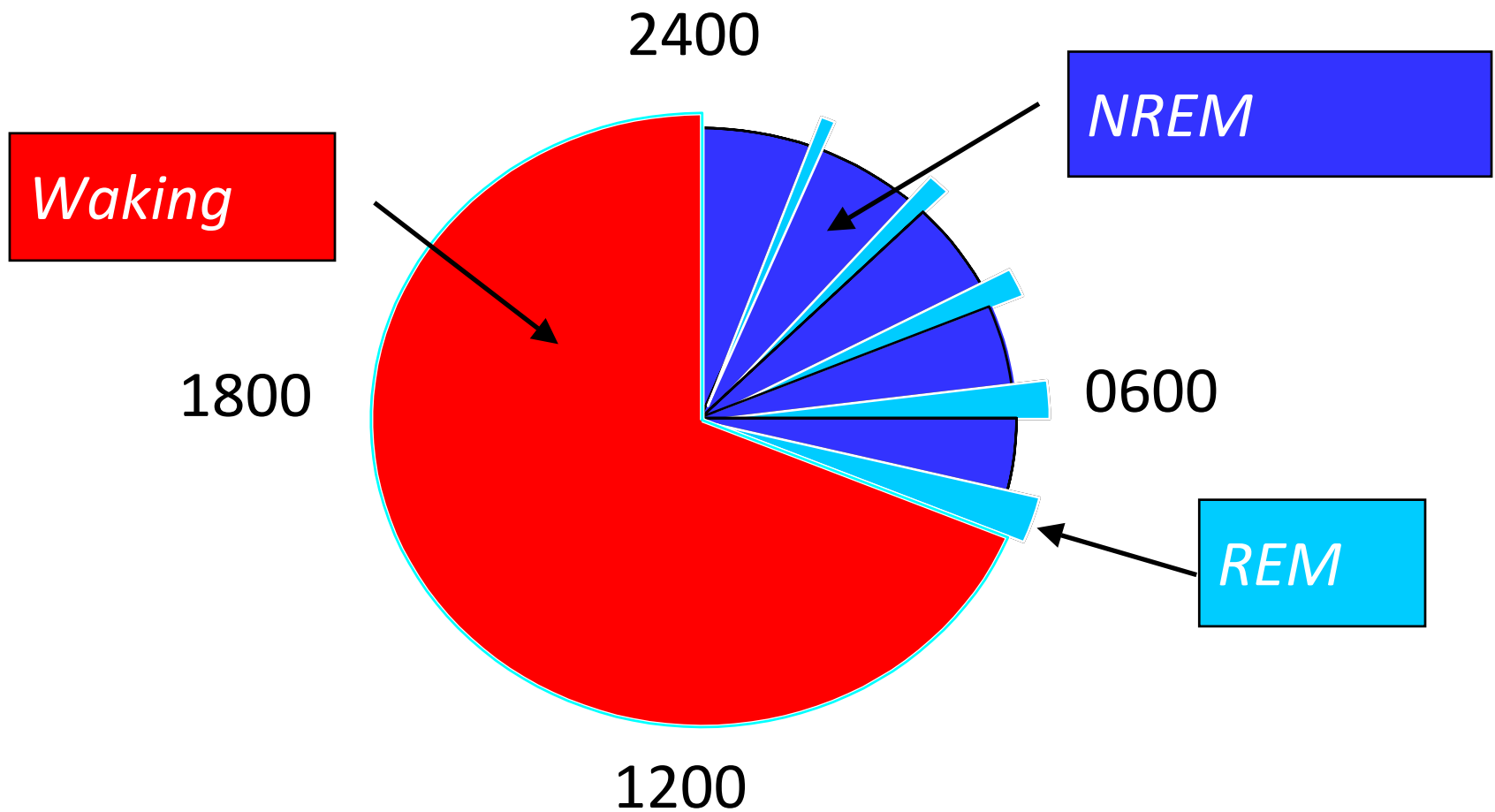


# Interaction of Time Awake, Time of Day, and Time on Task

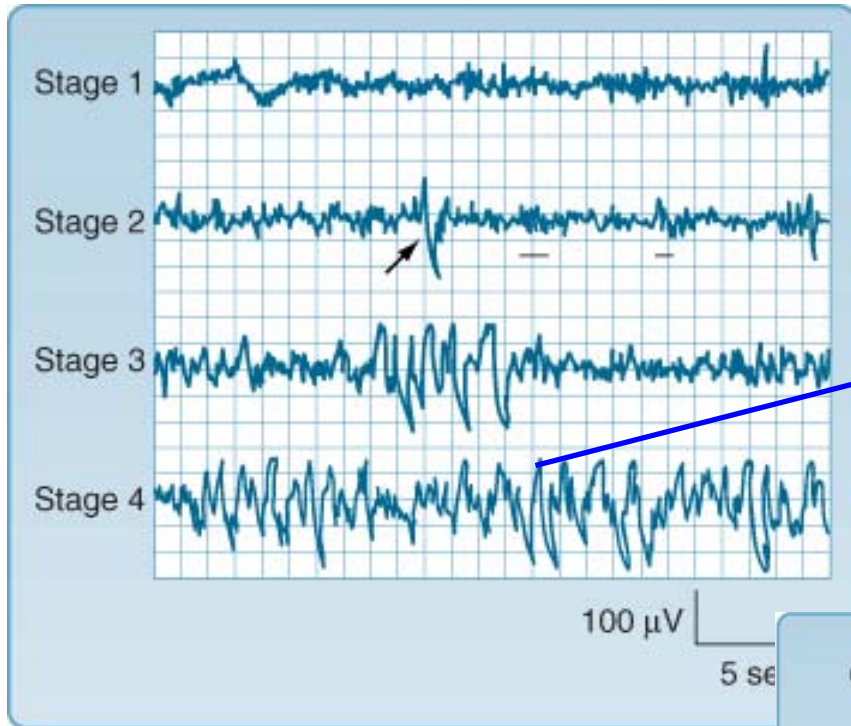


# The Science of Sleep and Circadian Rhythms

# The Sleep/Wake Cycle



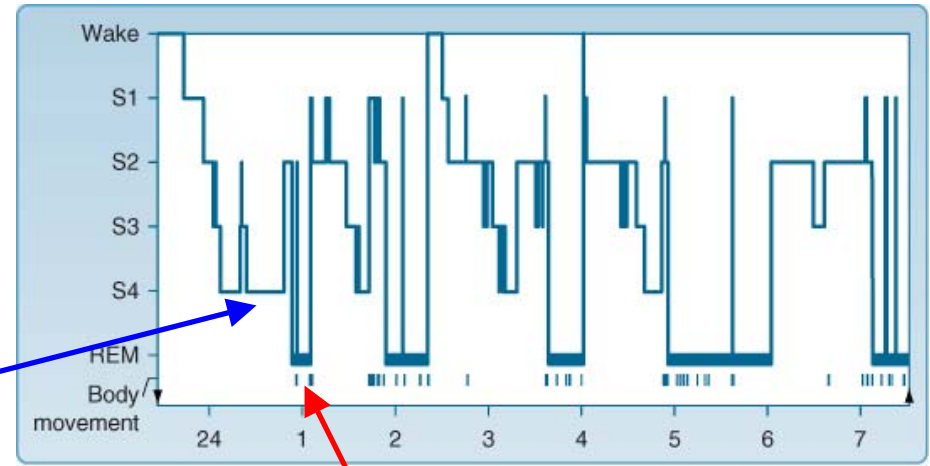
# Physiology of Non-REM and Rapid Eye Movement (REM) Sleep



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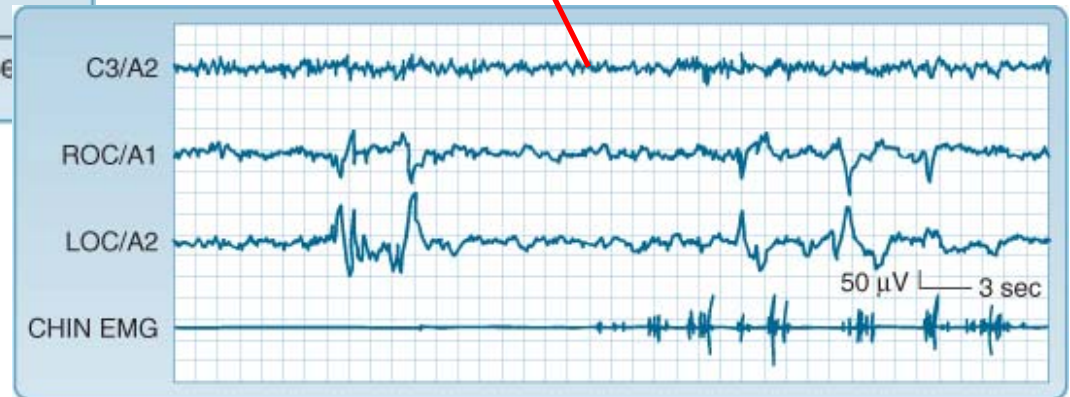
## Slow Wave Sleep

Kryger, Roth and Dement,  
*Principles and Practice of  
Sleep Medicine*, 2005



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## Sleep Cycle



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## REM Sleep

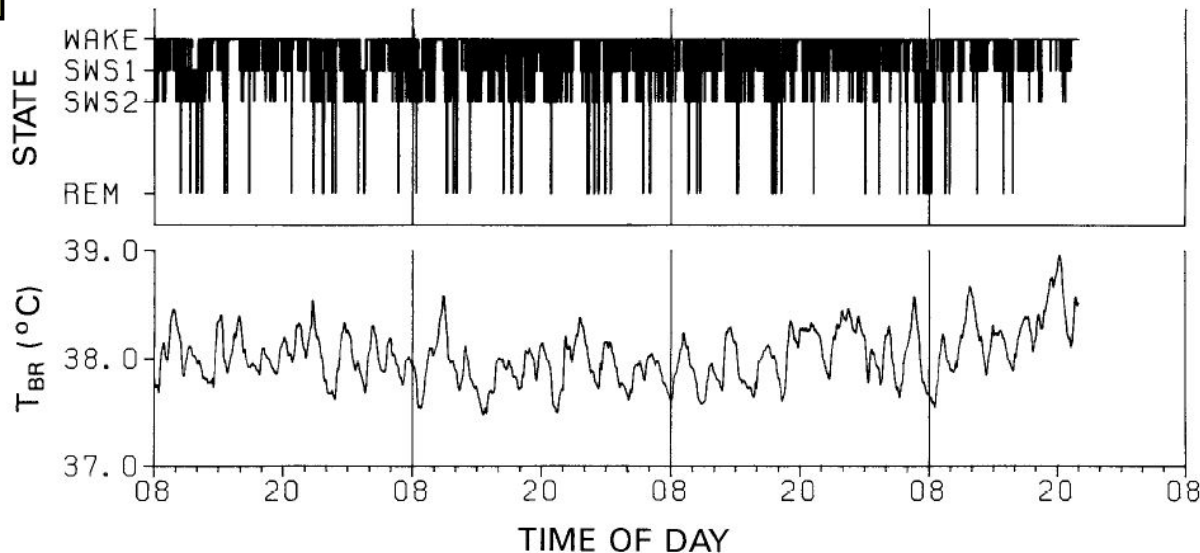
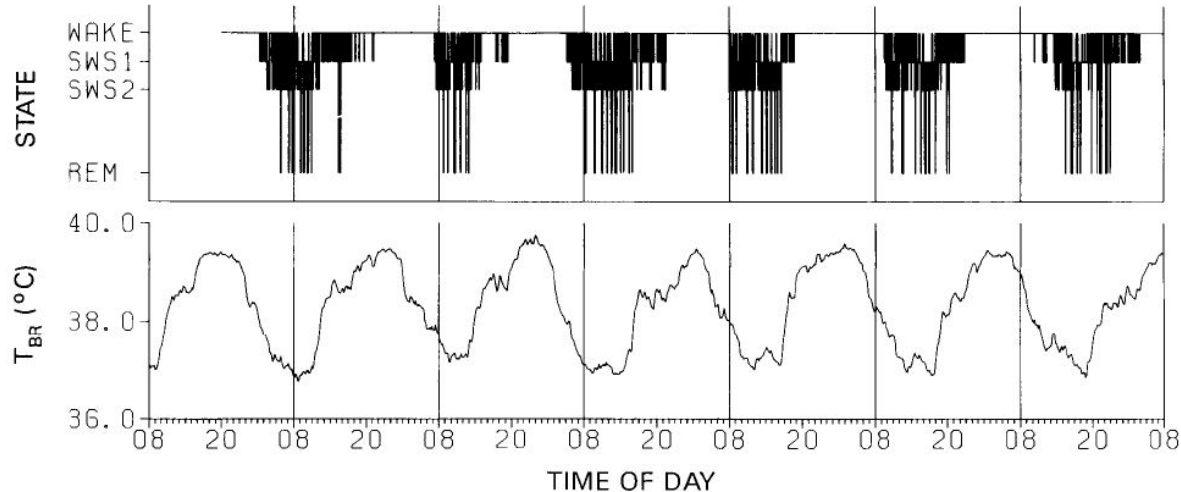
# The Internal Body Clock (Circadian Rhythm)



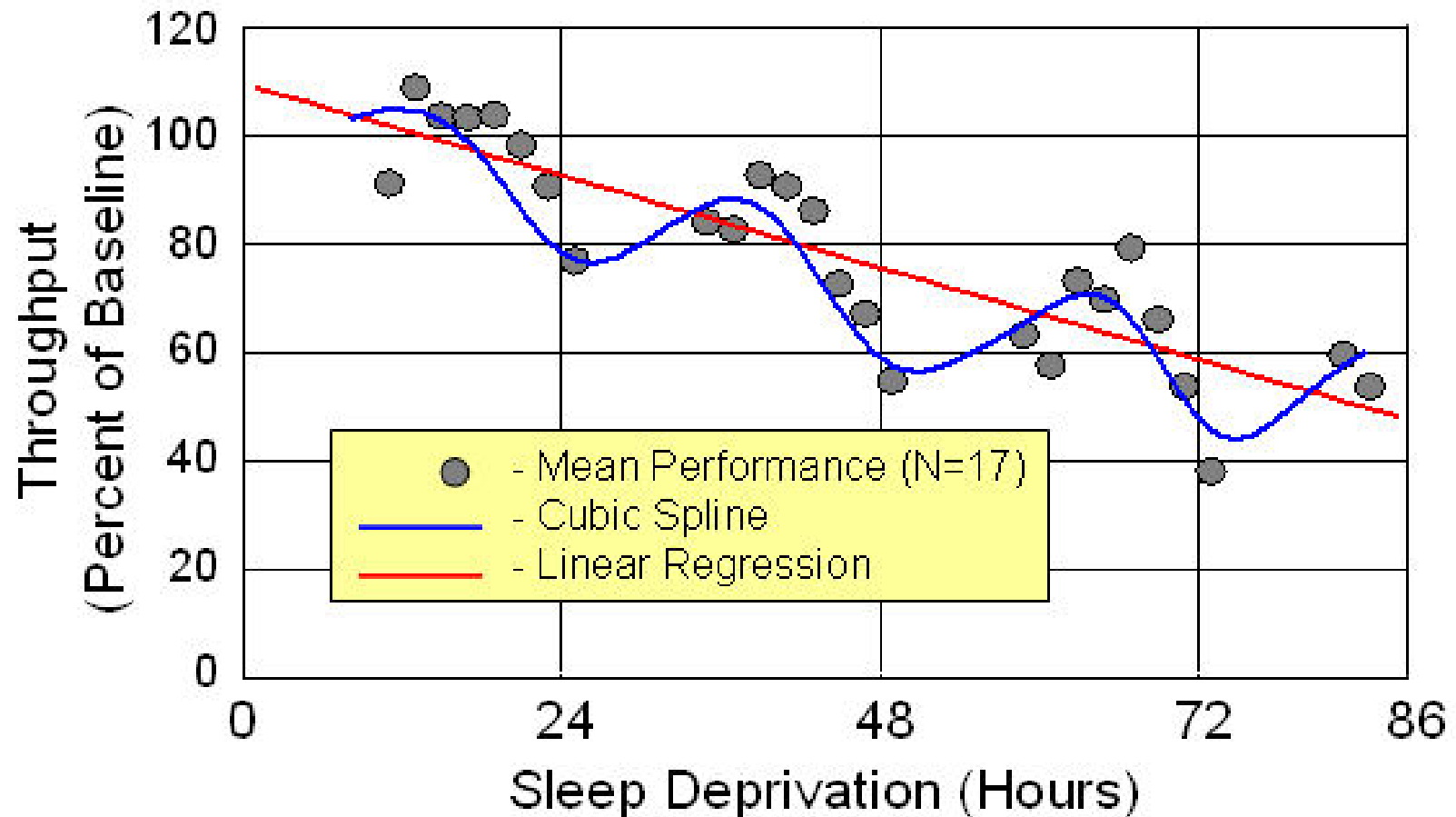
Mistlberger and Rusak (2005) In  
Kryger, Roth, and Dement,  
*Principles and Practice of Sleep  
Medicine*

# The Circadian Rhythm Consolidates Sleep

**Edgar,  
Dement, &  
Fuller, 1993**



# 85 Hours of Total Sleep Deprivation: Effect on Performance

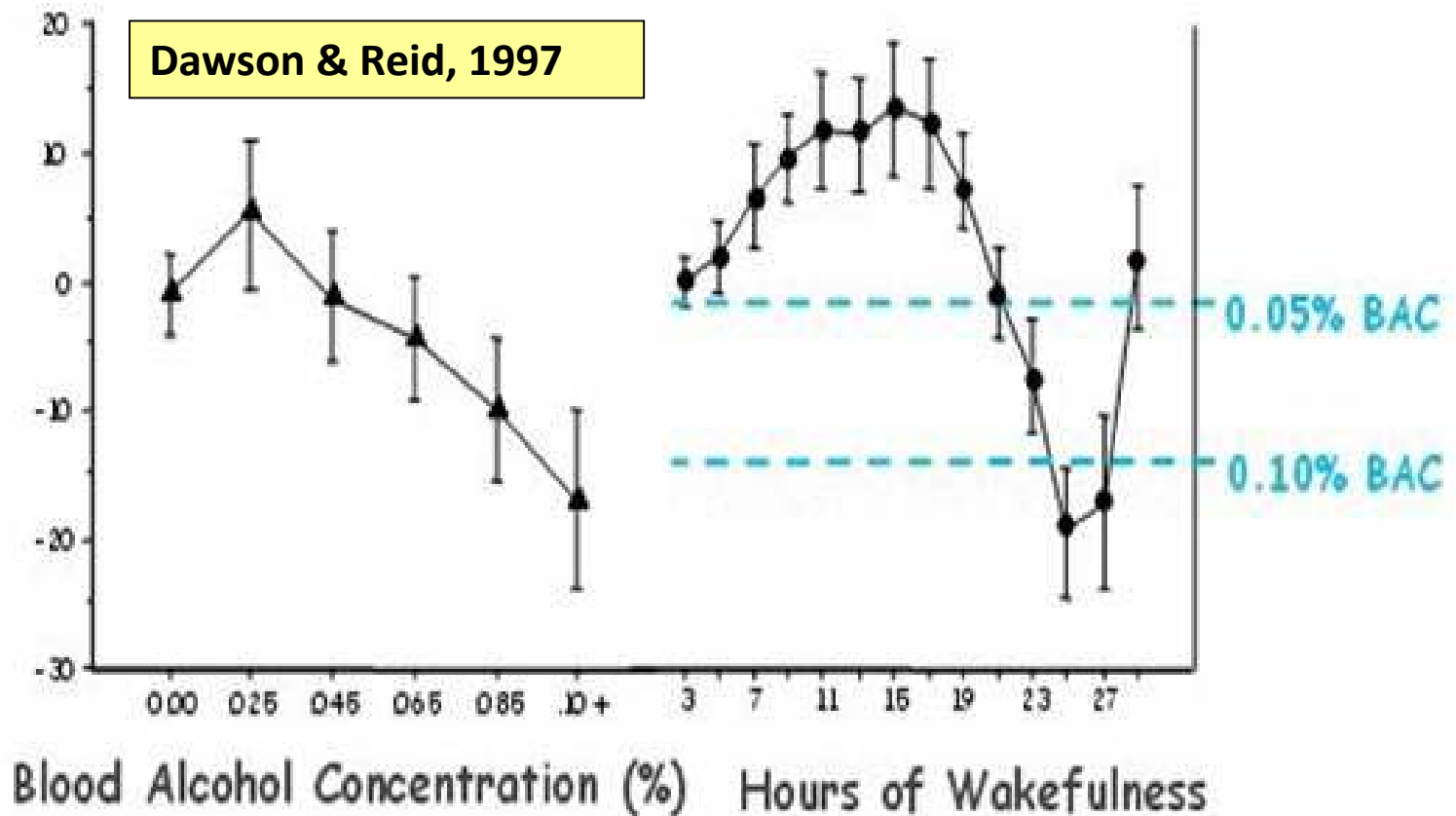


Adapted from Thomas,  
et al., 2000



# Sleep Deprivation and Alcohol Intoxication

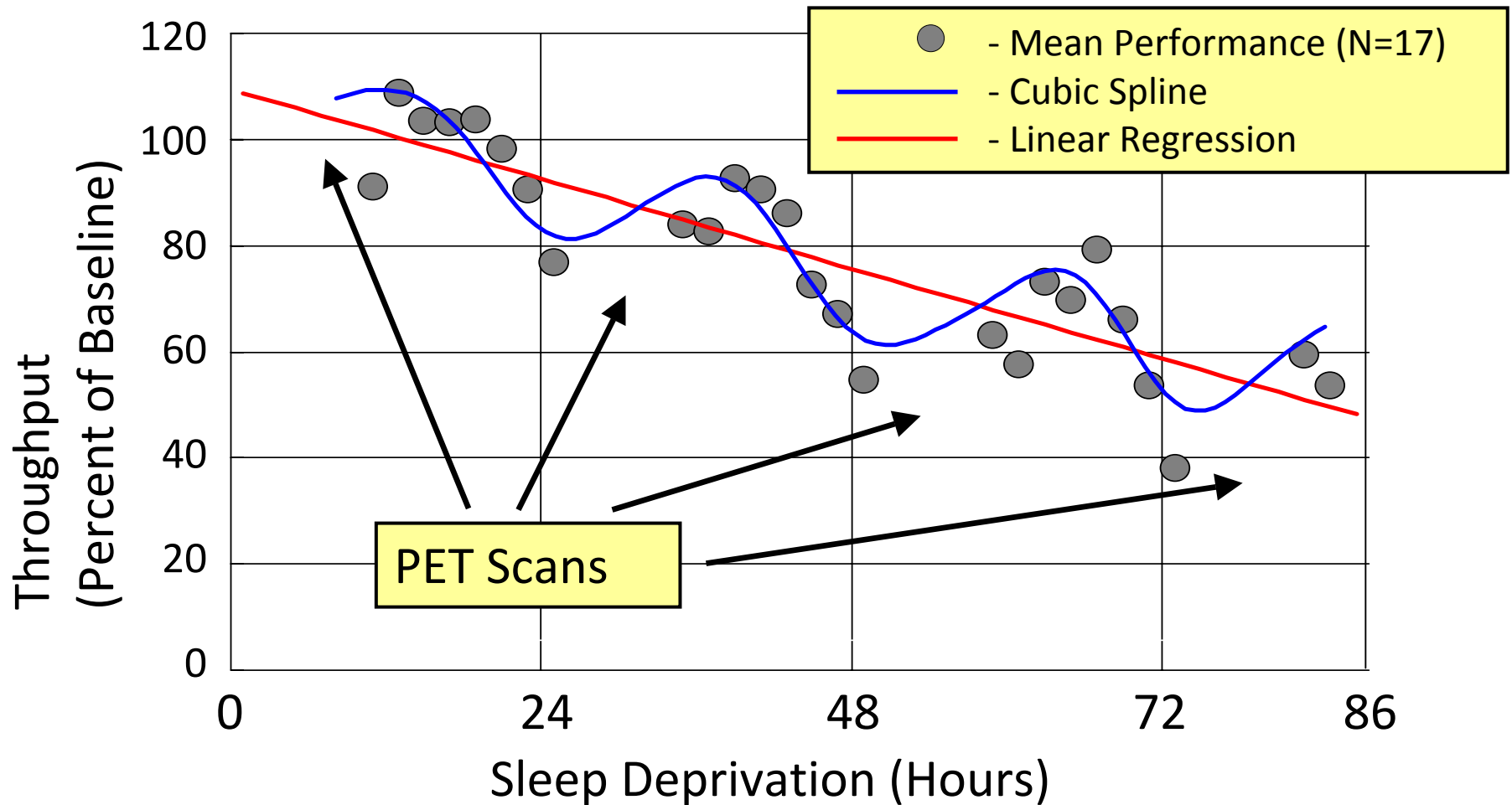
Mean Relative Performance



# Consequences of Sleep Restriction and Sleep Deprivation

- Short term
  - Minutes, hours
  - Error, accident, catastrophe
- Mid-term
  - Weeks, months, years
  - Bad planning, inadequate strategizing, poor life decisions
- Long-term
  - Years
  - Overweight/obesity, Type II Diabetes, Sleep Disorder Breathing, Metabolic Syndrome, etc.
- Triad of factors supporting health, productivity, and well-being
  - Diet
  - Exercise
  - Sleep

# Total Sleep Deprivation Imaging Studies



# Brain Metabolism at 24, 48, & 72 Hours of Sleep Deprivation

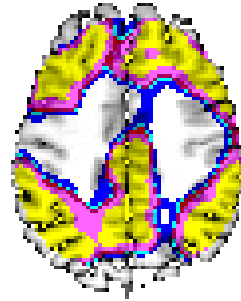
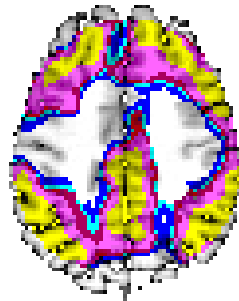
N = 17

24 h SD

48 h SD

72 h SD

+ 32 mm  
AC-PC



$\geq 4.16$

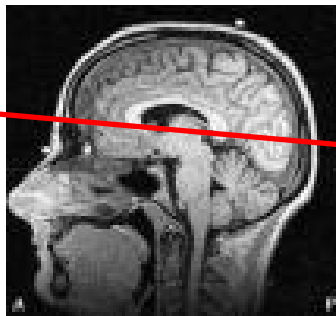
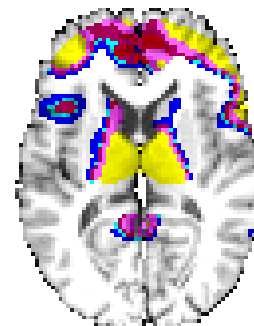
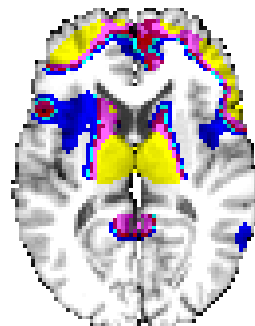
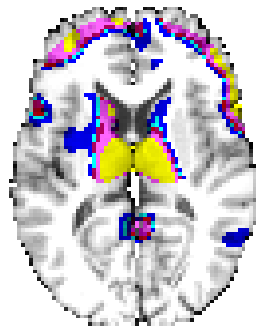
3.08

2.58

2.33

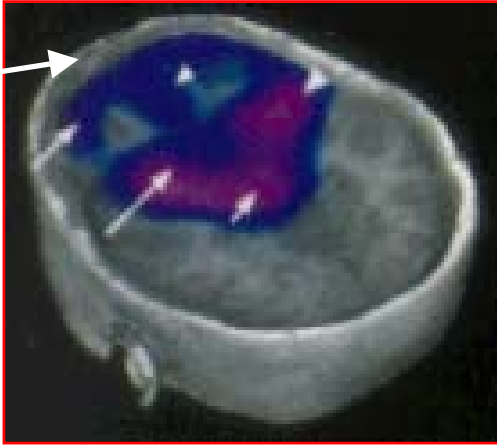
1.65

+ 8 mm  
AC-PC



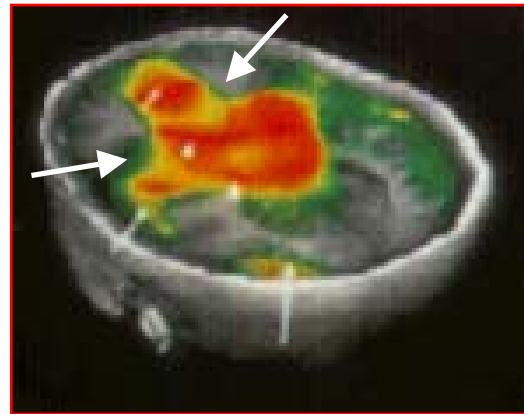
Thomas, et al., *J. Sleep Res.* 2000

# Brain Metabolism during Slow Wave and REM Sleep

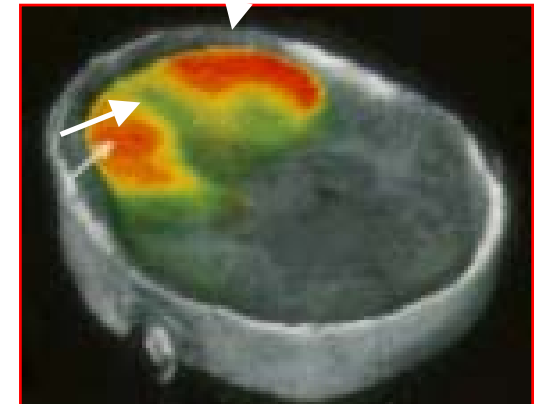
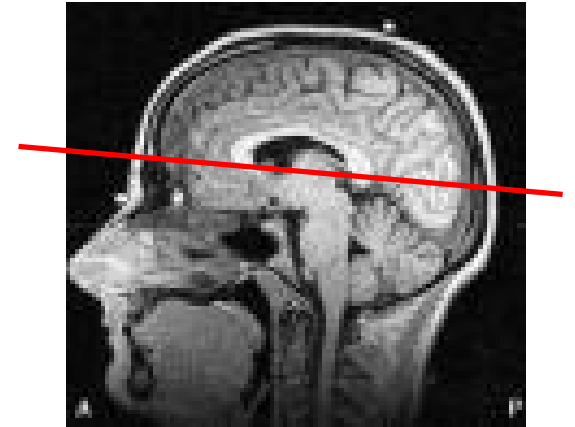


*Frontal areas are deactivated during Slow Wave Sleep; decline in flow of ~30%*

**Braun et al., *Brain*, 1997**



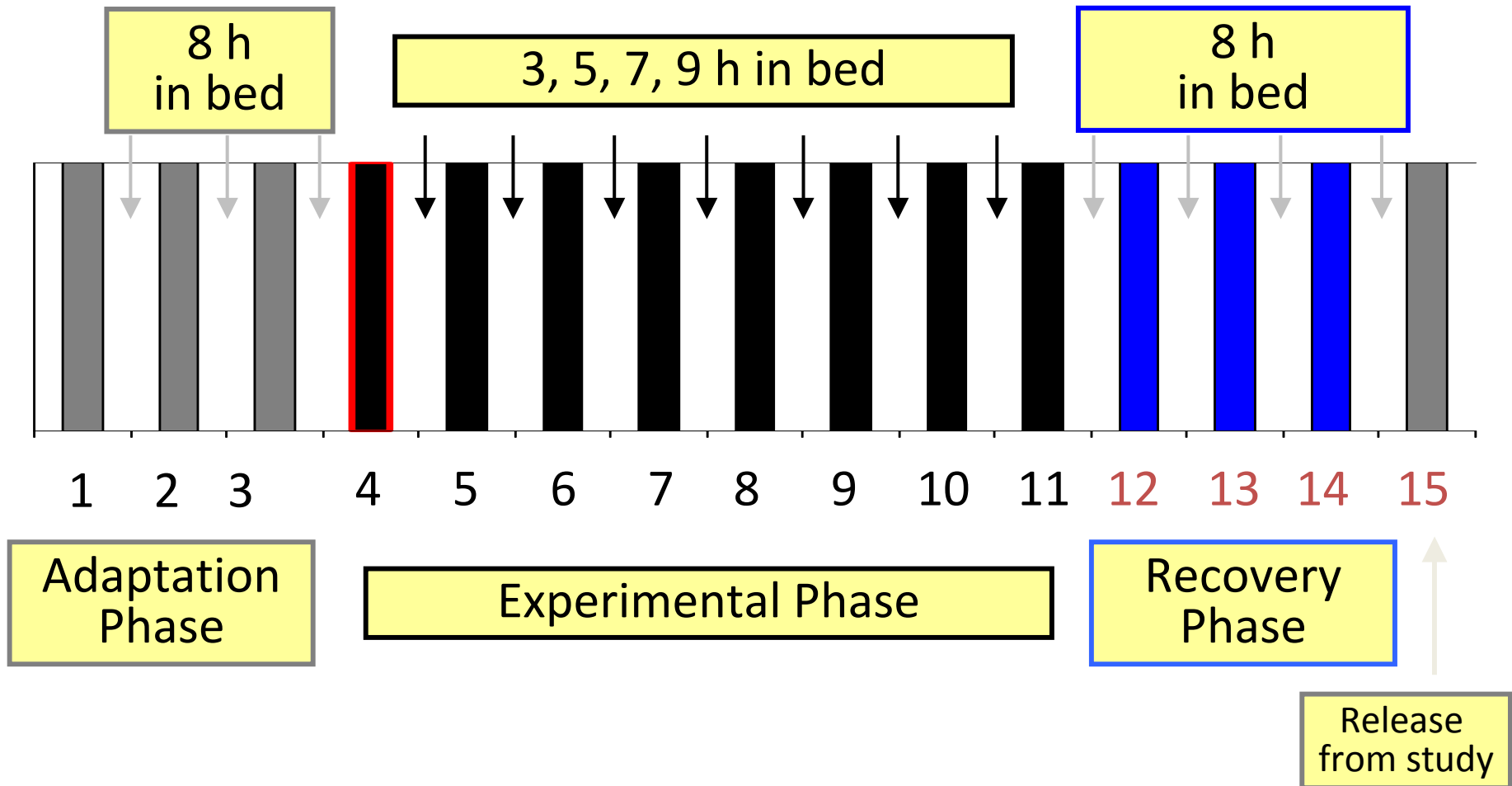
*Frontal areas remain deactivated during REM; increase in flow to waking levels or above except in prefrontal cortex*



*Frontal areas are re-activated only after awakening*

# Sleep Restriction and Performance

# Effects of Sleep Restriction in Performance: A Sleep Dose/Response Study



# Volunteers in the Laboratory

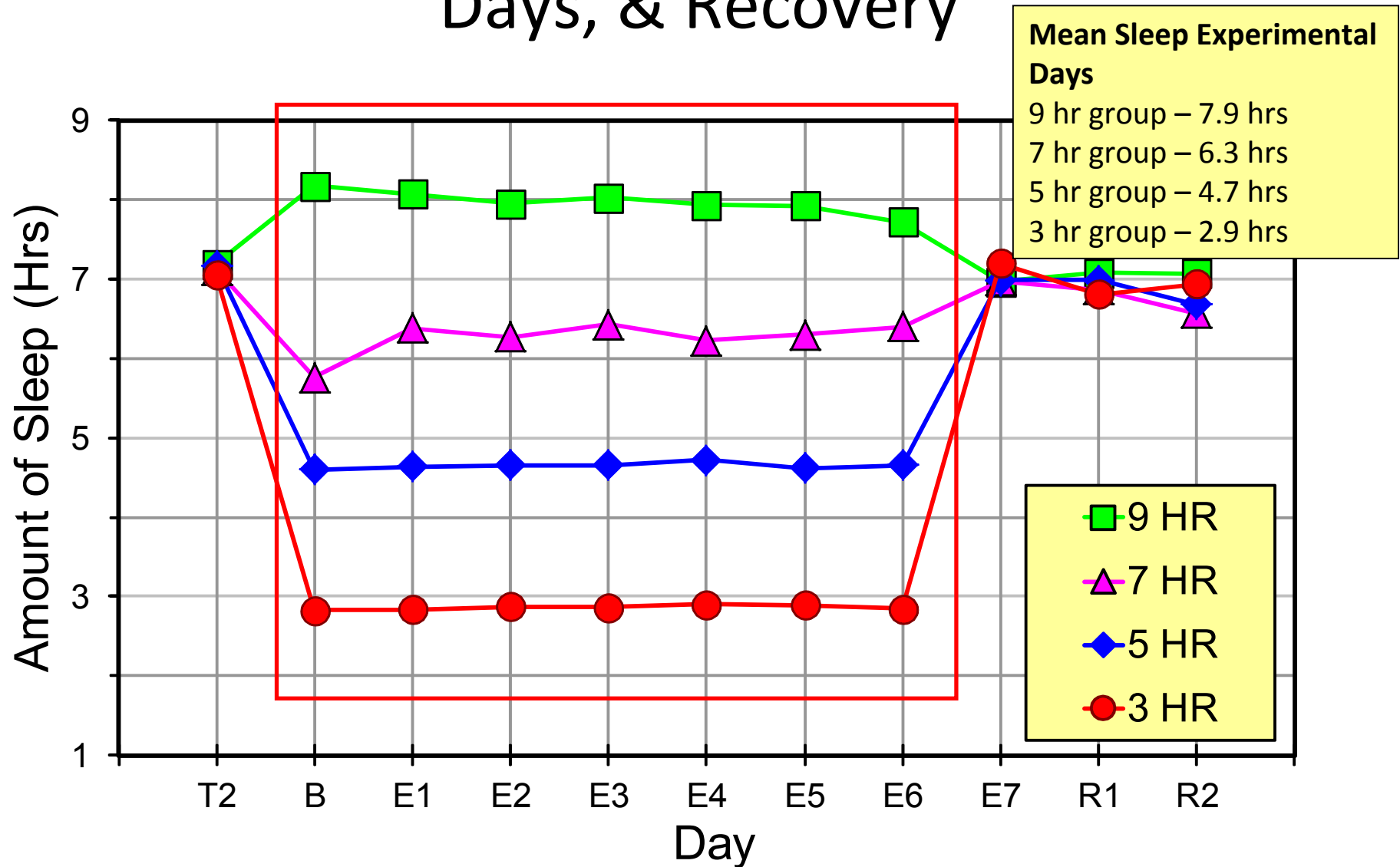


- Sleep measured with polysomnography (electrodes, wires, recorders)
- Performance measured with computer-based tests.

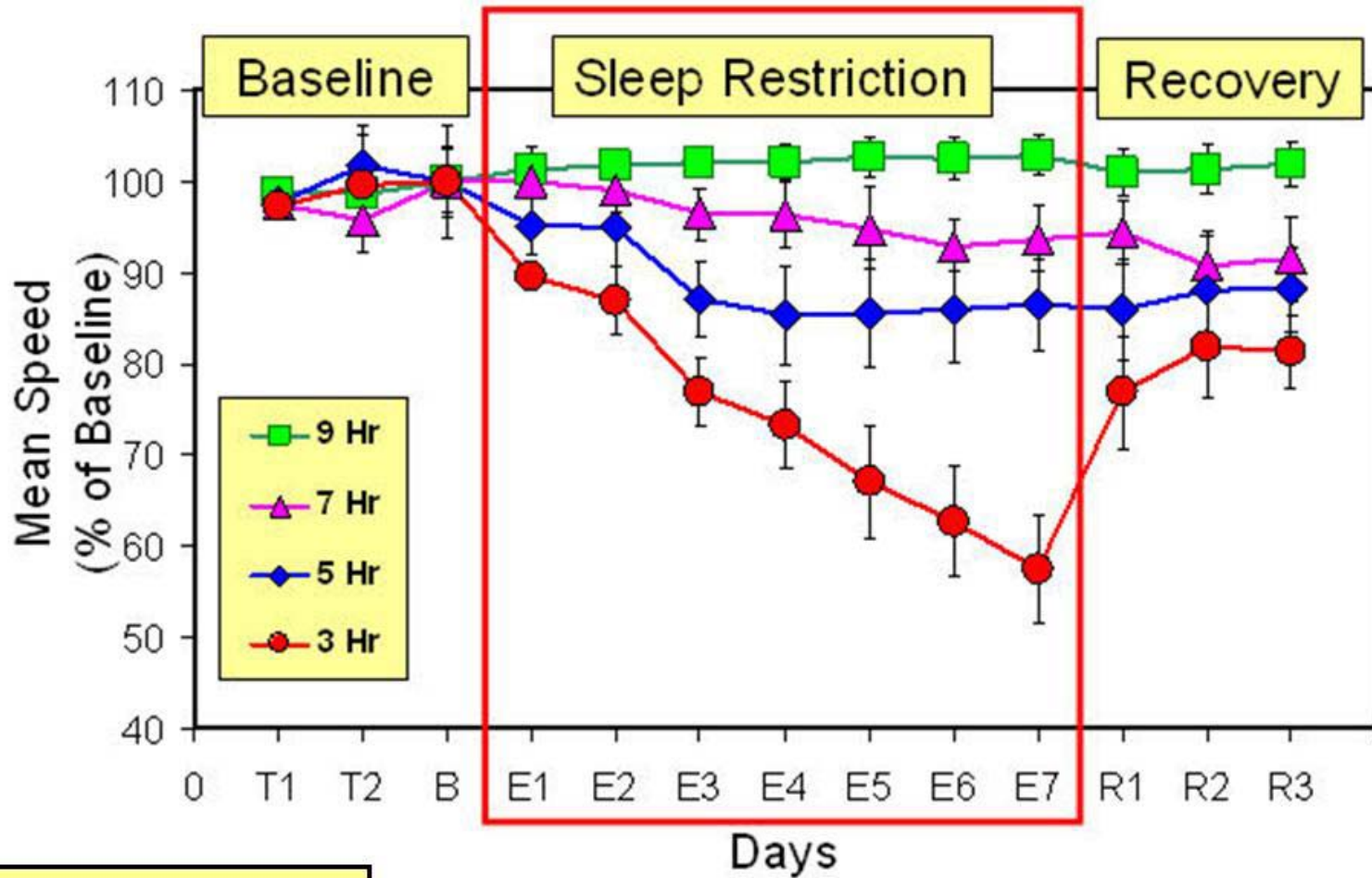




# Mean Sleep, Baseline, Experimental Days, & Recovery



# Psychomotor Vigilance Task (PVT) Performance



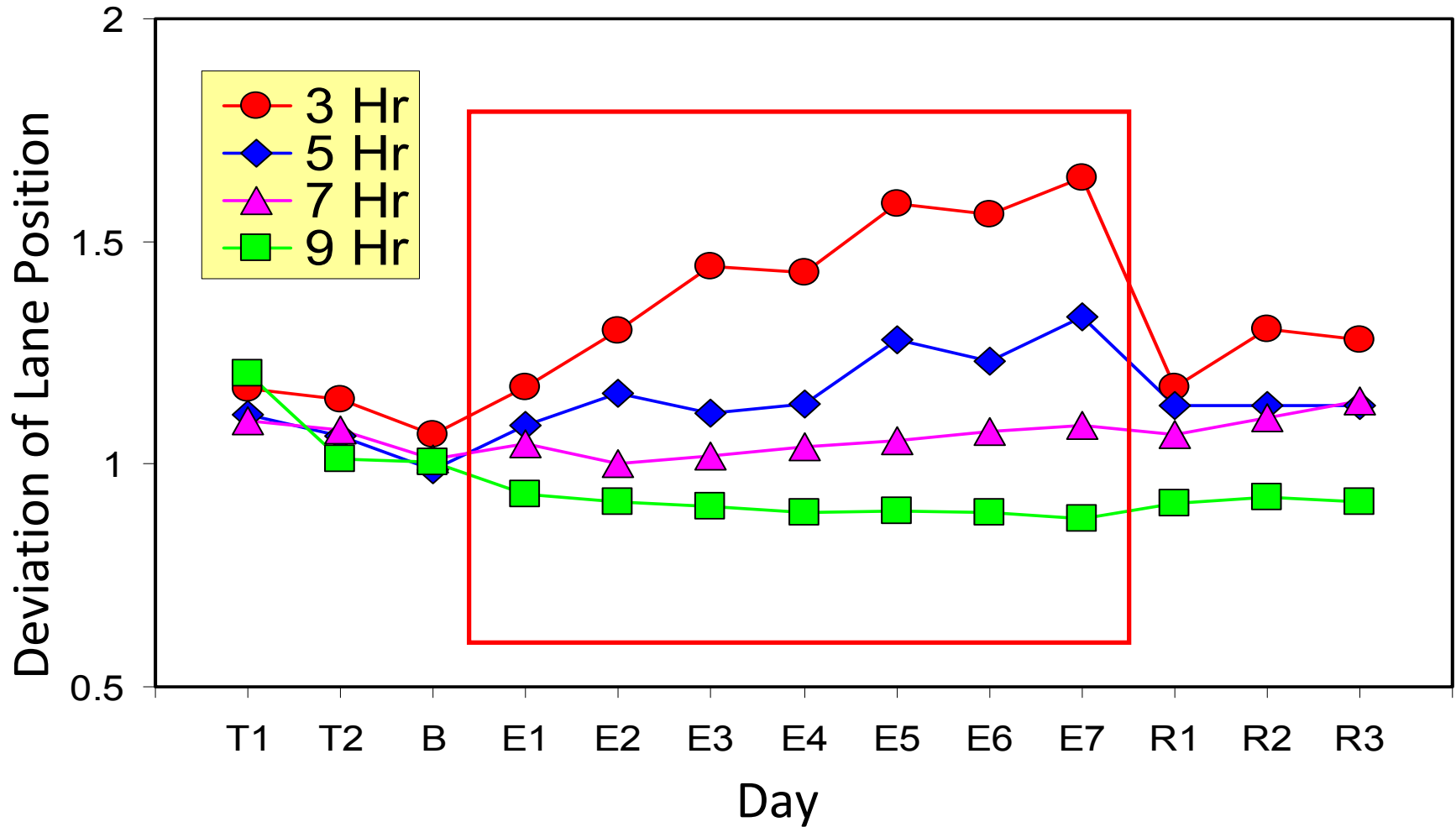
Belenky, et al., 2003

n = 16-18/group

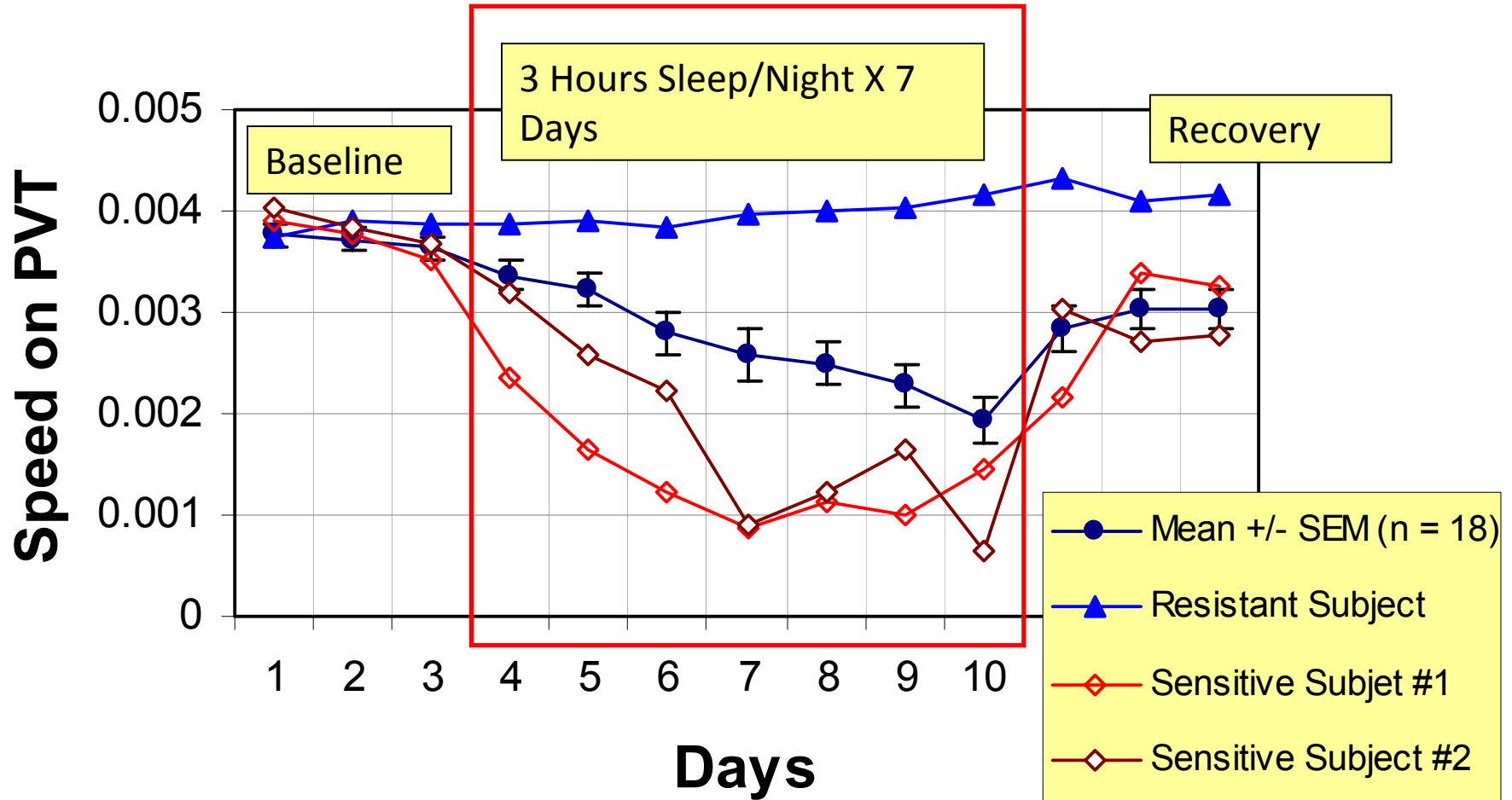
# Driving Simulator



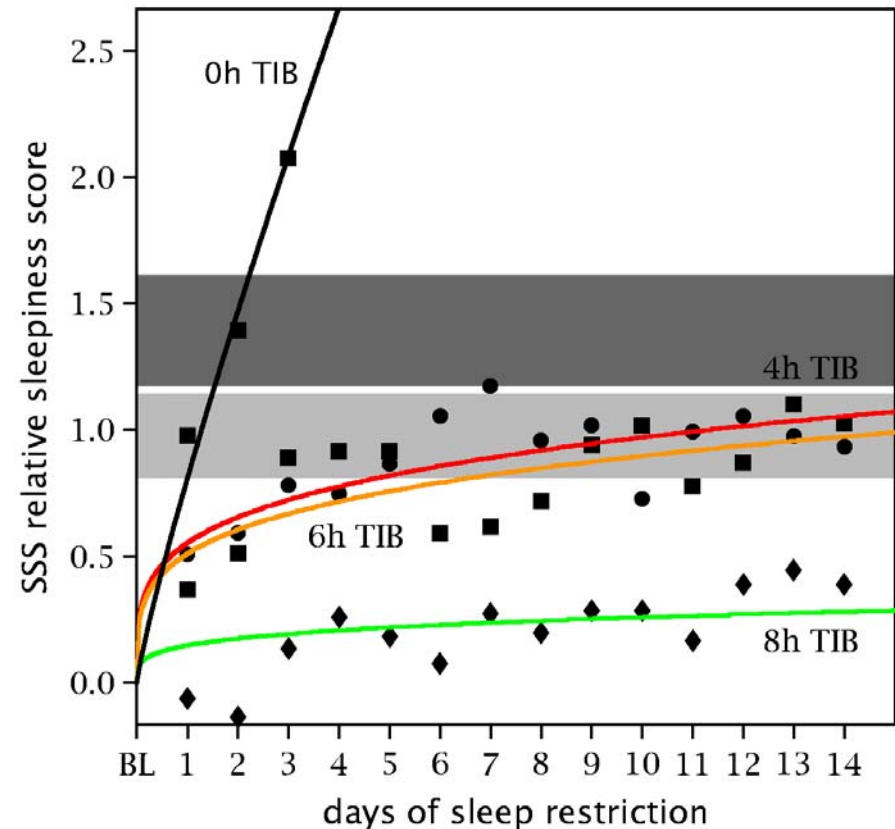
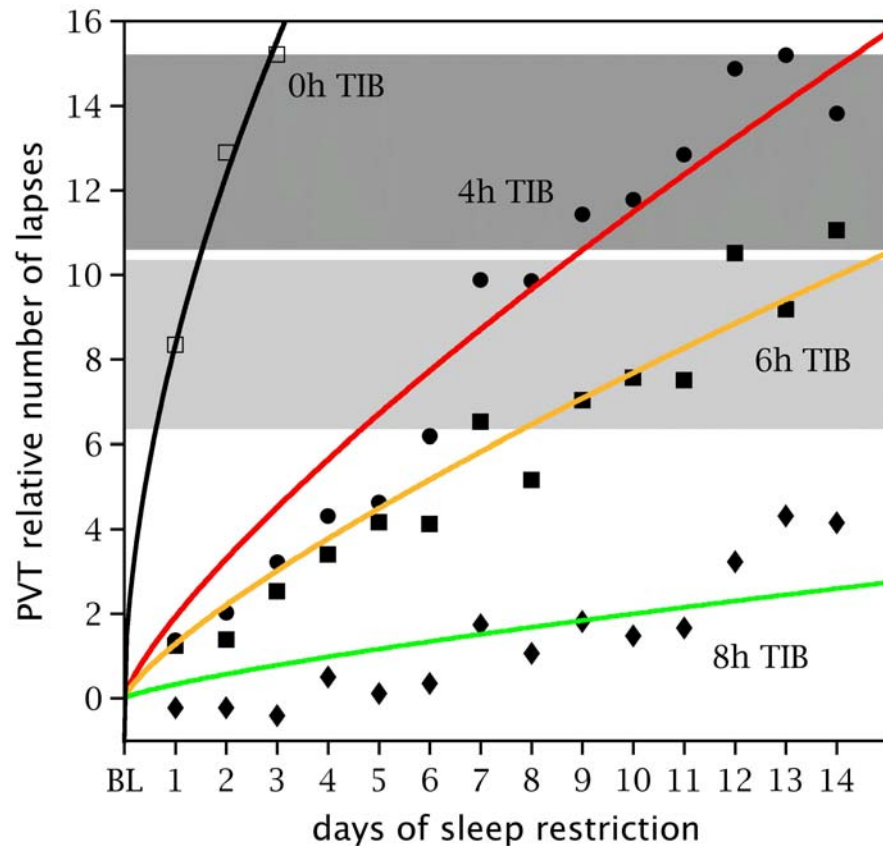
# Driving Simulator – Lane Deviation



# Individual Variability in Resistance to Sleep Restriction

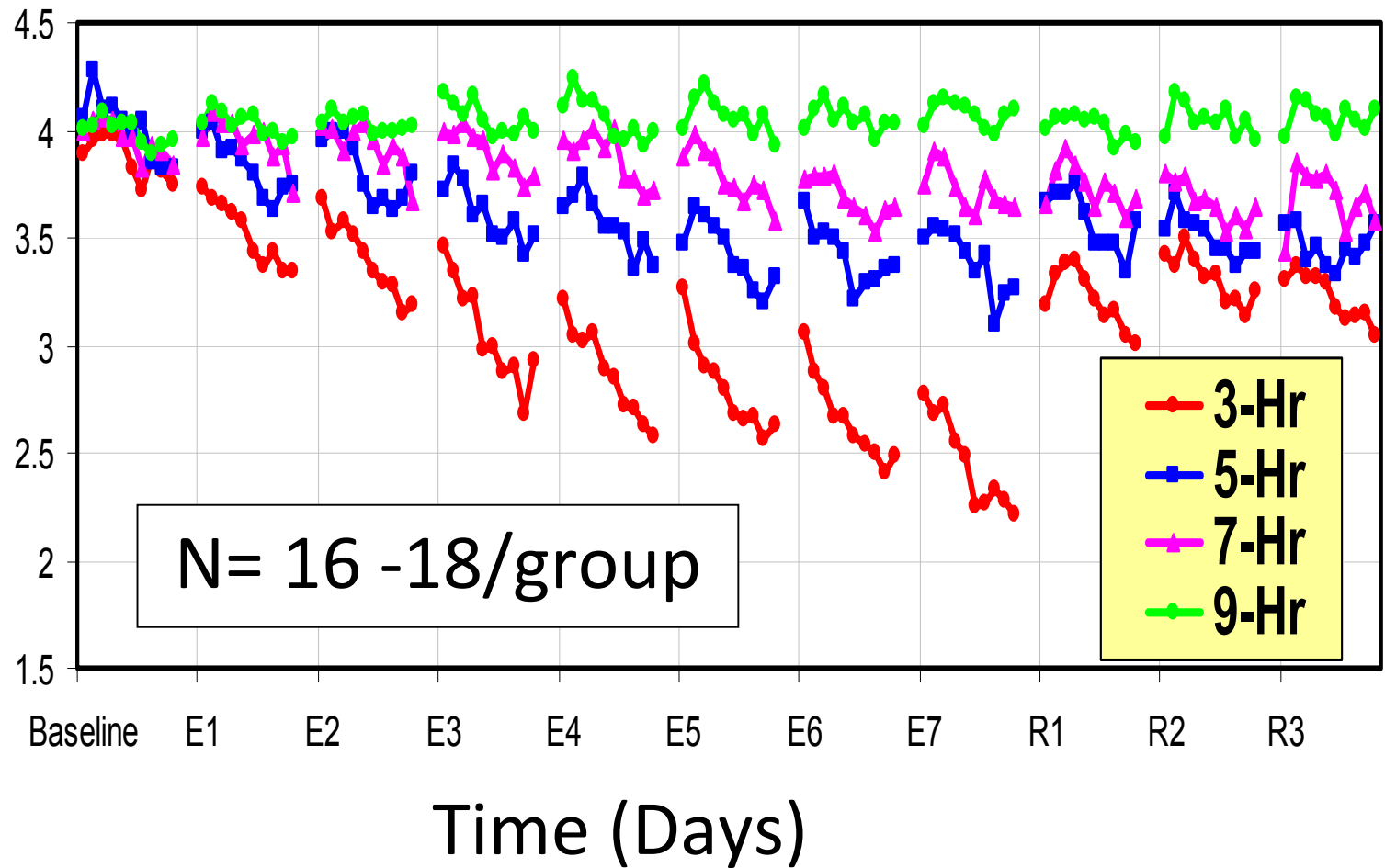


# Chronic Sleep Loss: Objective and Subjective Effects



# Time on Task Effects during 7 Days of Sleep Restriction and Subsequent Recovery

Psychomotor Vigilance Task  
(PVT) Performance



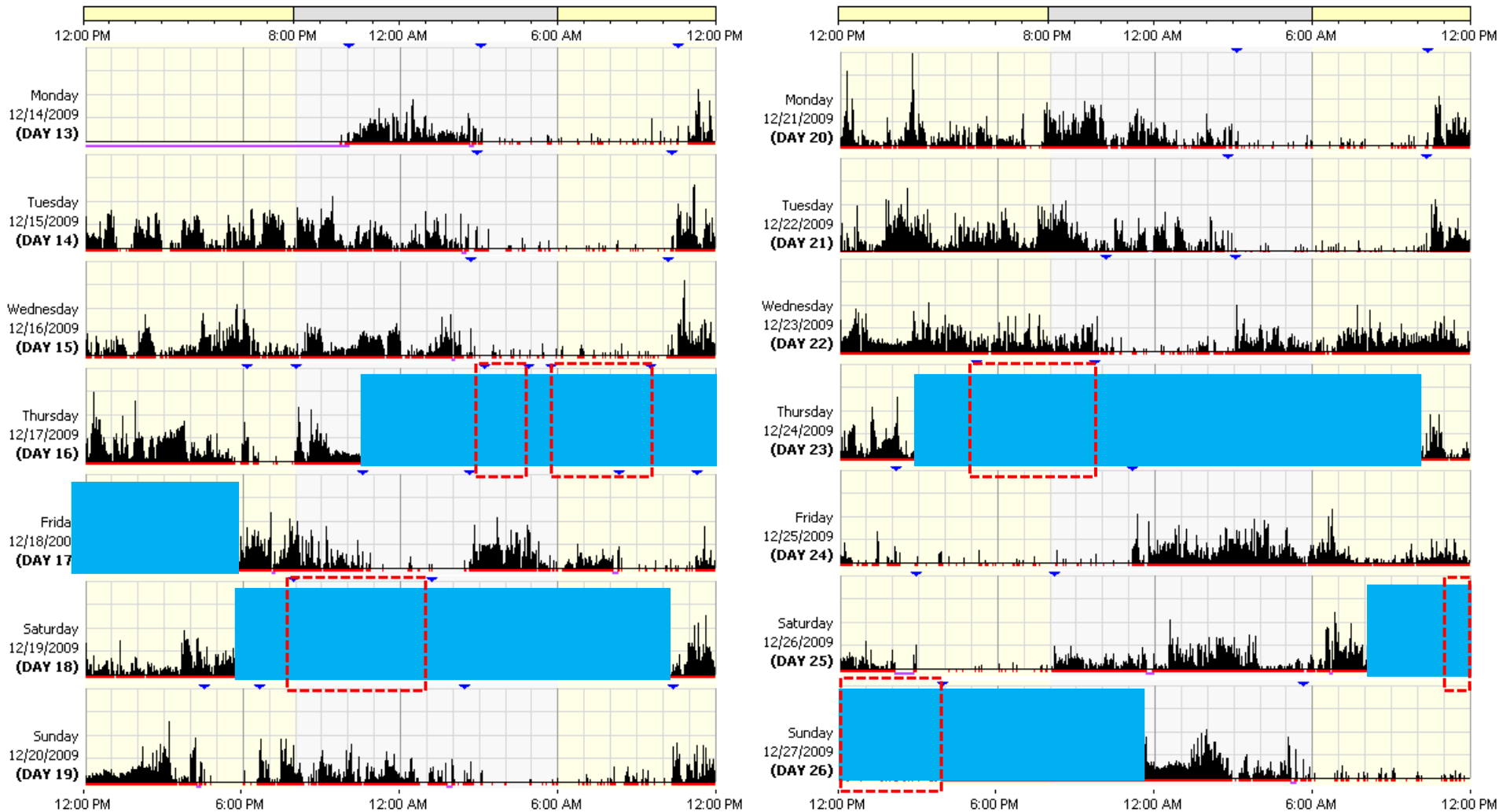
Split Sleep and Napping and Sleep



# Newark to Hong Kong – Over the North Pole



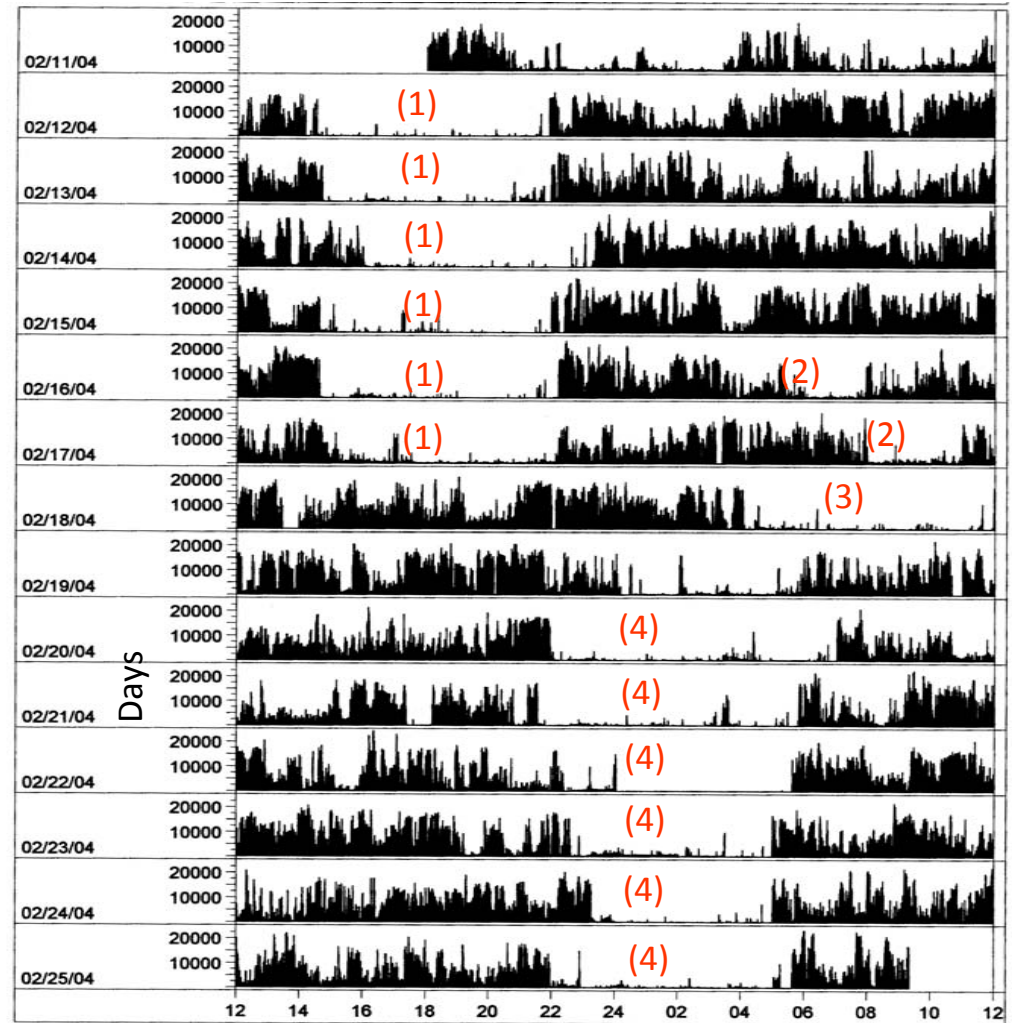
# Home, Layover, and In-Flight Sleep in a Boeing 777 Pilot



Belenky, et al., in preparation

# Transmeridian Travel: Actigraph Record

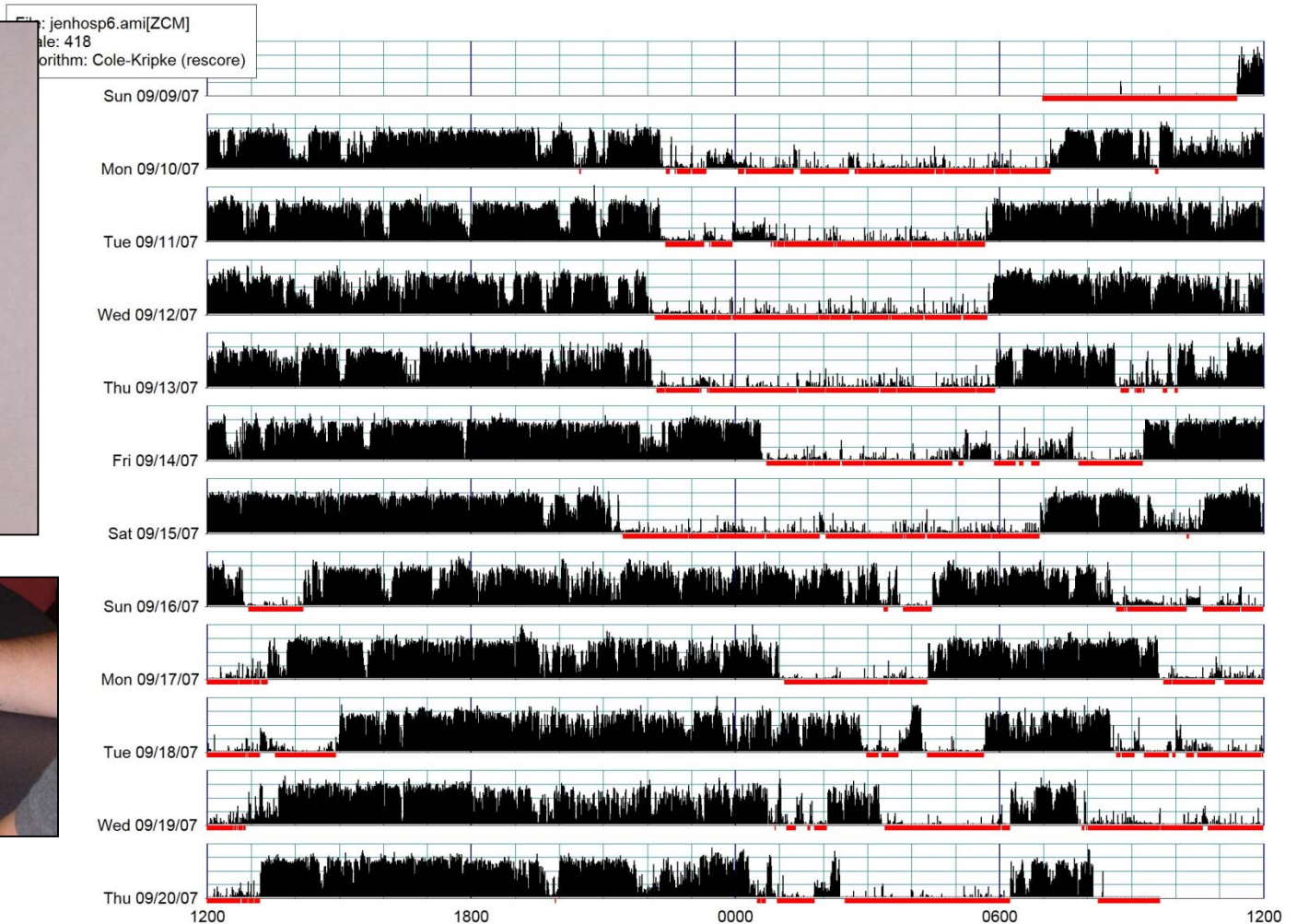
- Overseas Travel
  - 2/11: Leave Eastern US
  - 2/12 - 2/16: SWA
  - 2/17: Germany
  - 2/18 - 2/19: Hawaii
  - 2/20: Arrive Eastern US
- Sleep in afternoon (EST) (1) and some divided sleep (2) during time in SWA and Germany
- Sleep in mid-morning hours (EST) (3) during time in Hawaii
- Sleep during normal sleeping hours (EST) (4) on return to Eastern US



Eastern Standard Time (EST)

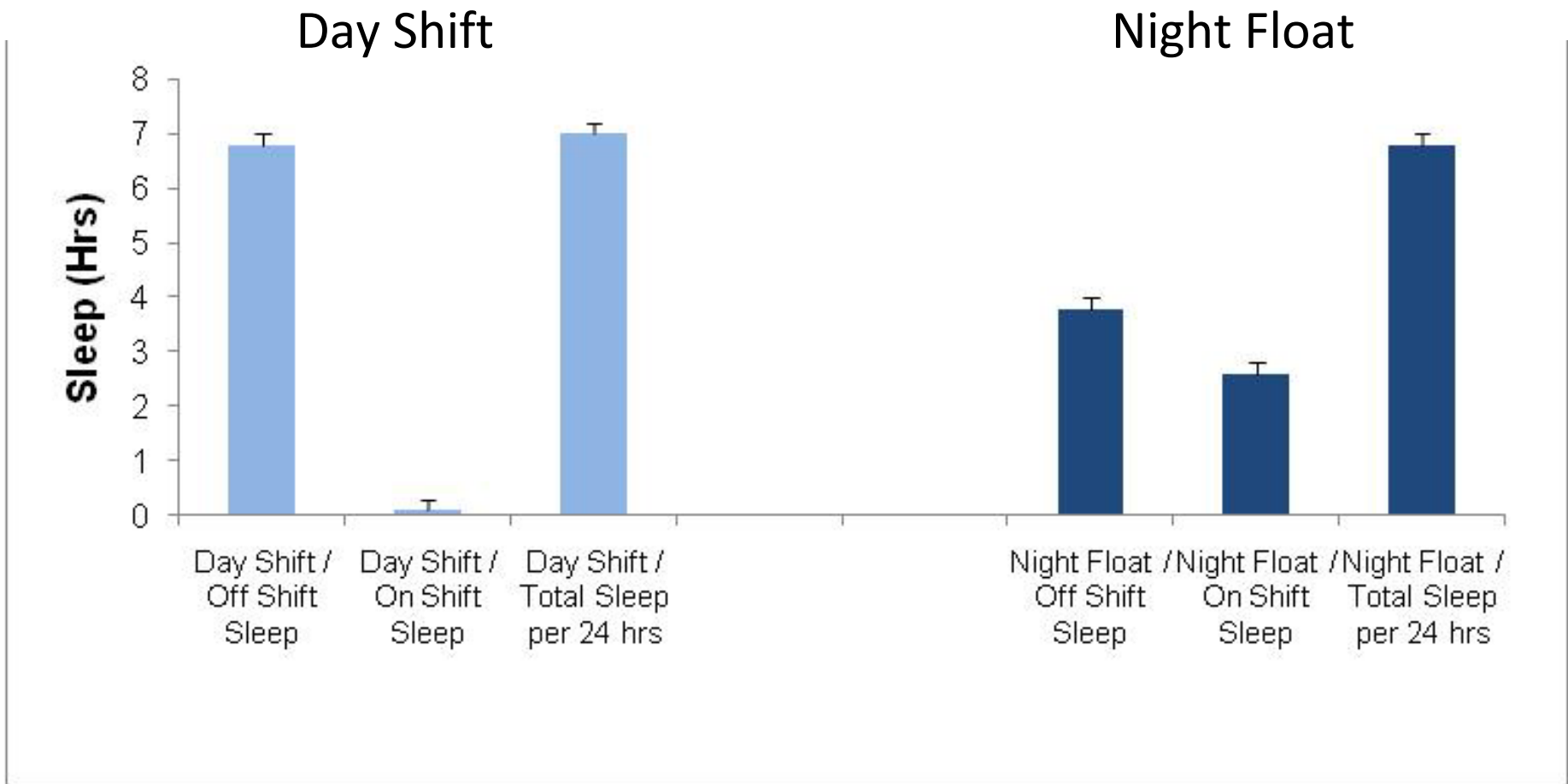
# Night Float vs. Day Shift in Physicians in Training

# Physician on Day Shift and Night Float Sequence



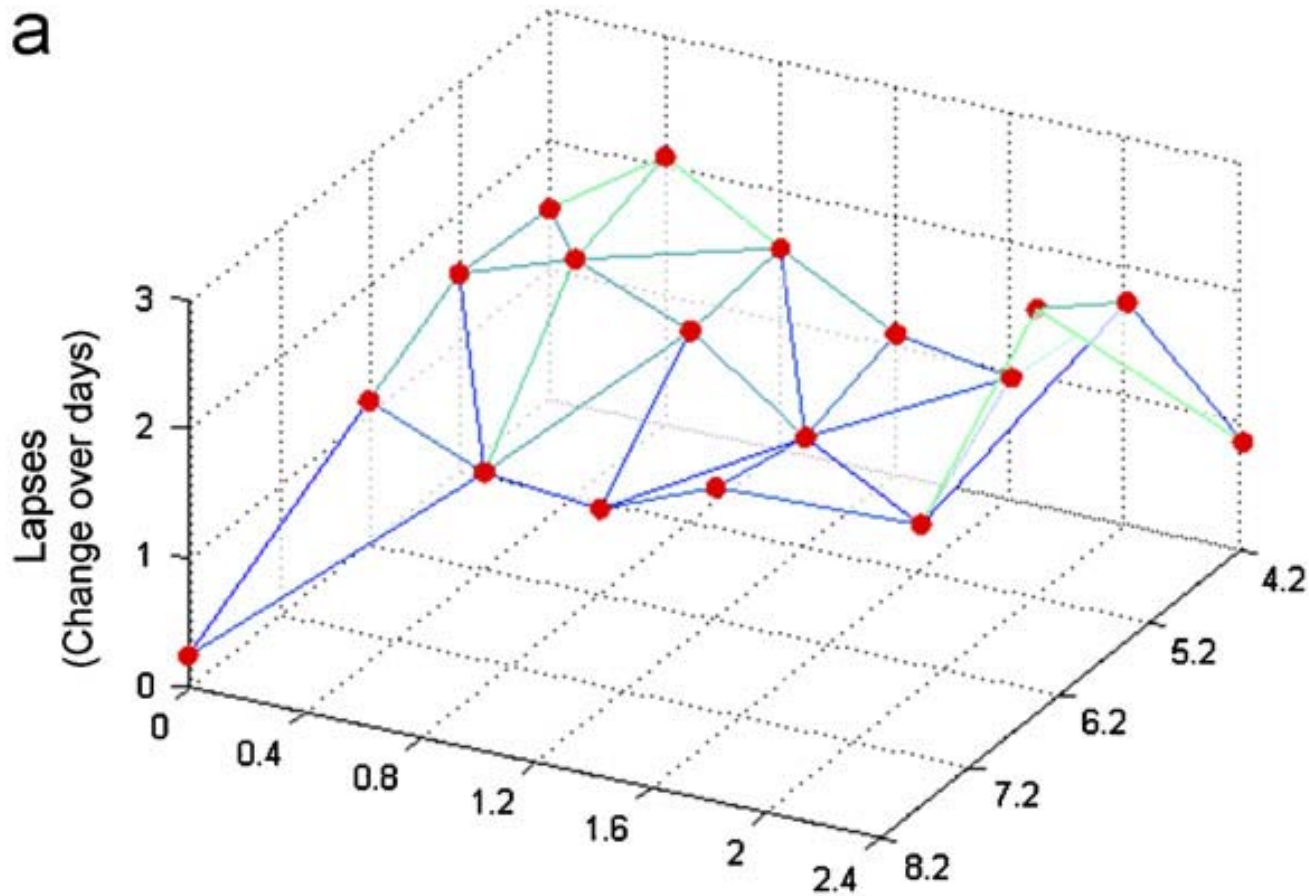


# Sleep Off Shift & On Shift / Day Shift vs. Night Float



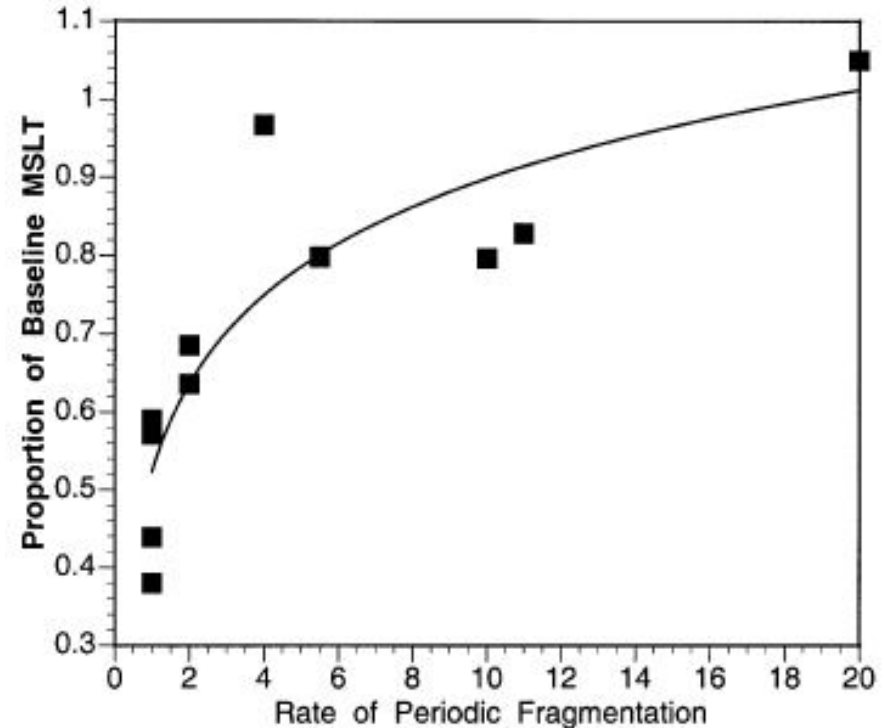
# Response Surface Mapping of Psychomotor Vigilance Task (PVT) Lapses in Split Restricted Sleep

a



# Consolidated vs. Split vs. Fragmented Sleep

- Recuperative value of sleep depends on total sleep time over 24 hours
- Consolidated sleep
  - Nocturnal (night) – typically 7-8 hours; facilitated by circadian rhythm
  - Diurnal (day) – typically ~ 5 hours; truncated by circadian rhythm
- Split sleep
  - 5 hours nocturnal / 2-3 hours diurnal
- Fragmented sleep
  - Awakening every 2-3 minutes
  - Fragmentation to this degree abolishes recuperative value of sleep
- Sleep interrupted every 20+ minutes as recuperative as uninterrupted sleep



Bonnet M & Arand D (2003) Clinical effects of sleep fragmentation vs. sleep deprivation. *Sleep Medicine Reviews*, 7(4) 297-310



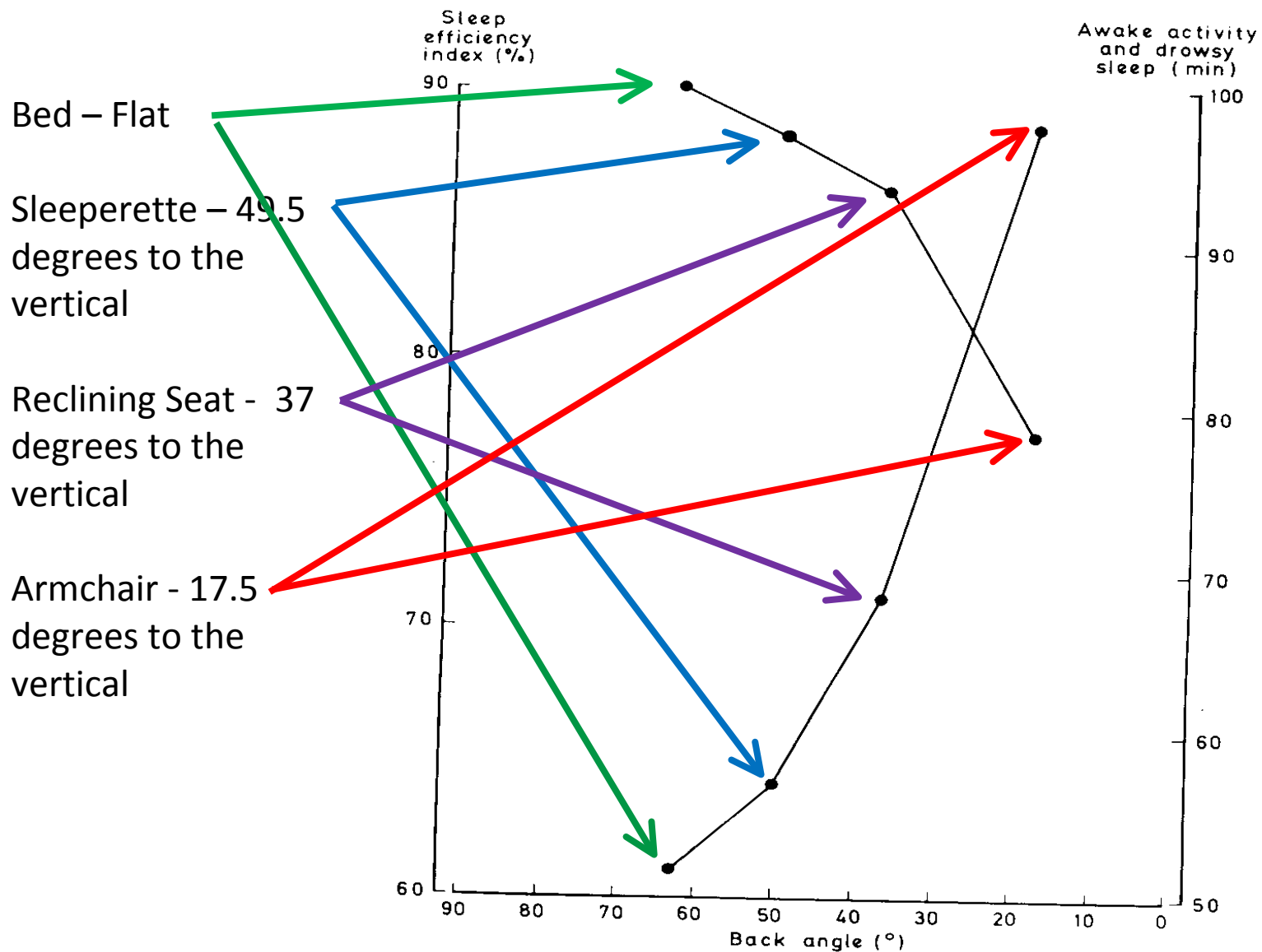
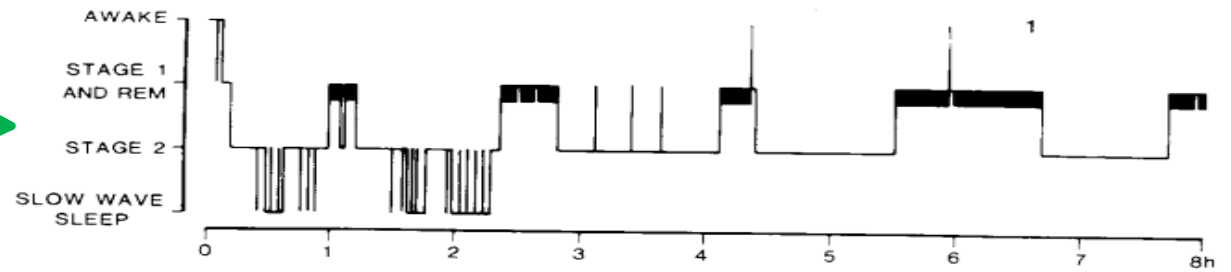
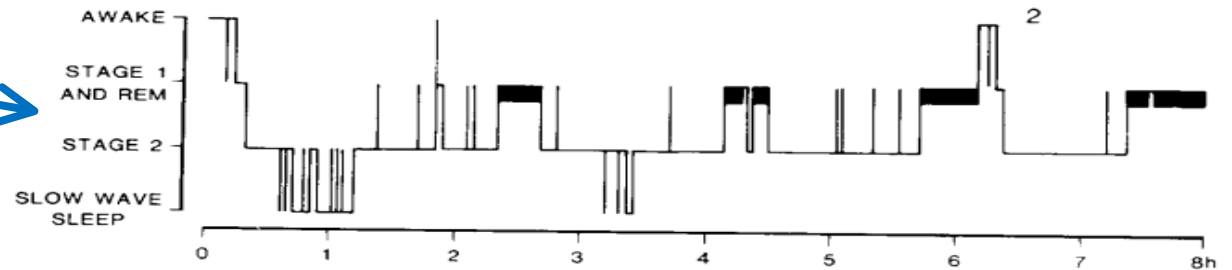


Figure 6. Relationship between back angle and sleep efficiency index (SEI) and awake and drowsy sleep (0+1). The back angle in the bed was measured using two pillows. With a back angle of less than 40° there was a marked increase in awake activity and stage 1 (drowsy) sleep, and a reduction in the sleep efficiency index.

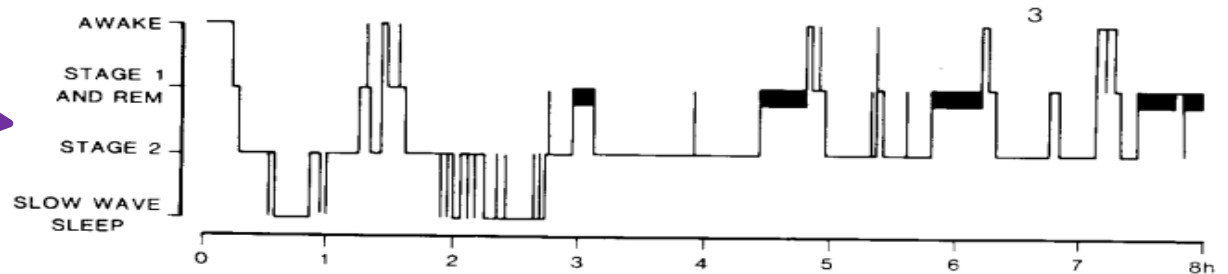
Bed – Flat



Sleeperette – 49.5  
degrees to the  
vertical



Reclining Seat - 37  
degrees to the  
vertical



Armchair - 17.5  
degrees to the  
vertical

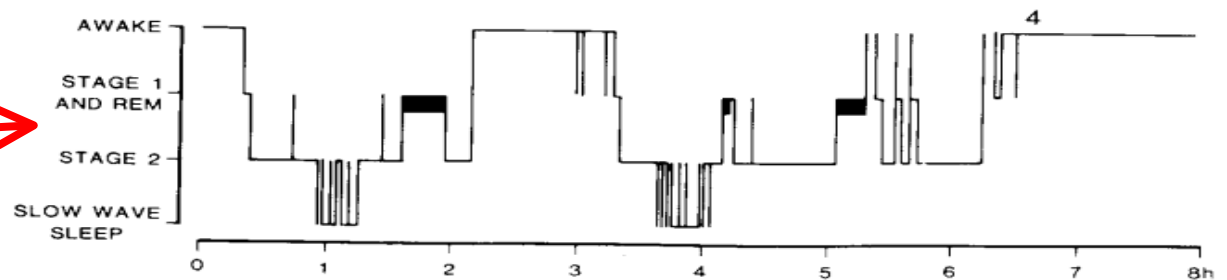
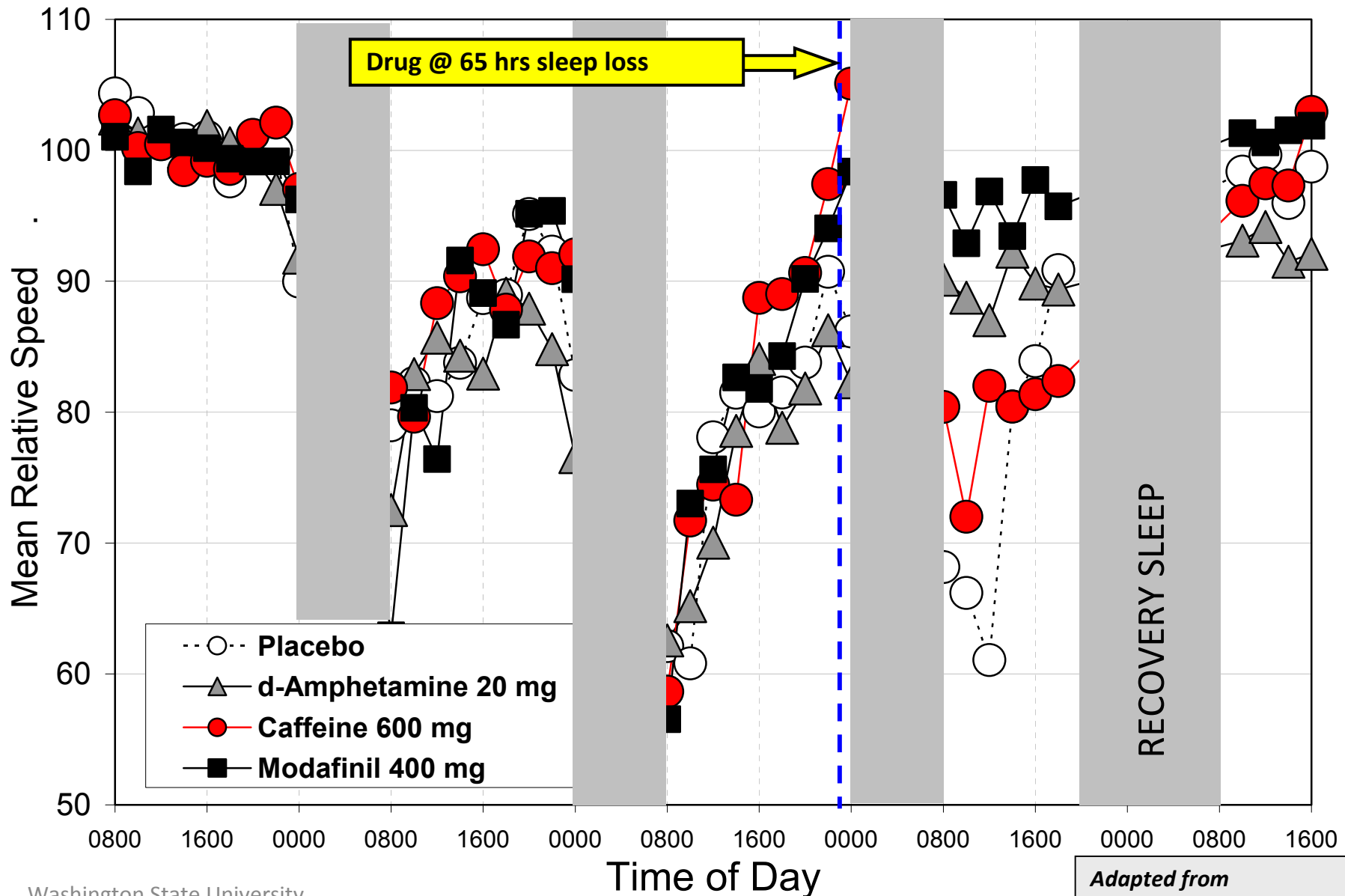


Figure 5. Hypnograms for a subject in bed (1), and on the sleeperette (2), reclining seat (3) and armchair (4). Sleep was markedly disturbed in the armchair with an hour period of wakefulness, and shortened sleep. Sleep in the reclining seat also showed some disturbance, with more awakenings particularly during the latter part of the night.

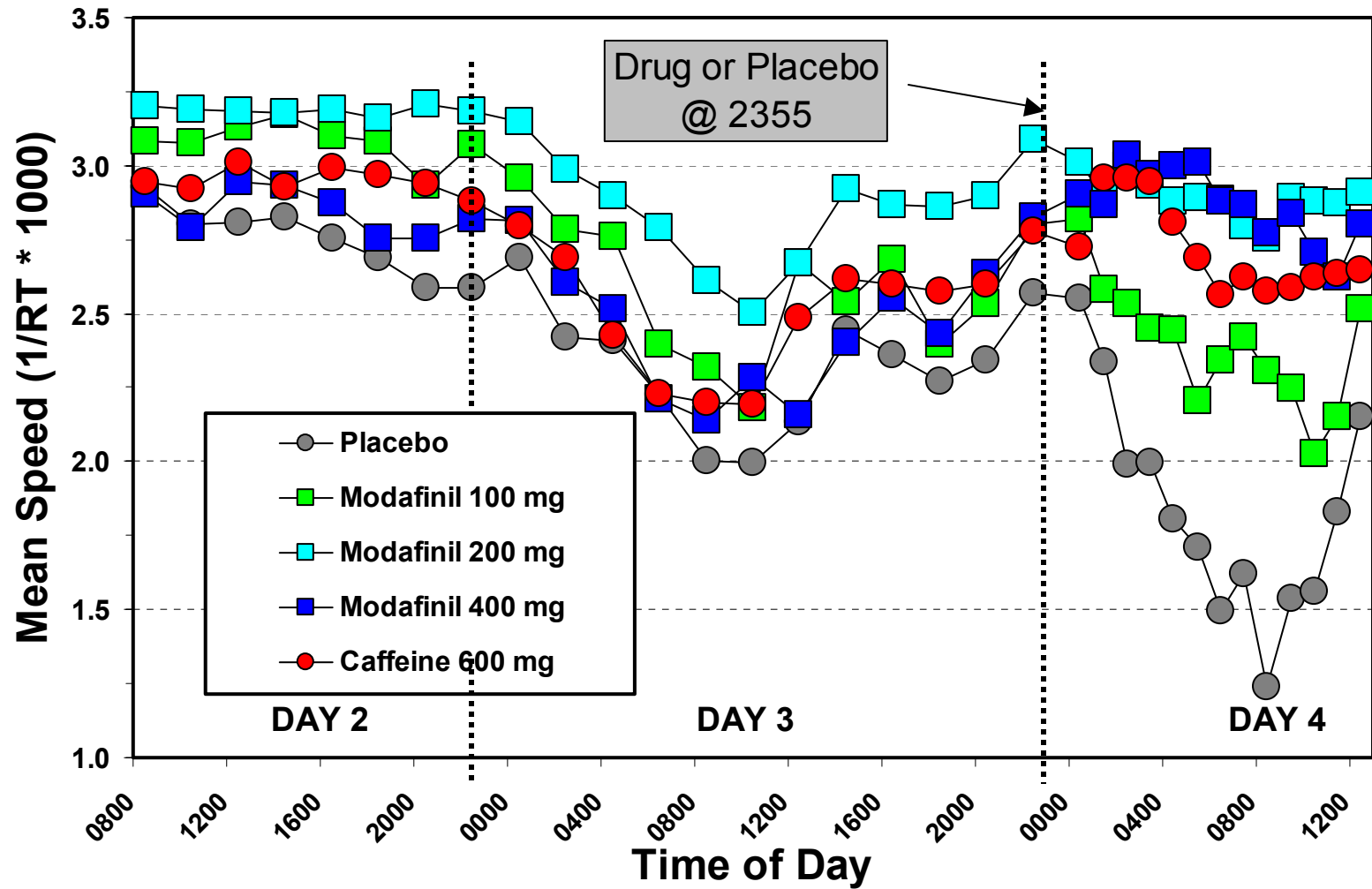
# Other Countermeasures

- Stimulants on shift Wesensten et al., 2005
  - Caffeine
  - Other stimulant drugs, e.g., modafinil
  - Stimulants (caffeine, d-amphetamine, modafinil) appear equivalent for first few hours in clinically acceptable doses
- Sleep-inducing drugs when sleeping off shift
  - BZD receptor agonists
  - Melatonin and melatonin analogues
- Naps on shift, e.g., cockpit napping
- Bright (blue) light on shift
- Strict environmental control when sleeping off shift
  - Light and noise while sleeping
  - Commute times to and from work

# Amphetamine vs. Modafinil vs. Caffeine



# Modafinil vs. Caffeine



# Sleep and Performance in Operations

Acute Total Sleep Deprivation in a  
Air Cargo Flight Accident:  
American International Flight 808  
18 August 1993

# Guantanamo Bay, Cuba





# Crash Site



*All 3 crew members were rescued from the cockpit and survived*

# The Approach to Guantanamo



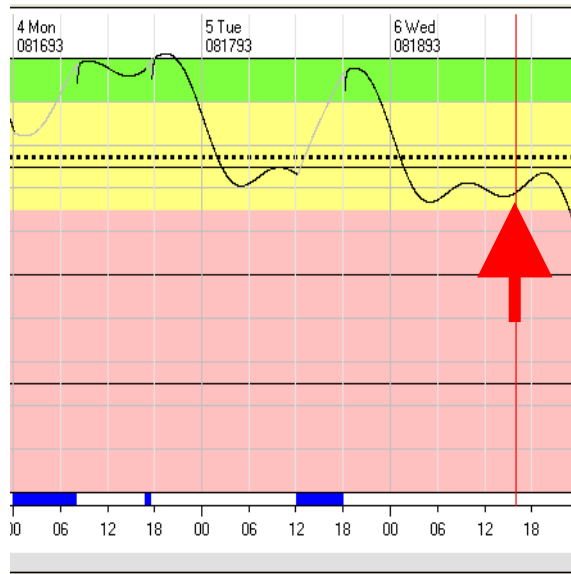
*Approach to Guantanamo  
requires a sharp right bank to avoid  
Cuban air space*



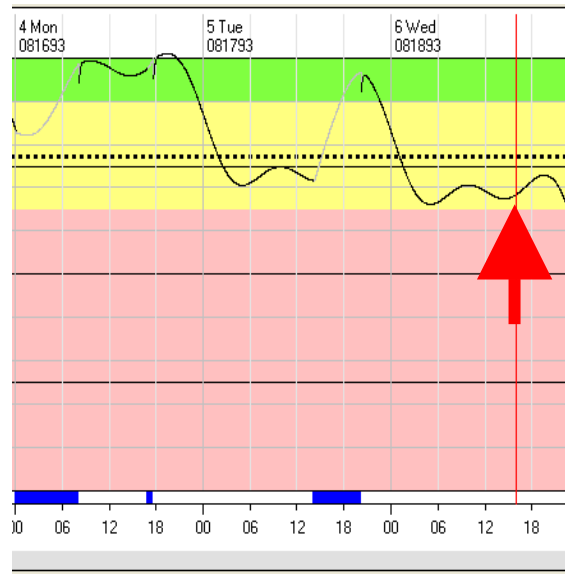


# Accident Investigation – American International Flight 808 (1993)

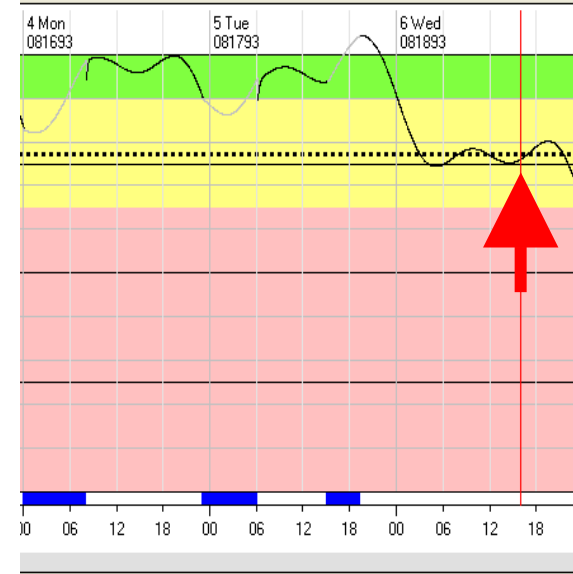
Captain: 71%



Co-Pilot: 70%

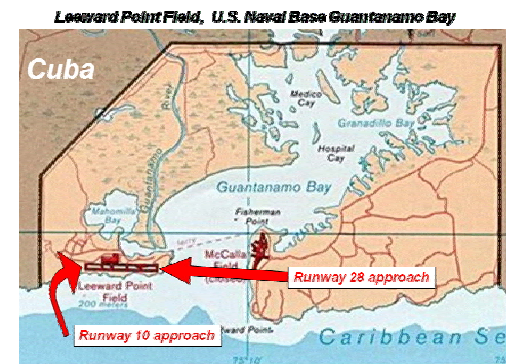


Engineer: 77%



*"The **impaired judgement, decision-making, and flying abilities** of the captain and flight crew **due to the effects of fatigue [sleep deprivation]**; the captain's **failure to properly assess the conditions for landing and maintaining vigilant situational awareness** of the airplane while manoeuvring onto final approach; his **failure to prevent the loss of airspeed** and avoid a stall while in the steep bank turn; and his **failure to execute immediate action** to recover from a stall."*

From NTSB Report



# Cockpit Voice Recorder just Prior to Crash

Engineer: Slow, Airspeed

Co-Pilot: Check the turn.

**Captain: Where's the strobe?**

Co-Pilot: Right over here.

**Captain: Where?**

Co-Pilot: Right inside there, right inside there.

Engineer: You know, we're not gettin' our  
airspeed back there.

**Captain: Where is the strobe?**

Co-Pilot: Right down there.

**Captain: I still don't see it.**

Engineer: #, we're never goin' to make this.

**Captain: Where do you see a strobe light?**

Co-Pilot: Right over here.

Captain: Gear, gear down, spoilers armed.

Engineer: Gear down, three green spoilers, flaps,  
checklist

???: *There you go, right there, lookin' good.*

**Captain: Where's the strobe?**

Co-Pilot: *Do you think you're gonna make this?*

**Captain: Yeah... if I can catch the strobe light.**

Co-Pilot: *500, you're in good shape.*

Engineer: *Watch the, keep your airspeed up.*

Co-Pilot: *140. [sound of stall warning]*

???: *Don't – stall warning.*

**Captain: I got it.**

Co-Pilot: *Stall warning.*

Engineer: *Stall Warning*

**Captain: I got it, back off.**

???: *Max power!*

???: *There it goes, there it goes!*

???: *Oh no!*

## ***Crash of American International Flight 808: Probable Causes***

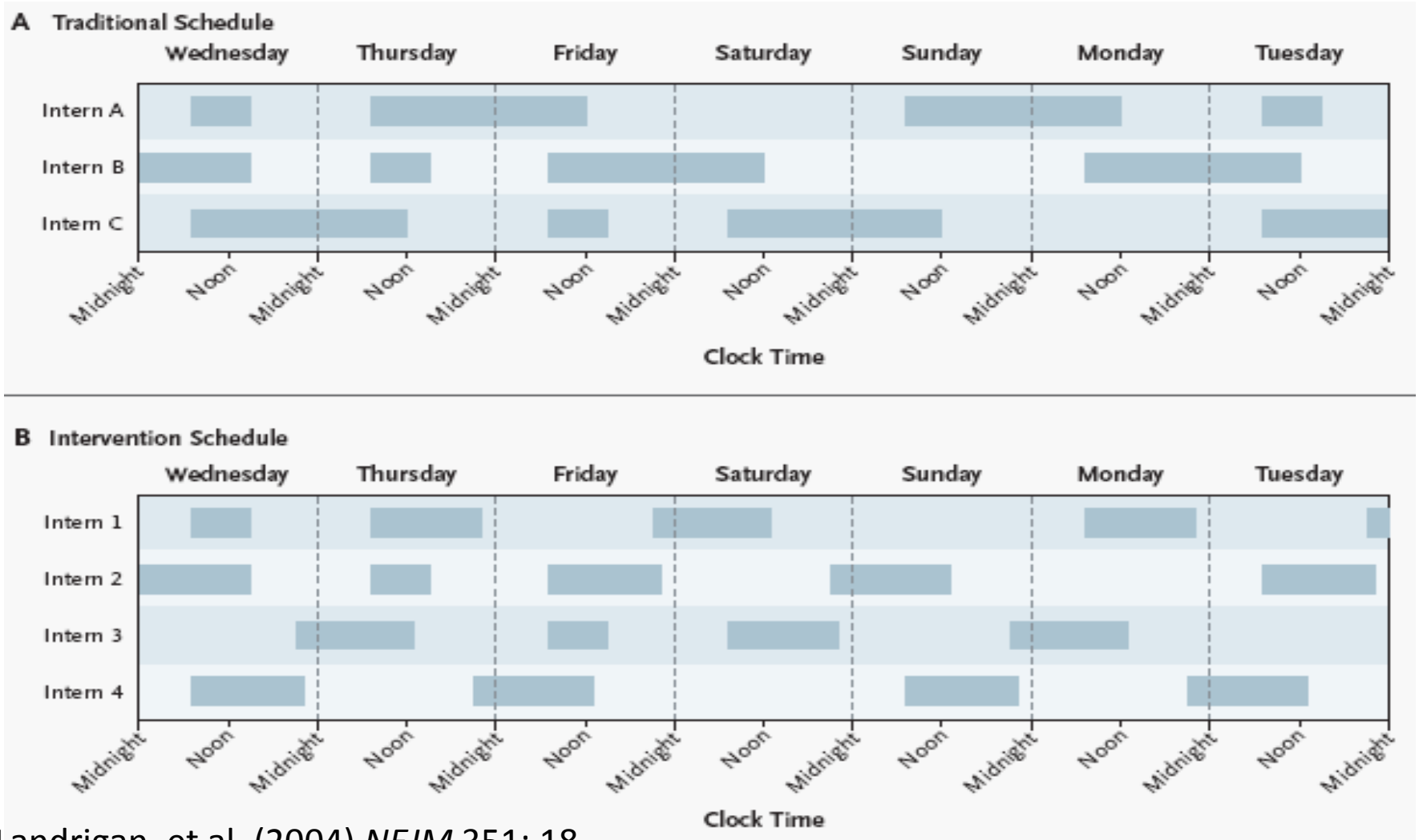
"The **impaired judgment, decision-making**, and flying abilities of the captain and flight crew **due to the effects of fatigue [sleep deprivation]**; the captain's **failure to properly assess the conditions for landing and maintaining vigilant situational awareness** of the airplane while maneuvering onto final approach; his failure to prevent the loss of airspeed and avoid a stall while in the steep bank turn; and his **failure to execute immediate action** to recover from a stall."

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From NTSB Report

# The Harvard Intervention Studies: A Simple Case of Fatigue Risk Management

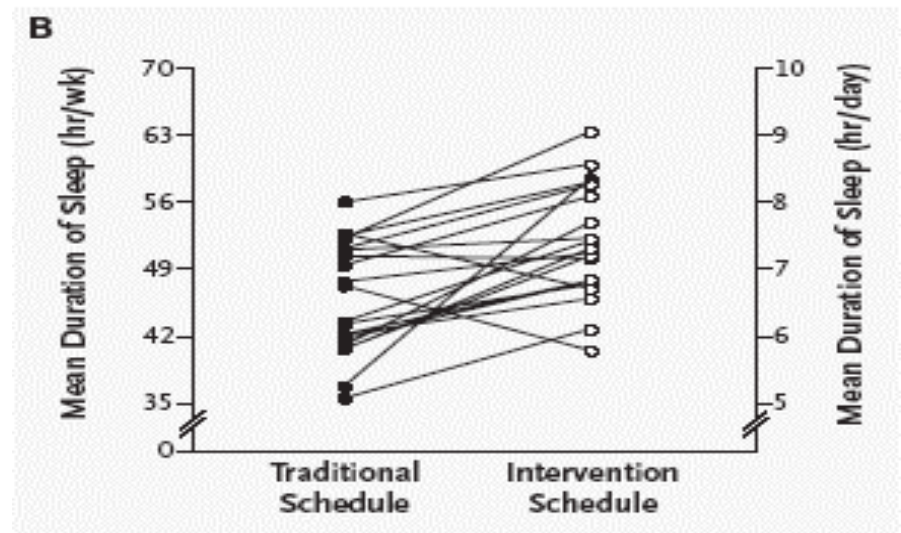
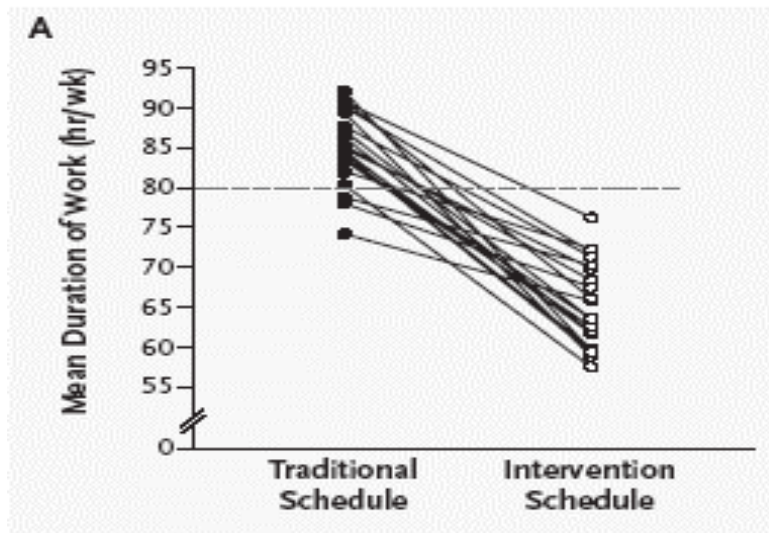
# Traditional vs. Intervention Schedule



Landrigan, et al. (2004) *NEJM* 351: 18,  
1838-1848

# Duration of Work Week and Effect on Sleep

- Duration of work week decreased from 85 hours to 65 hours
- Total sleep time/24 hours increased from 6.6 to 7.4 hours





# Limiting Work Hours: Effect on Serious Medical Errors

| Variable                                            | Traditional<br>Schedule                   | Intervention<br>Schedule | P Value |
|-----------------------------------------------------|-------------------------------------------|--------------------------|---------|
| Landrigan, et al. (2004)<br>NEJM 351: 18, 1838-1848 | no. of errors<br>(rate/1000 patient-days) |                          |         |
| Serious medical errors made<br>by interns           |                                           |                          |         |
|                                                     |                                           |                          |         |
| Preventable adverse events                          | 27 (20.9)                                 | 15 (16.5)                | 0.21    |
| Intercepted serious errors                          | 91 (70.3)                                 | 50 (55.0)                | 0.02    |
| Nonintercepted serious errors                       | 58 (44.8)                                 | 26 (28.6)                | <0.001  |
| Types of serious medical errors<br>made by interns  |                                           |                          |         |
| Medication                                          | 129 (99.7)                                | 75 (82.5)                | 0.03    |
| Procedural                                          | 11 (8.5)                                  | 6 (6.6)                  | 0.34    |
|                                                     |                                           |                          |         |
| Other                                               | 12 (9.3)                                  | 7 (7.7)                  | 0.47    |

# Medical Errors, Adverse Events, & Car Crashes

- Survey of 2737 residents (PGY 1s)
  - Extended ( $\geq 24$  hours) shifts vs. normal day shifts
- Barger et al., 2005
  - More crashes, near misses, and fall asleep while driving with extended work hours
- Barger et al., 2006
  - More significant medical errors, attentional failures, and fatigue-related preventable adverse events resulting in a fatality
- Ayas et al., 2008
  - Increased percutaneous injuries

Barger et al., NEJM 2005

Barger et al., NEJM 2006

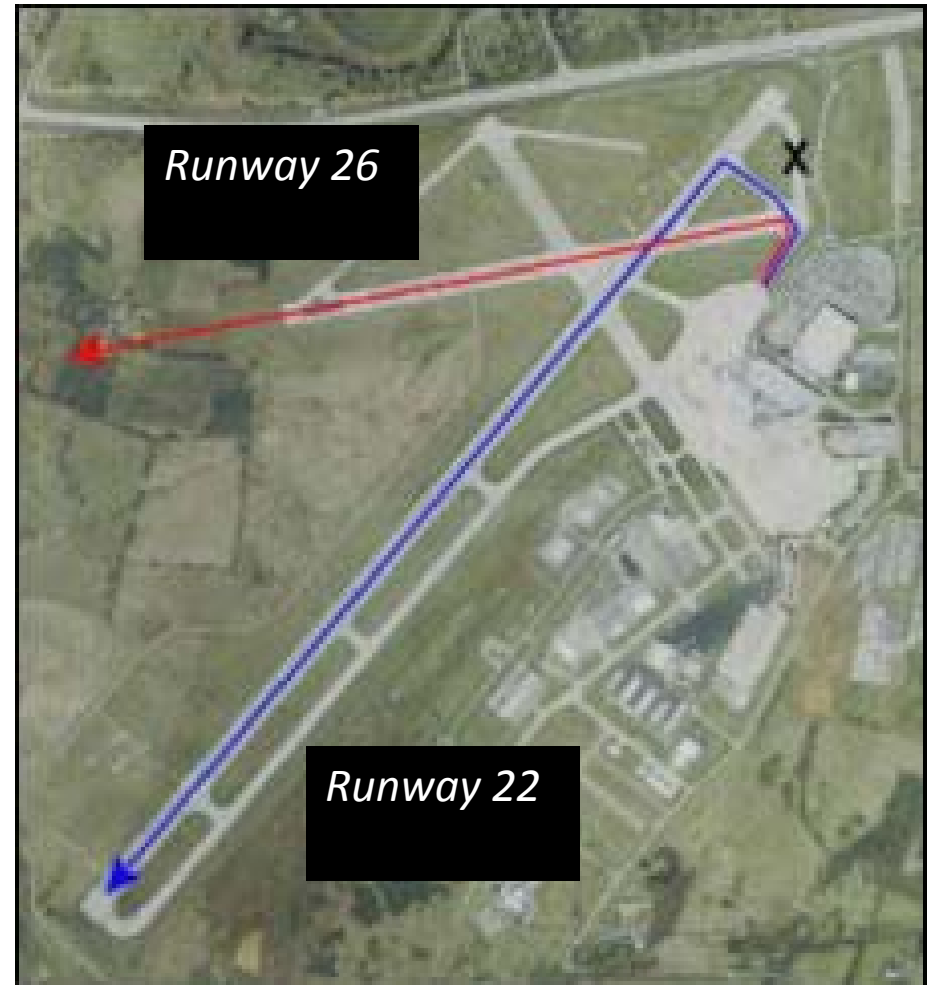
Ayas et al., PLoS 2008

# Acute Partial Sleep Deprivation in an Air Traffic Control and Pilot Error Accident

# Comair Flight 5191



- Lexington, KY to Atlanta, GA
- Take off ~ 0630 hrs
- Assigned the Runway 22
- Used Runway 26
- Pilot took wrong turn onto unlit Runway 26
- Neither pilots nor air traffic controller noticed error
- Turned aircraft over to First Officer for take off
- Crashed just past the end of the runway
- Killed all 47 passengers and two of the three crew
- Similar error in 1993
  - Caught prior to take-off roll
  - By both pilots and air traffic controller

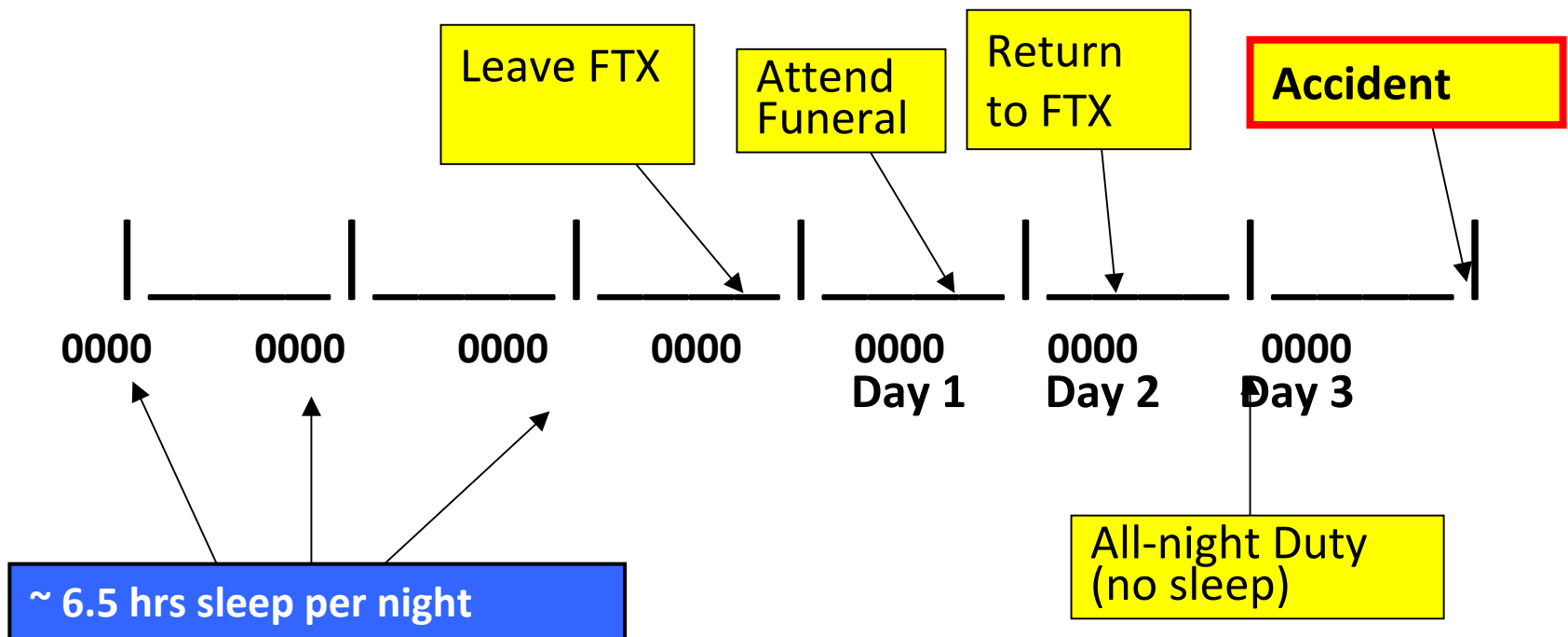


# Sleep in Air Traffic Controller and Pilots

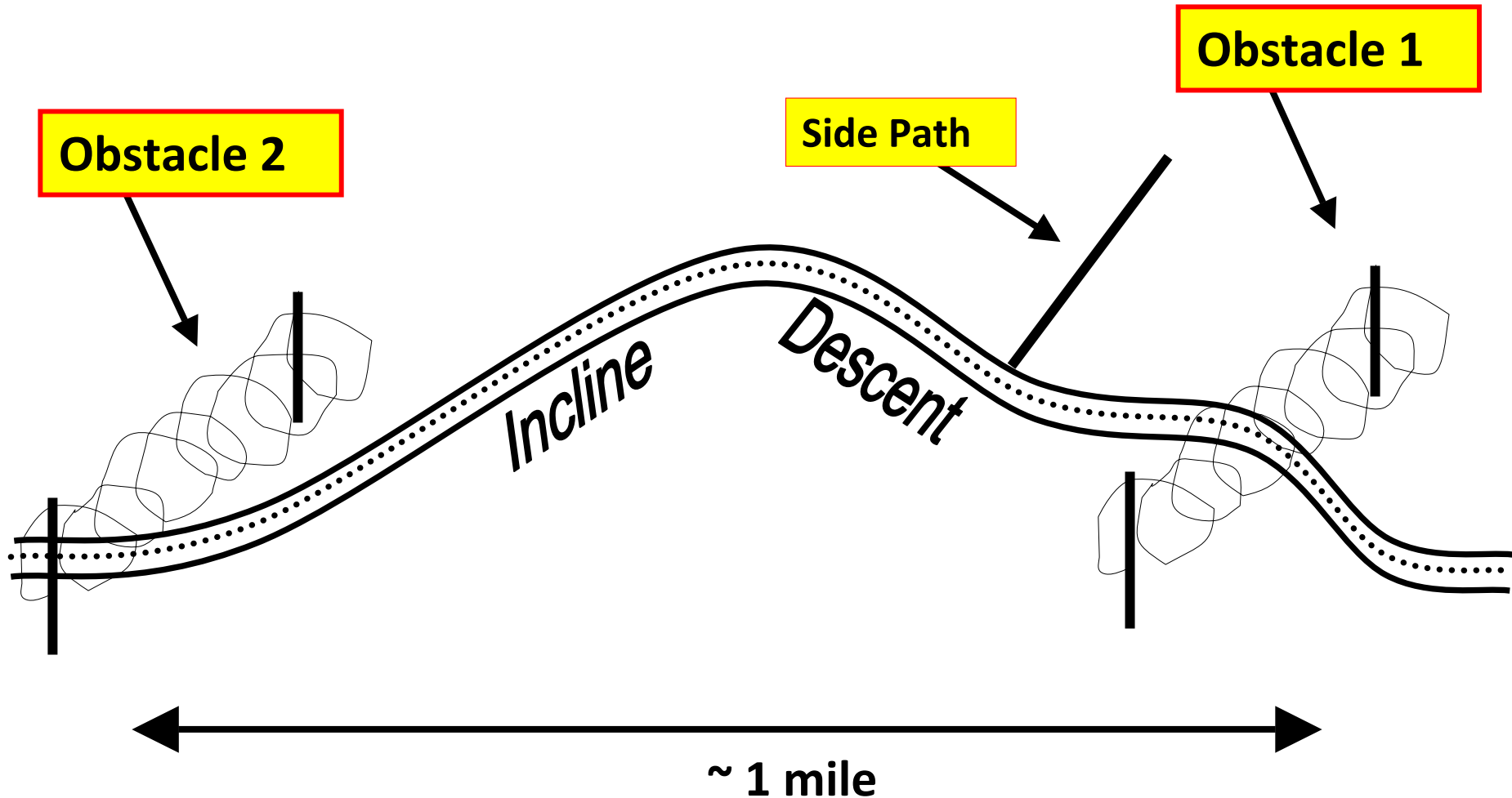
- Air traffic controller (a 17-year veteran) working alone at an airport in Kentucky
  - Worked early day shift from 0630-1430 hours (6:30 AM – 2:30 PM)
  - Had the mandatory by FAA rules 8 hours off
  - Slept ~ 2 hours in the late afternoon
  - Went back to work at 2330 (11:30 PM)
  - Worked through the night until the accident at ~0600 hrs
- Pilots and co-pilot scheduled for take-off at 0600 hrs
  - Likely in bed no earlier than 2200 hrs (10:00 PM)
  - Awake at 0400 hrs.
- Both air traffic controller and pilots were sleep restricted and at low point in circadian rhythm

# Model-Based Accident Reconstruction in a Court-martial on a Charge of Negligent Homicide

# Accident Reconstruction: Timeline

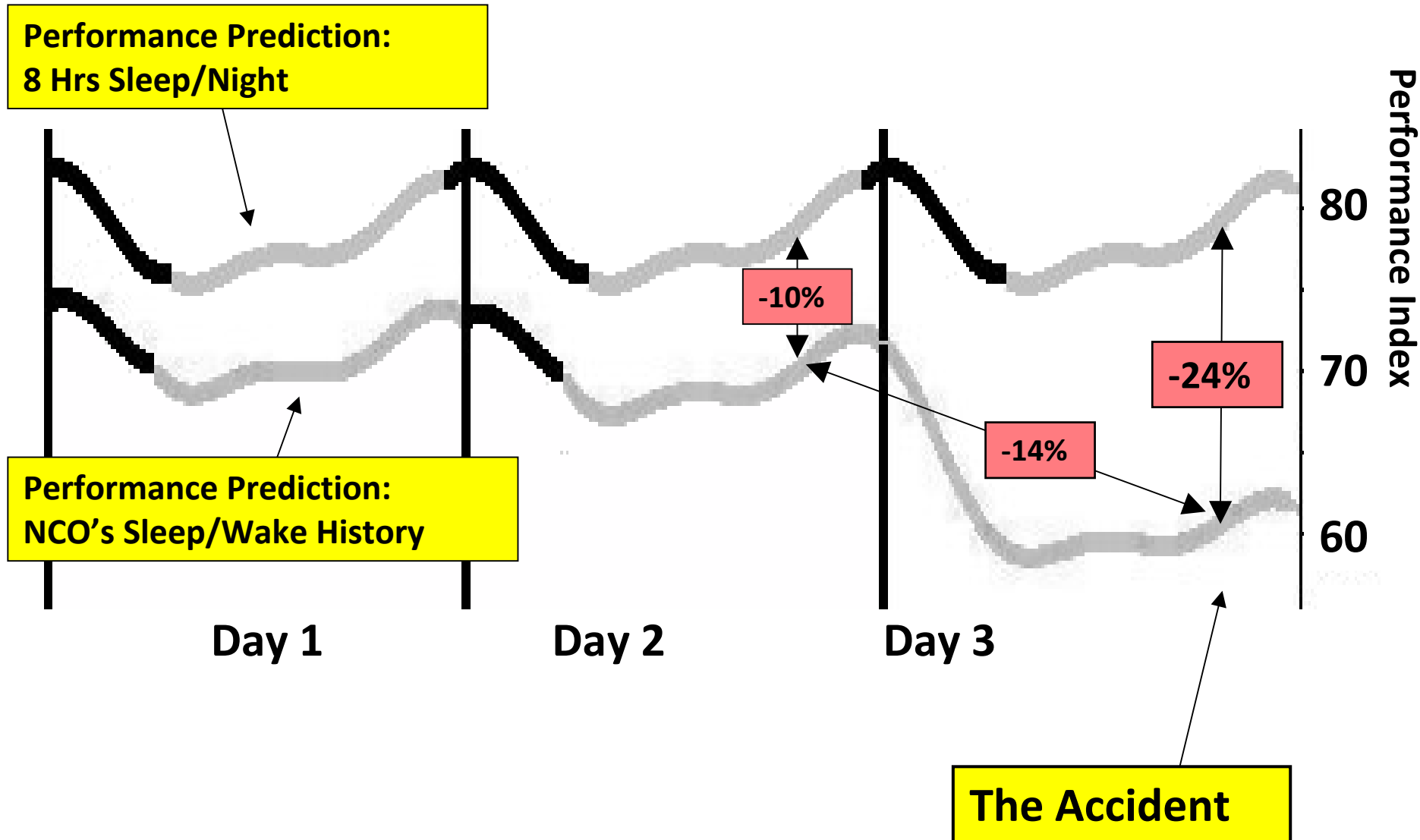


# Accident Reconstruction: Setting





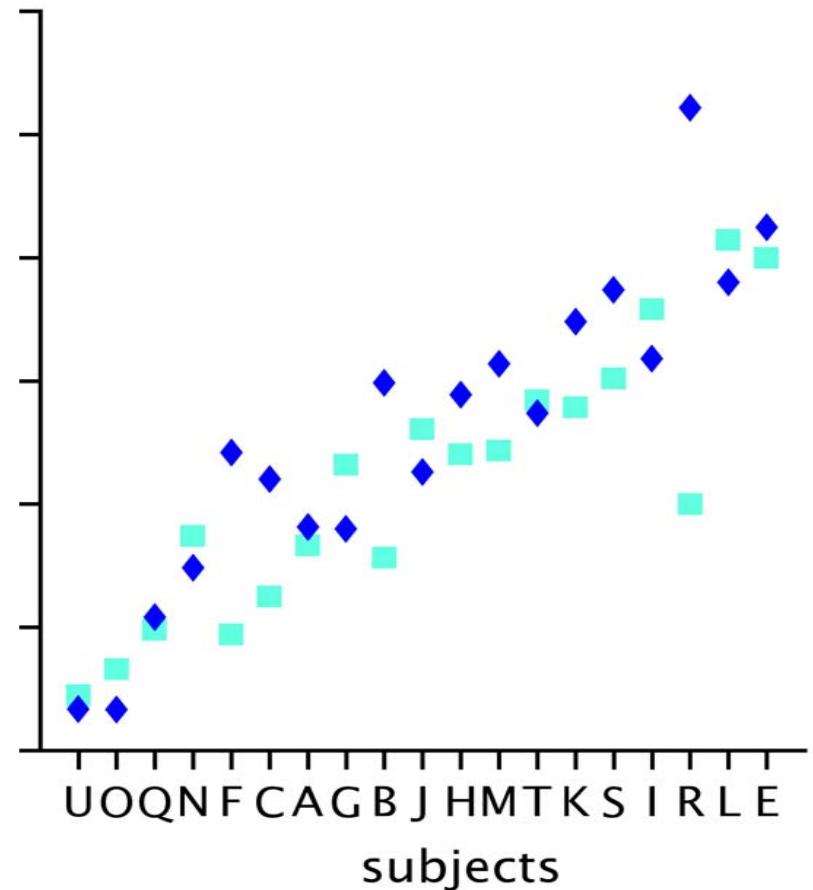
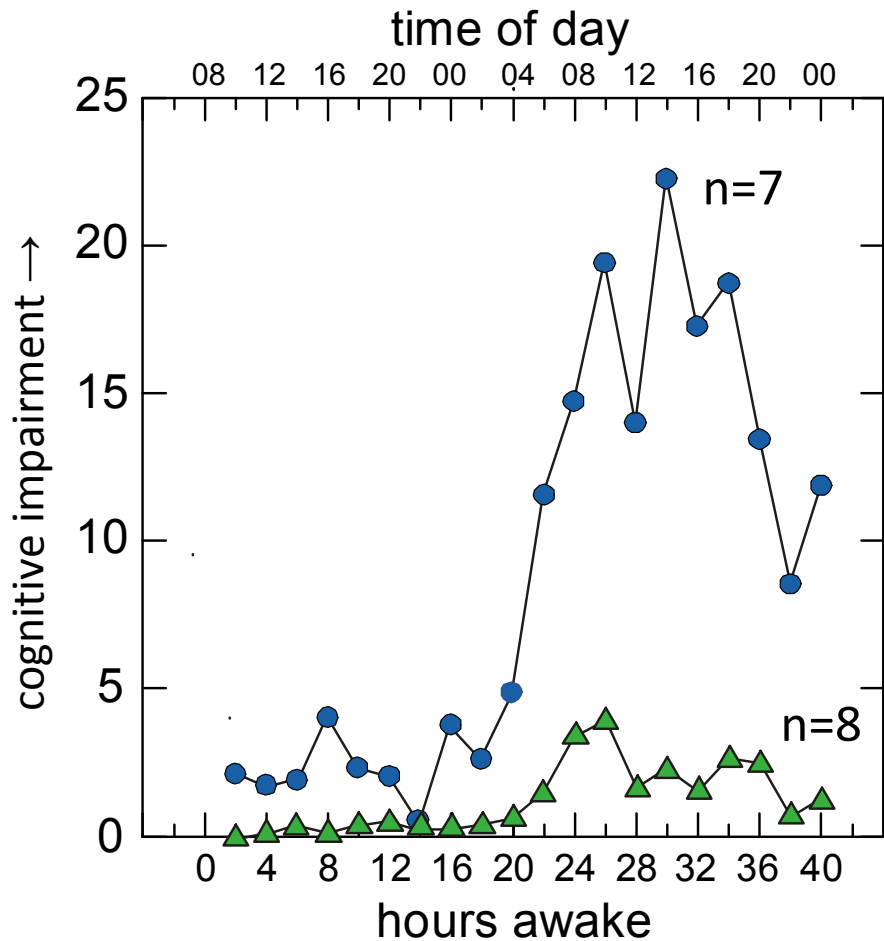
# Accident Reconstruction: Model Predictions



# Individual Differences in Sensitivity to Sleep Loss, Circadian Phase, and Workload

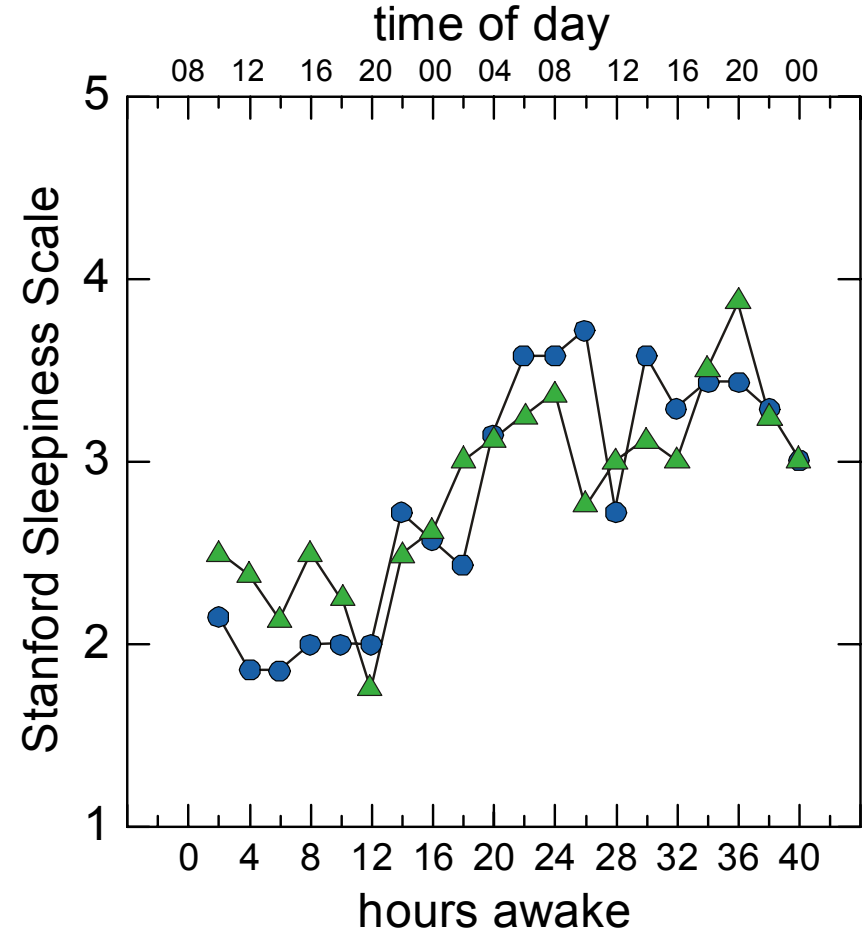
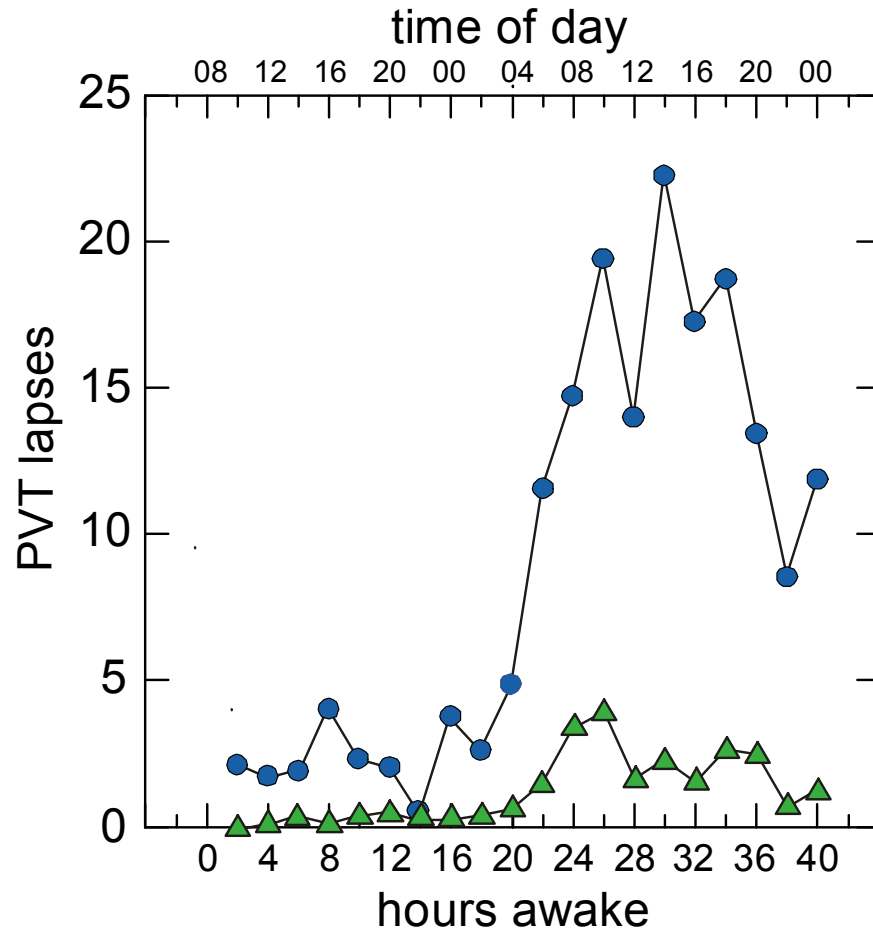
# Trait Individual Differences in Vulnerability to Performance Impairment from Sleep Loss

Adapted from Van Dongen et al (2004)



# Mismatch between Subjective Sleepiness and Objective Performance Deficits

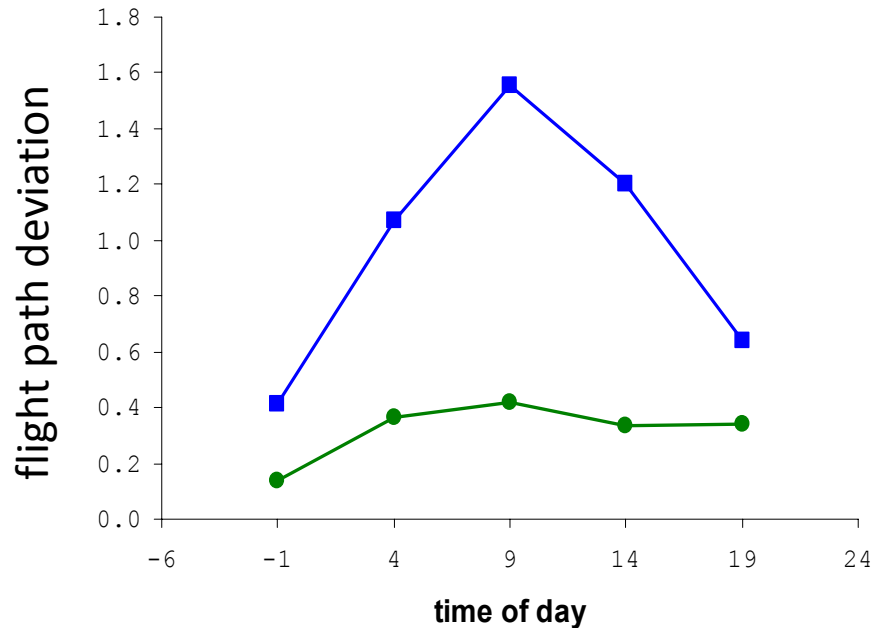
Adapted from Van Dongen et al (2004)



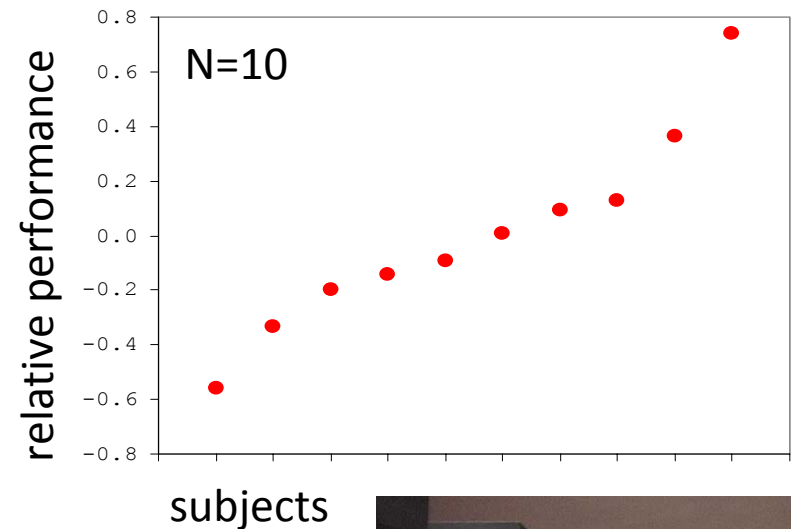
# Individual Differences in Active-Duty Air Force Pilots during Simulated F-117 Extended Night Flights

From Van Dongen et al (2006)

**left 720 degrees turn  
roll angle performance over time**



**performance distribution**



(Self-)selection mechanisms do not eliminate individual differences in vulnerability to sleep loss—even in highly specialized professions



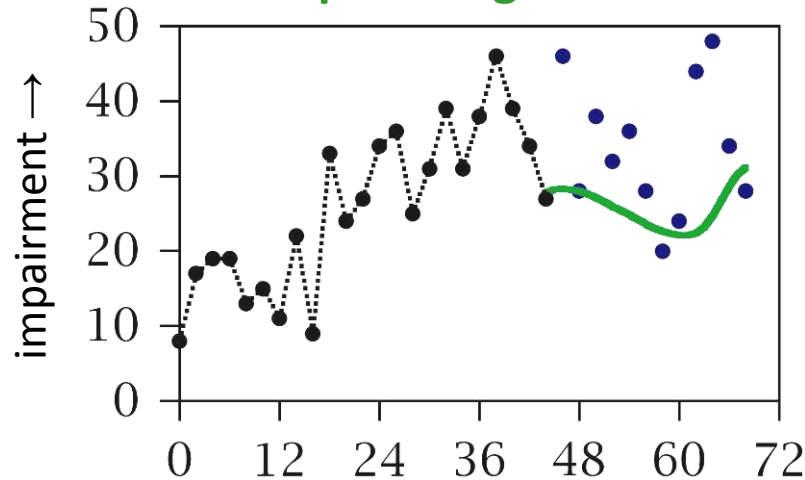
# Individualized Performance Modeling

**Subject A**

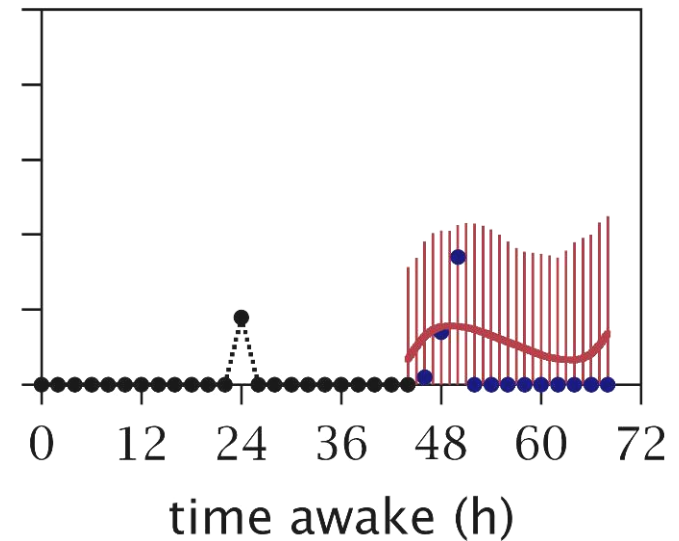
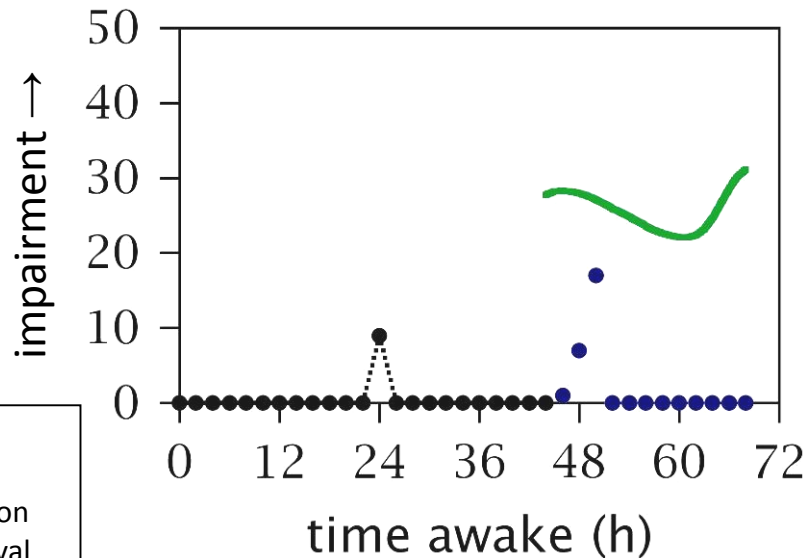
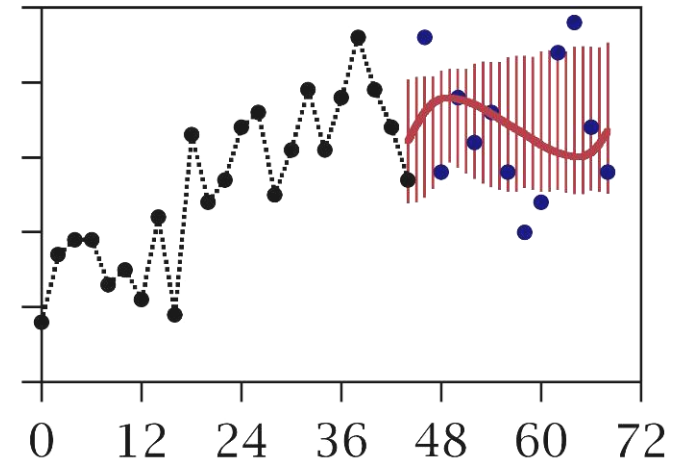
**24 h ahead  
performance  
prediction  
snapshots  
at 44h awake  
(time 03:30)**

**Subject B**

**Group-Average Model**

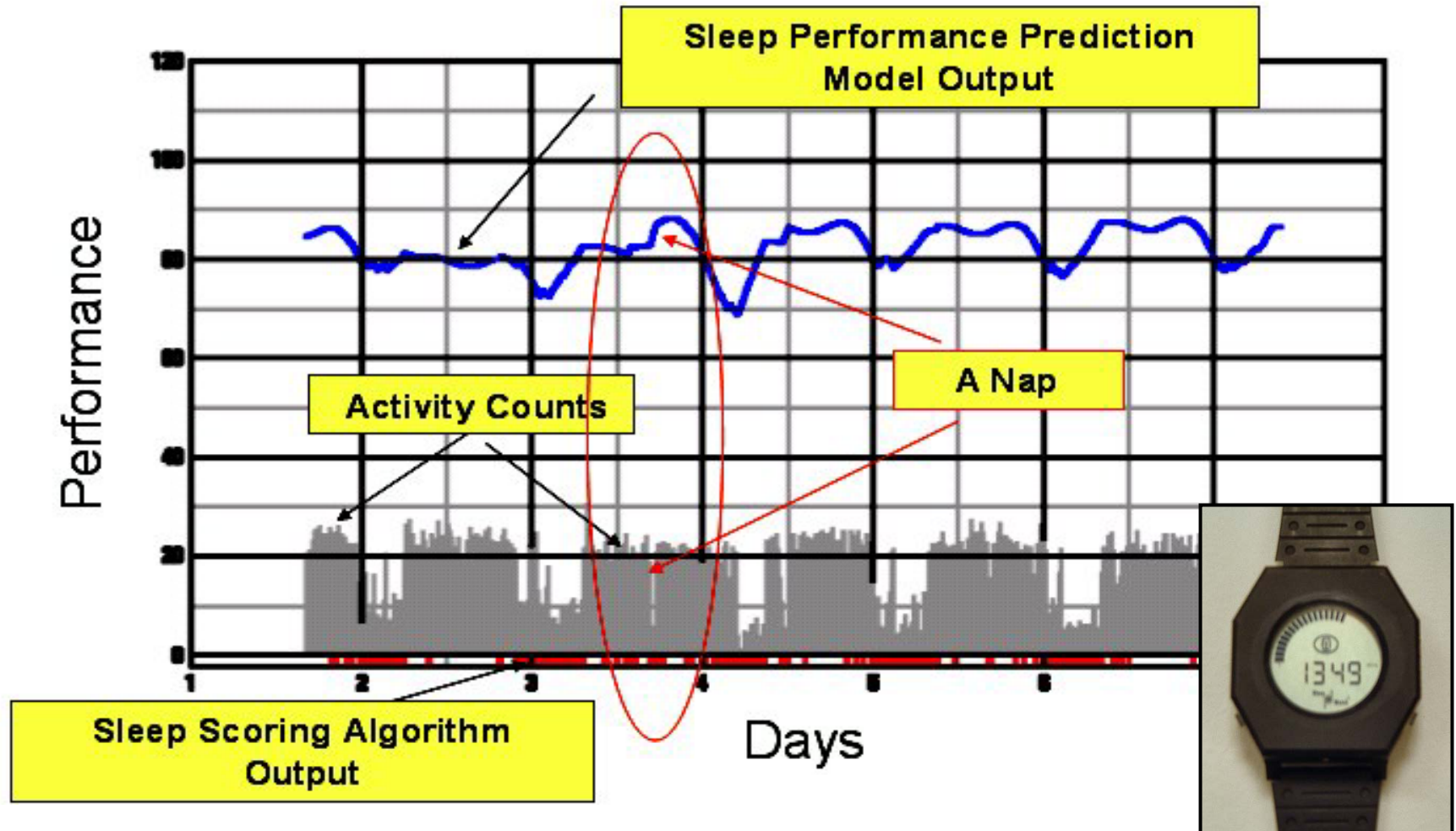


**Individualized Model**



- past performance
- future performance
- performance prediction
- | 95% confidence interval

# Predicting Performance from Actigraphically-Derived Sleep Wake History



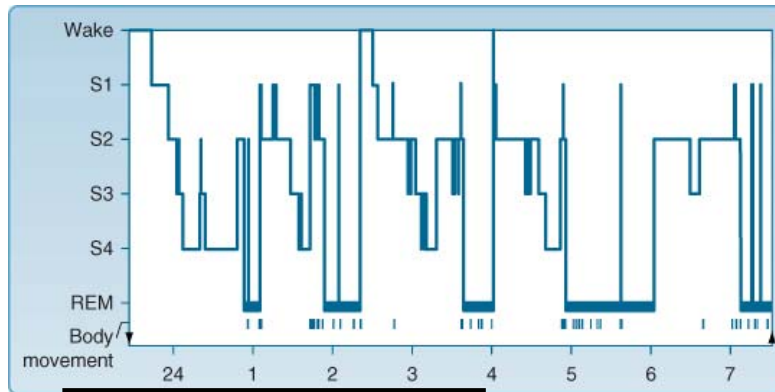
# The Internal Body Clock (Circadian Rhythm)



Kryger, Roth and Dement,  
*Principles and Practice of Sleep  
Medicine*, 2005

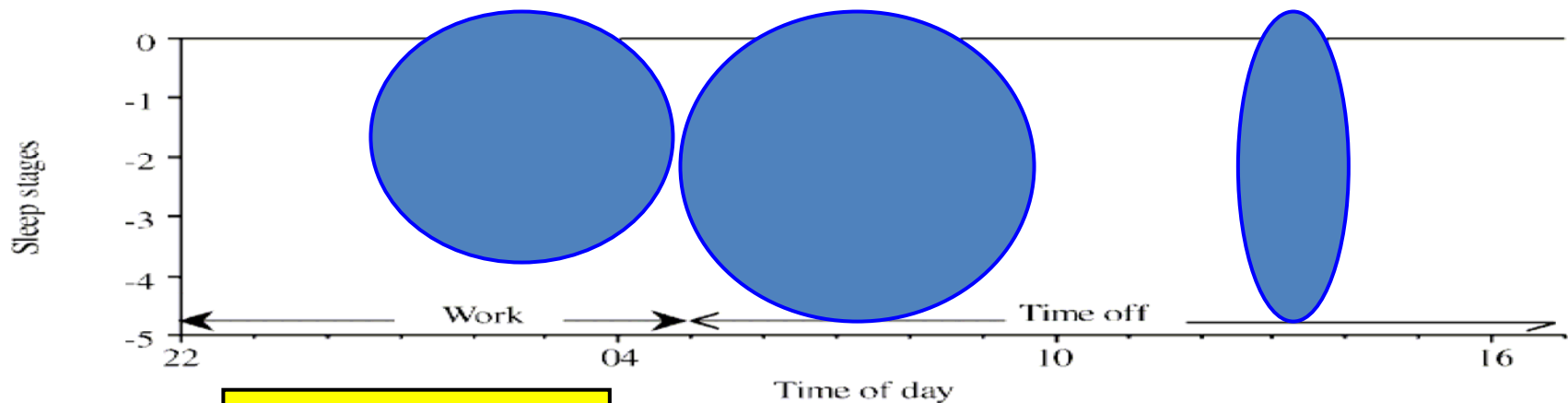


# Normal vs. Night Shift-Work Sleep



**Normal Sleep**

- Graphs matched on time scale
- Note naps during work shift and in late afternoon
- Note truncated main daytime sleep



**Shift-Worker Sleep**

# The New Science and Art of Fatigue Risk Management

# Humans and Machines: The Person in the Loop

- Alternative futures (as envisioned ~30 years ago):
  - Man without computer
  - Computer without man
  - Man against computer
  - Man with computer against man with computer
- Current state:
  - Persons embedded in robotic systems
  - Monitored, assisted, sustained



... all watched over by machines of loving grace.”

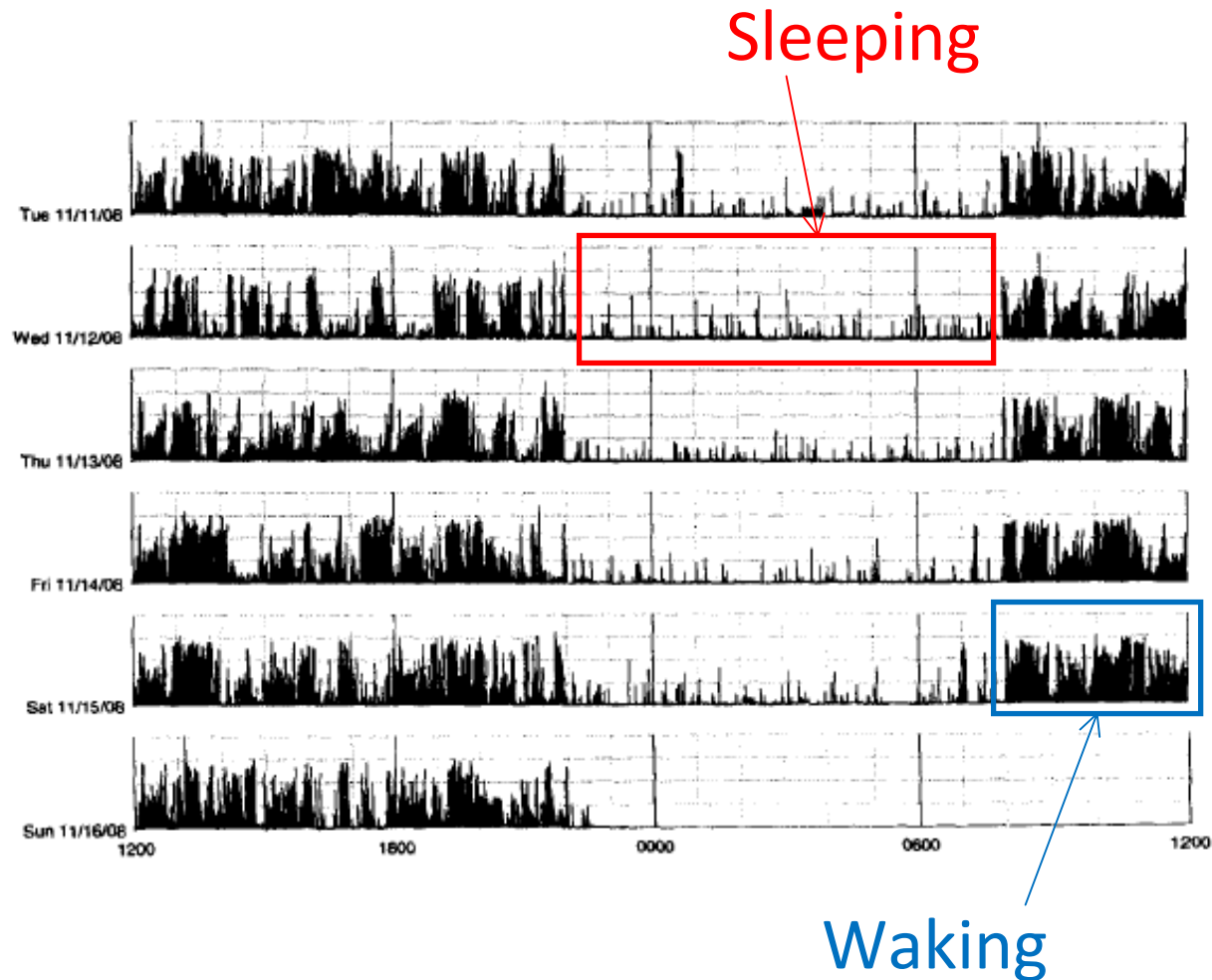
- Richard Brautigan (1963)

# Integration of Fatigue Risk Management into Rostering and Scheduling Software

- Personal biomedical status monitoring
  - Sleep/wake history (by sleep watch/actigraph)
  - Circadian rhythm phase (by technology TBD)
  - Predict performance in real time person by person (by biomathematical performance prediction model)
  - Validate with embedded performance metrics
    - Lane deviation (trucking)
    - Flight performance (commercial aviation)
- Integrate performance prediction into rostering and scheduling software
  - Integrate into objective function
  - Optimize along with other constraints

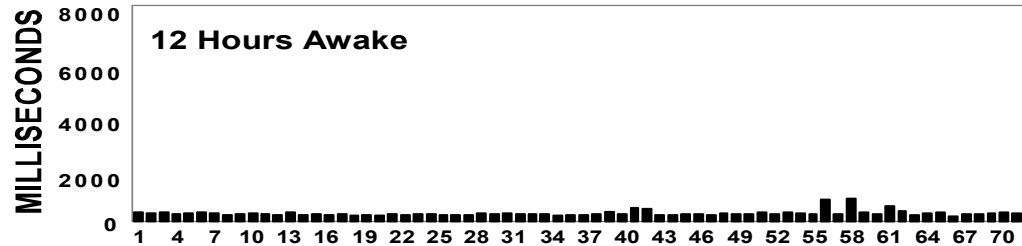
# Example of Actigraph Record

- An example of an actigraph record recorded over 6 days.
- This person slept from ~ 22:00 to 08:00.

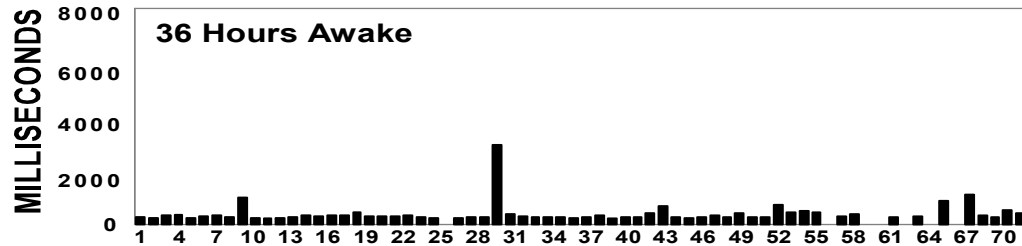


# Effect of Sleep Loss on Performance on the Psychomotor Vigilance Test (PVT)

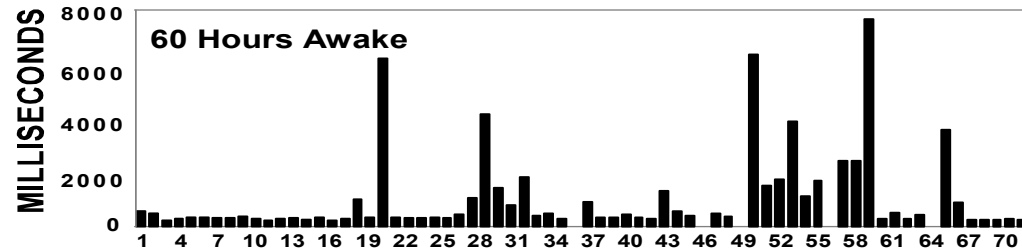
12 Hours  
Awake



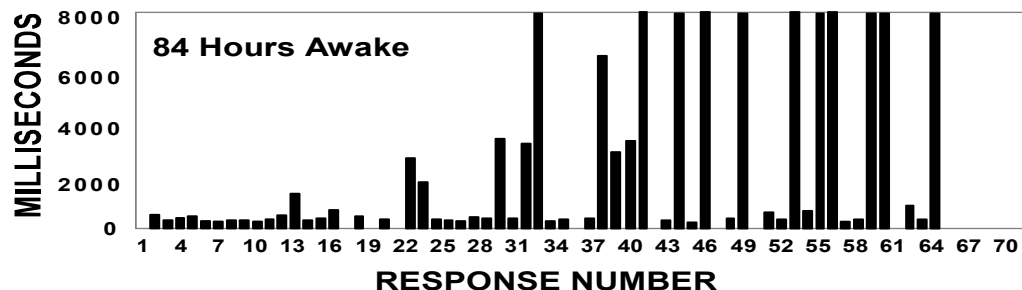
36 Hours  
Awake



60 Hours  
Awake

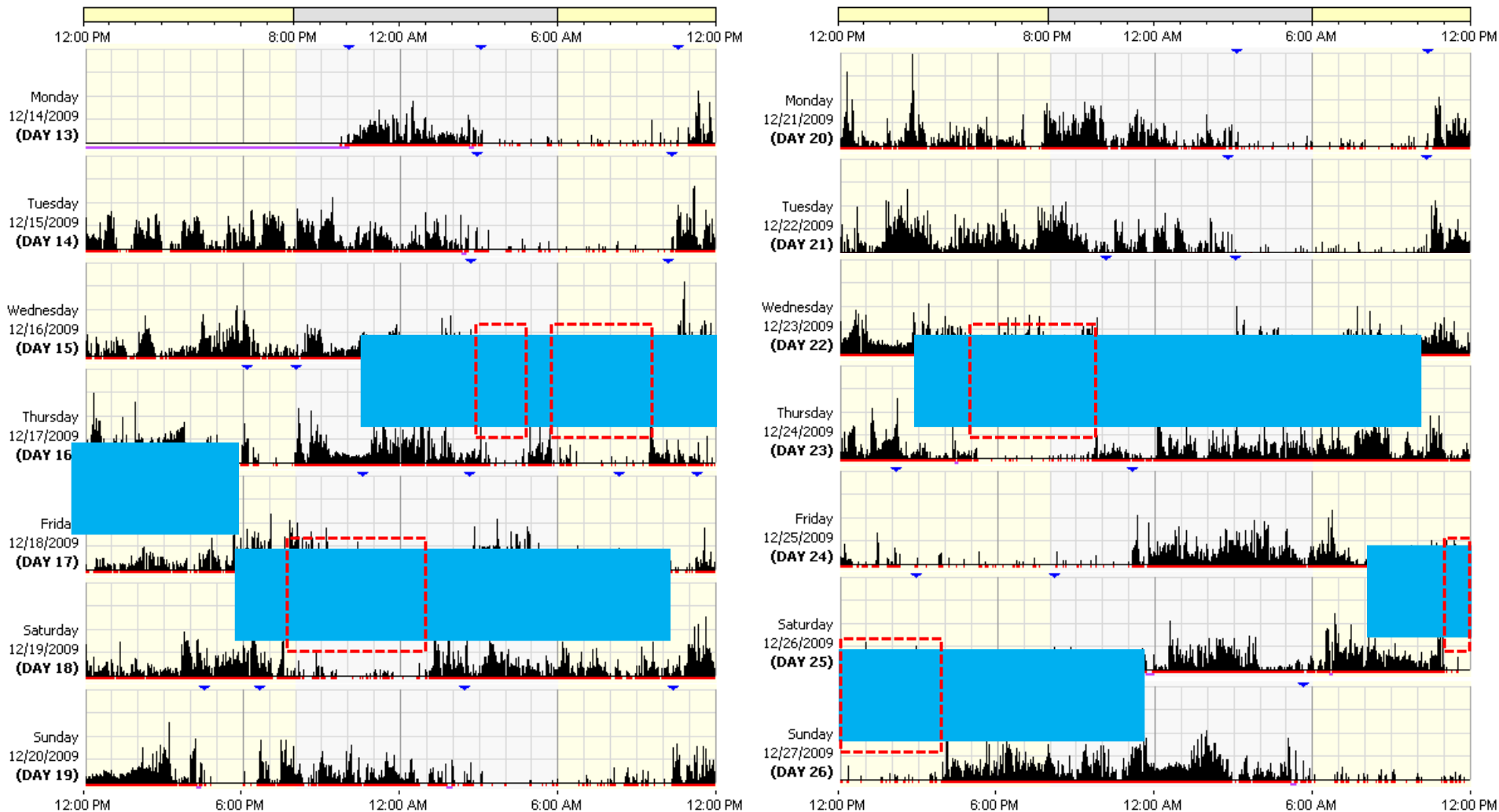


84 Hours  
Awake



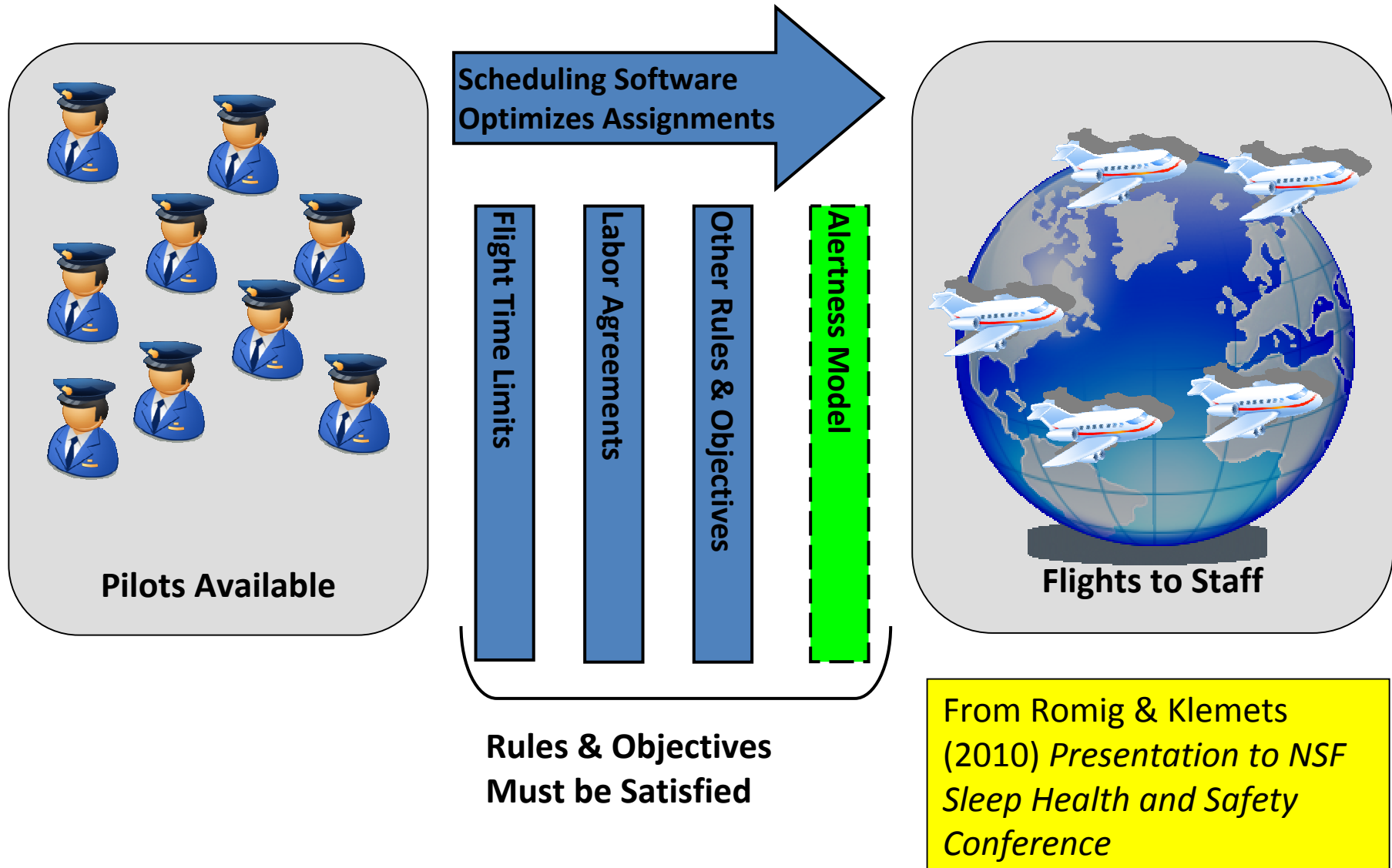
From Doran  
et al. (2001)  
*Arch Ital Biol.*

# At Home and In-Flight Sleep in a Boeing 777 Pilot



Belenky, et al., in preparation

# Crew Scheduling in Commercial Aviation is Controlled by Rules & Objectives





# Flight Time Limits Alone Do Not Protect Alertness

| Scenario Conditions |                            |                          |                         | Alertness & Productivity             |                                     |                     |
|---------------------|----------------------------|--------------------------|-------------------------|--------------------------------------|-------------------------------------|---------------------|
| Scenario            | Flight Time Limits Applied | Labor Agreements Applied | Alertness Model Applied | Alertness Improvement (Worst Flight) | Alertness Improvement (All Flights) | Productivity Change |
| 1                   |                            | No                       | No                      |                                      |                                     |                     |
| 2                   | Yes                        | Yes                      | No                      | + 3.9 %                              | + 0.1 %                             | - 20.74 %           |
| 3                   | Yes                        | Yes                      | Yes                     | + 7.8 %                              | + 3.0 %                             | - 20.75 %           |
| 4                   | No                         | No                       | Yes                     | + 10.7 %                             | + 2.1 %                             | + 0.66 %            |

From Romig & Klemets  
(2010) *Presentation to NSF  
Sleep Health and Safety  
Conference*

# Labor Agreements Add Extra Protection – At A Cost

| Scenario Conditions |                            |                          |                         | Alertness & Productivity             |                                     |                     |
|---------------------|----------------------------|--------------------------|-------------------------|--------------------------------------|-------------------------------------|---------------------|
| Scenario            | Flight Time Limits Applied | Labor Agreements Applied | Alertness Model Applied | Alertness Improvement (Worst Flight) | Alertness Improvement (All Flights) | Productivity Change |
| 1                   | Yes                        | No                       | No                      | Reference                            | Reference                           | Reference           |
| 2                   |                            |                          | No                      |                                      |                                     |                     |
| 3                   | Yes                        | Yes                      | Yes                     | + 7.8 %                              | + 3.0 %                             | - 20.75 %           |
| 4                   | No                         | No                       | Yes                     | + 10.7 %                             | + 2.1 %                             | + 0.66 %            |

From Romig & Klemets  
(2010) *Presentation to NSF  
Sleep Health and Safety  
Conference*

# A Model Within Existing Constraints Improves Alertness

| Scenario Conditions |                            |                          |                         | Alertness & Productivity             |                                     |                     |
|---------------------|----------------------------|--------------------------|-------------------------|--------------------------------------|-------------------------------------|---------------------|
| Scenario            | Flight Time Limits Applied | Labor Agreements Applied | Alertness Model Applied | Alertness Improvement (Worst Flight) | Alertness Improvement (All Flights) | Productivity Change |
| 1                   | Yes                        | No                       | No                      | Reference                            | Reference                           | Reference           |
| 2                   | Yes                        | Yes                      | No                      | + 3.9 %                              | + 0.1 %                             | - 20.74 %           |
| 3                   |                            |                          |                         |                                      |                                     |                     |
| 4                   | No                         | No                       | Yes                     | + 10.7 %                             | + 2.1 %                             | + 0.66 %            |

From Romig & Klemets  
(2010) *Presentation to NSF  
Sleep Health and Safety  
Conference*

# Modeling Alone Improves Alertness & Productivity

| Scenario Conditions |                            |                          |                         | Alertness & Productivity             |                                     |                     |
|---------------------|----------------------------|--------------------------|-------------------------|--------------------------------------|-------------------------------------|---------------------|
| Scenario            | Flight Time Limits Applied | Labor Agreements Applied | Alertness Model Applied | Alertness Improvement (Worst Flight) | Alertness Improvement (All Flights) | Productivity Change |
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| 3                   | Yes                        | Yes                      | Yes                     | + 7.8 %                              | + 3.0 %                             | - 20.75 %           |
| 4                   | No                         | No                       |                         |                                      |                                     |                     |

From Romig & Klemets  
(2010) *Presentation to NSF  
Sleep Health and Safety  
Conference*

# Sleep as an Item of Logistic Resupply

- A Battalion Commander manages fuel by knowing:
  - How much the unit has on hand
  - Rates of utilization
  - Anticipated operations
  - With these quantities, the Commander can plan for timely resupply to sustain operational performance
- To manage sleep the Commander must know:
  - How much sleep his unit has been getting
  - How long this will sustain acceptable performance
  - Ensure that adequate opportunity for sleep exists to sustain operational performance

# Integration of Fatigue Risk Management into Rostering and Scheduling Software

- Personal biomedical status monitoring
  - Sleep/wake history (by sleep watch)
  - Circadian rhythm phase (by technology TBD)
  - Predict performance in real time person by person (by biomathematical performance prediction model)
  - Validate with embedded performance metrics
    - Lane deviation (trucking)
    - Flight performance (commercial aviation)
- Integrate performance prediction into rostering and scheduling software
  - Integrate into objective function
  - Optimize along with other constraints

# Fatigue Risk Management & Safety Management

- Embed within corporate safety management system (SMS)
  - Move fatigue issues from labor/management to safety
  - Safety enhances productivity (and the reverse)
  - SMS has built-in structure, yields economies of scale
- Fatigue risk management systems (FRMS)
  - Multi-layered defense against fatigue-related error, incident, and accident
  - Each layer “sloppy” but in the Swiss cheese model highly efficient at preventing fatigue-related errors
- Current examples are Union Pacific Railroad and easyJet Airlines

# Fatigue Risk Management System (FRMS)

- Five-tiered defense-in-depth to prevent fatigue related errors, incidents, and accidents
- Tier 1 – Does system of shift timing and duration allow for adequate opportunity for sleep?
  - Computer-based rostering and scheduling
  - Predictive modeling
- Tier 2 – Do employees take advantage of the sleep opportunity?
  - Self-report
  - Wrist-worn actigraph (sleep watch)
- Tier 3 – In the workplace, do they maintain adequate alertness and performance?
  - Self-report & co-worker report
  - Palm Pilot Psychomotor Vigilance Task (PVT)
  - Embedded performance metrics
- Tier 4 – Are there errors, near-misses?
- Tier 5 – Are there incidents and accidents?

*Dawson &  
McCulloch 2005*





# Point of Contact

Gregory Belenky, MD  
Research Professor and Director  
Sleep and Performance Research  
Center  
Washington State University  
P.O. Box 1495  
Spokane, WA 99210-1495

Phone: (509) 358-7738  
FAX: (509) 358-7810  
Email: [belenky@wsu.edu](mailto:belenky@wsu.edu)



1. The fog of fatigue is analogous to the concept of the fog of war. In fact, much of the fog of war is the result of the interaction of fatigue with the uncertainties and ambiguities of the battlefield. The term “fog of war” appears to have originated, albeit not the exact phrase, with Carl von Clausewitz, the Prussian military analyst and author of “On War”, who wrote: *“The great uncertainty of all data in war is a peculiar difficulty, because all action must, to a certain extent, be planned in a mere twilight, which in addition not infrequently—like the effect of a fog or moonshine—gives to things exaggerated dimensions and unnatural appearance.”*
2. The operational environment broadly is construed is a system in which the outcome is critical and human performance is critical to a successful outcome. Further, there are temporal boundaries (a temporal envelope) during which the correct decision must be reached or the system will fail. This dependence on a correct and timely human response is captured in the “observe, orient, decide, act” loop conceptualized by the American Air Force fighter pilot, John Boyd. Boyd’s conceptualization applies to operation in which the performance of the human in the loop is critical to an outcome. In the parlance of operations research, most operational settings are complex and tightly coupled – a small error in one area can set off a cascading sequence of failure. Examples of operational settings include all modes of transportation, resource extraction, energy generation, manufacturing, financial markets, and medicine. High reliability operational settings are ones in which the operating personnel remain mindful in day-to-day operations and maintain presence of mind in an emergency.
3. This is a composite image of the earth at night showing the pattern and extent of 24x7 human activity and enterprise. It presents in a compelling visual way the activity driving the need for extended work hours and backside of the clock (nighttime) operations to support economic and other human activity. As at least anecdotal support of the idea that light at night reflects economic activity, note the red arrow pointing to the green line dividing North Korea from South Korea. All the economic activity is in the south and so is the light at night. When the American Army developed and fielded night vision devices in the 1980s, it adopted the slogan – “We own the night.” In a wry commentary, a Colonel of my acquaintance observed – “... and now we will have to staff it.”
4. Sleep is found in humans, all other mammals, birds, reptiles, fish, insects, and possibly jellyfish. Apparently, any animal that has one or more assemblies of nerve cells (neuronal assemblies) is capable of and has the need for sleep. In one insect, the fruit fly, sleep deprivation leads to rebound sleep during recovery, degraded performance during the sleep deprivation, and shortened life span when the sleep loss is continued. After over a hundred years of experimental sleep loss studies in humans we know that extended wakefulness degrades performance, that recovery sleep restores it, and that approximately 8 hours of actual sleep time in every 24 hours sustains sleep relatively indefinitely. Much is

understood the brain regulation of sleep stages, nevertheless what it is that goes wrong in the brain during sleep loss and what is restored by recovery sleep remains a mystery.

5. Sleep sustains productivity, safety, health, and well being. Obtaining a sleep/wake history in an off itself is of limited usefulness in predicting a person's performance. In and of itself, knowing how much someone sleeps is of only limited usefulness in predicting their performance. To predict performance requires a mathematical model that encapsulates and integrates the sleep and fatigue related factors relevant to performance.
6. The risks from sleep loss (both total sleep deprivation and chronic, partial sleep restriction) are short, mid, and long term. Short term (minutes, hours, days), sleep loss degrades performance and leads to error, incident, and accident. Mid term (weeks, months), sleep loss degrades planning, strategizing, and making good life decisions. Long term (over years) sleep loss can dysregulate glucose metabolism leading to weight gain, metabolic syndrome, Type II diabetes, and inflammation leading to cardiovascular disease. Further it is implicated in mild cognitive impairment, a precursor of Alzheimer's disease. We all accept that diet and exercise are important for performance, health, and well being. It is high time to add sleep to the list. My recommendation in terms of priority is to delay eating in order to exercise and to delay exercise in order to sleep.
7. An operational definition of fatigue is crucial to good research, operational planning, and policy making. A good operational definition tells us how to measure something. Fatigue can be defined both subjectively and objectively. Observations of fatigued behavior are also subjective measures. Subjectively, fatigue is defined by a person reporting "I am tired" or by endorsing the high fatigue end of a fatigue scale e.g., the Samn-Perelli. Objectively, fatigue is defined by degraded performance. Performance can be measured by what we call added metrics – metrics extraneous to the task at hand, e.g., the psychomotor vigilance task (PVT) or by metrics embedded in the task itself, e.g., lane deviation in driving or flight operations quality assurance (FOQA) in commercial aviation. Embedded metrics have the advantage of not interrupting the normal flow of work.
8. The scientific study of sleep and performance requires the objective measurement of sleep and performance. In the laboratory, we use polysomnography, the combination of electroencephalographic, electrooculographic, and electromyographic recording, to determine the placement and duration of sleep periods as well as the stages of sleep. To measure performance in the laboratory we use a battery of cognitive performance tests including tests of attention and vigilance, e.g., the psychomotor vigilance test (PVT). In the field, we use actigraphy, the measurement of non-dominant wrist movements summed in one-minute bins, to determine the placement and duration of sleep periods. Actigraphy can

determine only if the person being studied is awake or asleep, not the stages of sleep. Still this is more than adequate for field work as it is total sleep time, not sleep stage distribution that determines recuperation. A sleep/wake history in itself, whether determined by PSG or actigraphy, is not enough to predict performance as there are issues of how proximate the sleep is to the performance point in question and other factors beside sleep/wake history involved, e.g., circadian rhythm phase, workload, and individual differences in response to all these factors. When we first developed the actigraph for field studies of sleep and performance and presented our novel technological wonder to U.S. Army General Max Thurman, he harrumphed and said, "I do not care how much they sleep; I want to know how well they perform." This set us on a search for a way to encapsulate what is known scientifically about the factors underlying fatigue. We determined to create a mathematical model that integrates at a minimum the effects of sleep/wake history and circadian rhythm phase in order to predict performance. The model inspired by General "Max" became the basis of the current, commercially available, and widely used SAFTE/FAST model.

9. This figure depicts sleep/wake history as measured by the actigraph. From left to right is a 24-hour period, measured from noon on one day to noon on the next day. Subsequent days run from top to bottom. The light blue boxes indicate scored sleep by actigraphy. The light green boxes indicate inactivity (rest) but not sleep. The dark blue area covering approximately 26 hours at the beginning of the record and approximately 4 hours at the end of the record are excluded from analysis as the actigraph software determined that the actigraph was off-wrist during that interval.
10. This figure depicts another sleep/wake history as measured by the actigraph. From left to right is a 24-hour period, measured from noon on one day to noon on the next day. Subsequent days run from top to bottom. The light blue boxes indicate scored sleep by actigraphy. The light green boxes indicate inactivity (rest) but not sleep. The dark blue area covering approximately 26 hours at the beginning of the record and approximately 4 hours at the end of the record are excluded from analysis as the actigraph software determined that the actigraph was off-wrist during that interval. Note the afternoon naps on Tuesday, Wednesday, and Friday.
11. The Psychomotor Vigilance Task (PVT) is a sensitive measure of vigilance and attention. It falls within the class of reaction time tests. The PVT can be administered in the laboratory by means of a PC and in the field by porting the PVT to a smartphone or other mobile computing platform. As indicated, it is a reaction time test. In a typical smartphone implementation, the study participant holds the smartphone on his/her hands and focuses attention on the screen. When the required stimulus, e.g., a bull's eye, appears the participant responds by pressing the designated button. The time it takes for the participant to press the button, the latency to the button press, is the participants score on that presentation. Typically, a well-rested, undistracted person will respond in 250

milliseconds (a quarter of a second). A typical PVT lasts 10 minutes. Somewhere between 8-10 stimuli are presented at 2-10 second random intervals each minute. This high rate of stimulus presentation makes the PVT unforgiving for even a slight lapse in attention and thus sensitive to total sleep deprivation and sleep restriction, circadian periodicity, and time on task (workload). Time on task effects can emerge in just a few minutes even in well rested persons. The PVT has other good psychometric properties. Performance on the PVT is independent of IQ, there is virtually no improvement through learning beyond a few practice sessions, and, again, it is unforgiving (never fails to detect) lapses in attention.

12. The figure shows attentional lapsing in a single person across the 10 minutes of a psychomotor vigilance task (PVT) after 12 hours awake, 36 hours awake, 60 hours awake, and 84 hours awake. Note that this is the response-by-response time in milliseconds for each stimulus presented across the 10 minutes of the PVT. A slight increase in response latency is evident even during the PVT at 12 hours awake indicating a time on task effect degradation of performance even when well rested. Conversely, performance for the first 10 or so randomly presented stimuli does not change across increasing sleep deprivation. Time on task is needed to unmask the underlying sleepiness and degraded performance.
13. The PVT is a test developed in the laboratory and ported to the field (operational environment). We are currently using the PC-based PVT in a laboratory study of the effectiveness of split vs. consolidated sleep in sustaining performance. We are using the PVT ported to the Palm Centro smartphone in field studies of sleep during ultra-long range flights in commercial aviation and in field studies of sleep during charter, long-haul scheduled, and short-haul charter operations. The question that arises is how lapsing on the PVT translates into, G errors, incidents, and accidents in actual operations since PVT lapses are common and errors, incidents, and accidents are, thankfully, rare. The accompanying figure depicts what we think is happening in the field environment to turn lapses in attention into accidents. We hypothesize that in addition to the lapse in attention are the coincident demands of the task environment and impact of failure if one occurs.
14. Laboratory and field studies indicate that fatigue is the final common pathway integrating the interacting effects of sleep/wake history (time awake, sleep loss), circadian rhythm (time of day), and workload (time on task, task intensity, and task complexity). There are trait like (enduring) individual differences in response to all three factors.
15. Clear, quantitative links have been established between fatigue and risk of error, incident, and accident. Epidemiological studies link sleep/wake history, circadian phase, and workload with accident risk. Mathematical models are being developed to encapsulate the interaction of sleep/wake history, circadian rhythm, and workload to predict individual performance (read fatigue risk) prospectively

in real time. Similarly, these models can be used for retrospective analysis of already occurred errors, incidents, and accidents.

16. This slides show performance on the PVT (PVT shown here as  $1/\text{reaction time}$  ( $1/\text{RT}$ )) as it is affected by time awake (sleep loss), time of day (circadian rhythm), and time on task (workload). As part of a larger study of 49 young healthy non-smoking volunteers (mean age 22.4, range 18-30; 13 women) were deprived of sleep for over 42 hours and tested on the PVT for ten minutes at two hour intervals (Wesensten, et al., 2004). The PVT is a reaction time test implemented on a personal computer, personal digital assistant, or smart phone. In a typical implementation, stimulus presentations occur at 2-10 second intervals with 7 to 8 stimulus presentations each minute for a total of 70 to 80 stimulus presentations over the ten-minutes of the PVT. There are sufficient responses each minute to look at the effect of time on task over the 10 minutes. Thus in these data we can see the interaction of the effect of time awake (sleep loss), time of day (circadian phase), and time on task (workload). This interaction will be examined in detail in the next two slides.
17. In this slide are added some marks to aid in interpretation. In red line is an approximation of the overall linear effect of time awake (sleep loss) on performance (speed on the PVT). The green waxing and waning, sinusoidal, curve is an approximation of the effect of the circadian rhythm on performance. The turquoise ellipses show the decline in performance across the ten minutes of the PVT with the first ellipse marking a 10-minute PVT soon after awakening and while still well rested and the second ellipse marking a 10-minute PVT taken after being awake for just over 24 hours. Note that the time on task effect (decline in speed of performance) is evident even when well rested and amplified after 24 hours without sleep. In summary, the study depicted in the graph captures the time awake, time of day, and time on task interacting to create the fatigued state.
18. In this slide, again depicts the interaction of time awake, time of day, and time on task on performance on the PVT. The minute-by-minute average speed on the ten-minute are pulled out and exploded (to equivalent scale) for the 2nd (1.5 hours awake) PVT and the 13th (25.5 hours awake) PVT. Again, note that the time on task effect (decline in speed of performance) is evident even when well rested and amplified after 24 hours without sleep.
19. Nil
20. This slide depicts an idealized 24-hour sleep-wake cycle in a person who sleeps from midnight to 8 AM. It shows 8 hours of sleep because 8 hours a night is considered optimal for sustaining complex mental operations indefinitely. During sleep, non-rapid eye movement (NREM) sleep alternates with rapid eye movement (REM) sleep, with a periodicity of 90 to 100 minutes. As the night of sleep wears on NREM episodes become shorter and less intense and REM

episodes become longer and more intense. In ways which we are now just beginning to understand, this cyclic alternation between slow-wave and REM sleep sustains complex mental operations during the ensuing period of wakefulness. Folk wisdom sees humans existing in two distinct states, sleep and wake. However, as you can see in the figure and as will be reinforced in later slides, humans exist in three physiologically distinct states, waking, NREM sleep, and REM sleep. REM sleep is associated with dreaming. Humans awakened from REM sleep will typically report dreaming. This is not the case for NREM sleep. All mammals, not just humans, exist in these three states – waking, NREM sleep, and REM sleep.

21. Waking, NREM sleep, and REM sleep are measured and distinguished one from the other by means of electrophysiological recordings of electroencephalogram (EEG) (brain waves), electrooculogram (EOG) (electrical activity generated from eye movements), and electromyogram (EMG) (electrical activity generated by muscle movement). The left hand graph shows the stages of NREM sleep. The progression through the stages of NREM sleep is characterized by a gradual increase of high amplitude slow waves in the EEG. The bottom right graph shows REM sleep. REM sleep is characterized by an EEG (C3/A2) resembling the low amplitude, high frequency activity similar to that seen in waking, rapid eye movements (ROC/A1 & LOC/A2), and relative lack of muscle activity (Chin EMG), with occasional muscle twitches as seen on the right hand of the Chin EMG tracing. The stages of NREM and REM are integrated and displayed in the upper right graph as a “hypnogram” showing the descent through the stages of NREM sleep followed by an episode of REM sleep with this cycle repeating every 90 to 100 minutes throughout the night of sleep.
22. The graph depicts the circadian rhythm in core body temperature [Core Tb (deg)] over 24 hours. The circadian rhythm in humans and other mammals is driven by the circadian clock, which is anatomically in the suprachiasmatic nucleus in the hypothalamus deep in the brain. The period of this clock is genetically controlled with most humans having an intrinsic rhythm of slightly more than 24 hours. The circadian clock in the suprachiasmatic nucleus anticipates earth’s orbital dynamics. The circadian clock is entrained (synchronized) with the light/dark cycle by light exposure. The retina of the eye contains specialized (non-visual) receptors that are sensitive to blue light (they are blue sky detectors). There are circadian rhythms in core body temperature, melatonin secretion, other hormones, performance and sleep propensity. All these rhythms are roughly in synchrony. Performance is better when body temperature is rising or high and worse when body temperature is falling or low. Conversely, it is easier to fall asleep and stay asleep when body temperature is falling or low and harder to fall asleep when body temperature is rising or high. The so-called window of circadian low brackets the low point in body temperature.
23. The circadian clock in the suprachiasmatic nucleus in the hypothalamus when synchronized to the light/dark cycle serves to consolidate sleep during the light or

dark period (depending on whether the animal in question is nocturnal or diurnal). In the top half of the graph, the graph shows the circadian rhythm in sleep (top of top half) and core body temperature (bottom of top half) in a monkey with an intact suprachiasmatic nucleus. In this monkey, sleep is consolidated when body temperature is low. In the bottom half of the graph, the graph shows the loss of the circadian rhythm in sleep (top of bottom half) and core body temperature (bottom of bottom half) in a monkey whose suprachiasmatic nucleus has been selectively destroyed. In this monkey, there is no longer a circadian rhythm in body temperature and sleep spread out across the 24 hours the day/night cycle.

24. This slide shows the effects of 85 hours of total sleep deprivation on performance, measured as throughput – the product of speed and accuracy – on a serial addition subtraction task. The grey circles are the actual average performance data on the add and subtract task. The solid red line shows the linear decline in performance across the 85 hours of total sleep deprivation, with the decline in performance being approximately 17% for each successive 24 hours awake. The solid blue line shows that circadian rhythmicity modulates the linear decline in performance in a sinusoidal fashion.
25. In a study comparing the effects of varying levels of sleep deprivation with alcohol intoxication, that performance after having been awake for 24-27 hours is similar to that seen when more than legally drunk (blood alcohol concentration greater than 0.10 %). In the United States the standard for being legally drunk is blood alcohol concentration of 0.08 %.
26. The consequences of sleep restriction and sleep deprivation range across short-term, mid-term, and long-term. Short-term consequences (over minutes and hours) are error, accident, or catastrophe. Mid-term consequences (over weeks, months, and years) are bad planning, inadequate strategizing, and poor life decisions. Long-term consequences include a variety of health effects promoting chronic illness to include overweight, obesity, metabolic syndrome, sleep disorders, increased inflammation, cardiovascular disease, and high blood pressure.
27. This slide shows the effects of 85 hours of total sleep deprivation on performance, measured as throughput – the product of speed and accuracy – on a serial addition subtraction task. The grey circles are the actual average performance data on the add and subtract task. The solid red line shows the linear decline in performance across the 85 hours of total sleep deprivation, with the decline in performance being approximately 17% for each successive 24 hours awake. The solid blue line shows that circadian rhythmicity modulates the linear decline in performance in a sinusoidal fashion. In order to characterize the changes in brain activation accompanying sleep deprivation, 17 subjects were deprived of all sleep for 85 hours. We did positron emission tomography (a brain imaging technique) with fluorodeoxyglucose (FDG) as a tracer to measure regional brain glucose uptake, a correlate of regional brain activation. We



scanned our volunteers when rested, and after 24, 48, and 72 hours of sleep deprivation.

28. From well rested to 24 hours sleep deprived there was a whole brain decrease in brain activation of 6%. Larger decreases of 12-14% were in regional brain activation were found in the prefrontal cortex, parietal association cortex, and the thalamus, brain areas involved in anticipation, planning, and focused attention.
29. In a complimentary study, we examined regional brain activation using PET and radio-labeled water as the tracer, during waking, NREM, REM sleep, and subsequent waking. Brain metabolism dropped by around 30% from waking to NREM (Slow Wave) sleep, and came back to waking levels in most brain regions (except prefrontal cortex) in going from NREM to REM sleep. The prefrontal cortex (frontal areas) remain deactivated until one has been awake for 20 to 30 minutes, probably accounting for sleep inertia, the feeling of grogginess when you first wake up in the morning or from a long nap.
30. While fatigue is most easily demonstrated in the laboratory in the context of total sleep deprivation combined with adverse circadian phase and high workload, in real world operations, total sleep deprivation is rare. A much more common, ubiquitous, not to say omnipresent, problem is chronic sleep restriction, less than the optimal 8 hours of sleep/24 hours and its impact on performance over days and weeks. On average Americans sleep around 6 hours/night, averaging more or less sleep depending on gender and ethnicity, (Lauderdale, et al., 2006). To provide data for the development of mathematical models predicting performance from sleep/wake history, we investigated the effects of different degrees of sleep restriction over days in a sleep dose response study (Belenky, et al., 2003; Van Dongen, et al., 2003).
31. In this study (Belenky, et al., 2003), we studied in the laboratory a total of 68 volunteers who lived for two weeks in the laboratory. For the first 3 days (adaptation phase) all of the volunteers were allowed an 8-hour sleep opportunity (8 hours time in bed). During the adaptation phase they practiced the experimental tasks. The fourth day was baseline day for the performance on the experimental tasks. The next seven days were experimental phase in which the 68 volunteers were divided into 4 groups of 16-18 volunteers each. During the experimental phase, one group was allowed a 9-hour sleep opportunity (9 hours time in bed), another group was allowed a 7-hour sleep opportunity (7 hours time in bed), a third group was allowed a 5-hour sleep opportunity (5 hours time in bed), and the fourth group was allowed a 3-hour sleep opportunity (3 hours time in bed) on each of the nights of the experimental phase. All volunteers throughout all phases were awakened at 0700 h throughout all phases of the study.
32. This is a photo of three of our volunteers, photograph used with their permission, who are instrumented for polysomnographic sleep recording, shown on the 5th

day of the experimental phase. They were all three in the 3-hour sleep opportunity/night sleep condition.

33. This figure shows the effect of our experimental conditions on average polysomnographically scored sleep. On the baseline all 4 groups were allowed an 8-hour sleep opportunity and were on average able to obtain 7 hours of actual night time sleep. For the 7 days of the experimental phase, volunteers in the 9-hour sleep opportunity group averaged 7.9 hours of sleep of sleep each night, volunteers in the 7-hour sleep opportunity group averaged 6.3 hours of sleep each night, volunteers in the 5-hour sleep opportunity group averaged 4.7 hours of sleep each night, and volunteers in the 3-hour sleep opportunity group averaged 2.9 hours of sleep each night. During recovery, volunteers in all groups again averaged approximately 7 hours sleep during their 8-hour sleep opportunity. Thus our manipulation of sleep times during the experimental phase had the desired effect of creating different levels of sleep restriction across the experimental period. In fact we had one condition of sleep augmentation and three conditions of sleep restriction.
34. During the experimental phase (E1-E7), we found that on the psychomotor vigilance task (PVT), a test that is sensitive to sleep loss's effects on vigilance performance, there was a clear sleep dose dependent effect on performance. In the graph we depict speed on the PVT, so lower speed is worse performance. The 9-hour sleep opportunity group maintained stable performance across the days of the study. Performance in the 7-hour sleep opportunity declined over time. Performance in the 5-hour sleep opportunity group declined more. Performance in the 3-hour sleep opportunity group declined even more. Both the 5- and 7-hour sleep opportunity group appeared to decline over the first few days and then show stable although degraded performance on the PVT. In contrast, the 3-hour sleep opportunity group continued to decline across the 7 days of the experimental interval. None of the three conditions of sleep restriction recovered to baseline levels during the recovery period (R1-R3). These findings suggest that above 4 hours time in bed/night the brain can adjust and will stabilize at a lower level of performance (Belenky et al., 2003).
35. In addition to the PVT, we tested our volunteers in a driving simulator. Our volunteers were all professional drivers holding commercial drivers licenses (CDLs).
36. The performance findings were similar for the driving simulator as for the PVT. As our driving performance metric, we measured lane deviation. So, here higher deviation indicates worse performance. Again, we say sleep dose dependent degradation in performance with the 9-hour sleep opportunity group sustaining good performance across the experimental interval and the sleep-restricted groups, the 7-, 5-, and 3- hour sleep opportunity groups, degrading across the experimental interval (E1-E7). Again, the sleep restricted groups when allowed 8

hours time in bed during the recovery period (R1-R3) failed to recover to baseline levels of performance.

37. There are clear individual differences in response to sleep loss. In this figure one can see the average (in black) for the 3-hour sleep opportunity group in the sleep dose response study (Belenky, et al., 2003). Contrast this with the performance of individual subjects in this study. One subject, whose data are represented by the blue line, was unaffected by having the sleep opportunity restricted to 3 hours/night. In further contrast to the average, look at the two red lines representing two individuals who were more sensitive to sleep loss than the average.
38. In a similar study to Belenky, et al., 2003, Van Dongen, et al., 2003 also found sleep dose-dependent changes in performance. Here the sleep restriction period was 14 days and the sleep restriction was 8 hours time in bed, 6 hours time in bed or 4 hours time in bed. Here the metric is either lapses in attention on the PVT, or self-reported sleepiness on the Stanford Sleepiness Scale (SSS), so, degraded performance or increased sleepiness is seen as an increase in relative number of lapses or self-reported sleepiness. Again, there is a clear sleep dose dependent degradation in performance and increase in sleepiness.
39. The graph shows the time on task effect on the 10-minute, mid-day PVT in sleep restriction study conducted by Belenky, et al., 2003. Time on task effects are clearly visible and are amplified in a dose dependent manner such that the less sleep the larger the time on task effect. This is the speed metric (1/reaction time (RT)), so, decrease in speed indicates a degradation of PVT performance. Thus, time on task effects are similarly amplified by total sleep deprivation (shown previously) and varying levels of chronic sleep restriction.
40. As indicated earlier, operational fatigue is the outcome of the interaction of sleep loss, circadian rhythm phase, and workload. Also, as indicated above, sleep loss is not simply acute total sleep deprivation but also chronic sleep restriction. Similarly, in the operational environment, performance is largely a function of total sleep in 24 hours, relatively speaking, irrespective of how that sleep is consolidated or split. As long as total sleep in 24 hours is reasonable performance will on average be sustained.
41. This is the view from the flight deck of a Continental Airlines Boeing 777 flying over the North Pole from Newark, New Jersey to Hong Kong, China. In the view from the flight deck the North Pole is 150 miles to the left. Flight crew performance in such ultra-long range flights depends on sleep obtained before the flight, during the flight, during the layover, and during the return flight making this the ideal venue for the study of fatigue and fatigue risk management.
42. Here is an example of a sleep/wake history covering two weeks of the life and work of a Boeing 777 pilot obtained from the use of the sleep watch (wrist worn

actigraph) to measure arm movement with the arm movement record then scored for sleep and wake by specialized software. Each horizontal block is noon from one day until noon the next day. Subsequent horizontal blocks are subsequent days. Waking is marked with red underscores to the activity record. Blue boxes are flight times and the red boxes are in-flight sleep opportunities. The sleep/wake history includes sleep at home, sleep on board the 777, sleep during layover for two pairings, one ultra-long range (ULR) and one long range (LR). By inspecting this record one can see that this particular pilot slept well at home and was able to take advantage of in-flight and layover sleep opportunities, maintaining respectable amounts of sleep in each successive 24 hours across time at home, flight duty, and layover.

43. Travelling across times zones (transmeridian travel) shifts the sleep wake cycle and at least initially one is sleeping out of phase with ones normal period of high sleep propensity. The actigraph measures arm activity and the arm activity is then scored by a software algorithm for sleep or wake. Each horizontal block of activity record is noon of one day until noon the next. Each subsequent block is a subsequent 24 hour day. The actigraphy record shows a multi day trip around the world beginning on the east coast of the United States, travelling first to Germany (with mid-afternoon east coast U.S. sleep (1)), then to South West Asia (with some split sleep ( 1 & 2), then Hawaii (with some mid-morning east coast U.S. sleep (3), followed by return to the east coast of the United States (and sleep at the normal time for the east coast (4)).
44. While commercial airliners and hospitals are quite different operational venues, nevertheless pilots and physicians as human beings similarly respond to the effects of sleep loss, circadian rhythm phase, and workload in creating the state of fatigue and both are ripe areas for the application of fatigue risk management. We conducted a study of 17 physicians in training with each of these physicians working both day shift and night float (an extended night shift) (McDonald, et al., in preparation). We studied sleep as measured by the wrist worn actigraph (sleep watch) and performance as measured by the psychomotor vigilance task. The physicians wore the actigraph continuously while on day shift, night float and on days off, thus generating a continuous sleep wake history for the duration of their participation in the study. They took a PVT twice a day while working either the day shift or night float, once at the beginning and once at the end of each shift. As they day shift personnel relieved the night float personnel at the beginning of the day and the night float personnel relieved the day shift personnel at the end of the day, the PVTs for both shift were taken at roughly the same times.
45. The figure shows the wrist worn actigraph (sleep watch) and the Palm OS psychomotor vigilance task (PVT) on the left and 11-day continuous actigraph record on one of the participant's working day shift and then transitioning to night float. Each horizontal block is a 24 hour period measure from noon of one day until noon of the next. The red horizontal bars indicate computer scored sleep based on the wrist actigraphy record, with wrist activity summed over each

consecutive minute of the recording and graphed in one minute bins. The principle on which the actigraph works to measure sleep is that generally humans move much less when asleep than when awake. This difference implemented in a validated computer algorithm is used to score the records for sleep and wake and generate out of the activity record a continuous sleep wake history. From the actigraph record, one can see the physician working the day shift and sleeping at night from Monday 09/10/07 through Saturday 09/15/07 and then working night float from Sunday 09/16/07 through Thursday 09/20/07. Note that when working on day shift, the physician's sleep was largely consolidated into a single nighttime sleep bout and that in contrast that when working on night float, the physician's sleep was split between some sleep off duty during the day and some sleep while on duty at night float.

46. These graphs show the average sleep on day shift and night float for the 17 physicians in training who participated in our study. On both day shift and night float, total sleep in 24 hours was approximately 7 hours. When on day shift almost all of the sleep was obtained off shift at night. When on night float approximately 4 hours of sleep was obtained off shift during the day and another approximately 3 hours of sleep was obtained on shift at night. This was not planned. Physicians on night float will take advantage of lulls in activity to take unscheduled naps. In doing this, our study participant were able to maintain total sleep times of an average of 7 hours while on night float similar to what they obtained while working day shift. On the psychomotor vigilance task that the physicians-in-training took when going on shift and going off shift, there vigilance performance was the same when on night float as on day shift.
47. The figure shows some systematic experimental work also showing that split and consolidated sleep are equivalent in their effects on performance (Mollicone, et al., 2007, 2008). Attentional lapses on the psychomotor vigilance task are shown on the vertical axis as a function of nocturnal (night-time) anchor sleep (4.2-8.2 hours time in bed) plus diurnal (daytime) nap sleep (0.0 to 2.4 hours time in bed). The graphic shows stable performance as a function of total sleep time irrespective of how the sleep was split.
48. Sleep can be consolidated (one sleep bout/24 hours), split (two or three sleep bouts/24 hours), or fragmented (punctuated by awakenings every 2-3 minutes) (see Bonnet & Arand, 2003). Whereas split sleep can retain its recuperative value, highly fragmented sleep virtually abolishes recuperative value. The cross over point at which a bout of sleep appears to sustain the same recuperative value minute by minute as fully consolidated sleep appears to be about 20 minutes. Thus if sleep is fragmented, broken by a brief awakening, every 20 minutes (3 times an hour) its minute by minute recuperative value will be the same as it is for fully consolidated sleep, e.g., 8 hours of sleep without awakening.

49. Sleep is a function of sleeping position with the longest most continuous sleep obtained when lying flat. In this graph, one can see that the highest sleep efficiency, the greatest % of the sleep opportunity asleep. The closer to vertical the sleeping position, the less the sleep obtained. This is thought to be because in the more vertical the sleep position the greater the sympathetic nervous system (adrenalin/norepinephrine) release necessary to maintain blood flow to the head. Seat angles were flat, 49.5 degrees of vertical, 37 degrees off vertical, and finally 17.5 degrees off vertical. The sleep opportunity was 8 hours long and occurred at night.
50. In these experiments with different seating angles and subsequent sleep, the sleep opportunity was 8 hours. Above are the hypnograms from one of the 9 subjects. Note that although the sleep amounts varied over the 8 hours depending on seat angle, for this particular subject the sleep in the first two hours was similar across seat angle conditions suggesting the possibility that for short sleep (2 hours or less) at a sleep propitious time of day (normal bedtime) seating angle may make less of a difference.
51. Other countermeasures that would be effective in mitigating fatigue include stimulant drugs, sleep inducing drugs to facilitate sleep at non-sleep-conducive times of day, bright (especially blue) light, strict environmental control of light, noise, and temperature in the sleeping environment, and ensuring that all flight crew approach flight time adequately rested.
52. This is one of the few studies comparing the relative effects of different stimulant drugs under conditions of total sleep deprivation. In this study drug (d-Amphetamine, Caffeine, Modafinil, or Placebo) was given a little before midnight after 65 hours of total sleep deprivation. Note that for the first two hours, in comparison to placebo, all three of the stimulant drugs improved performance.
53. In a similar study, three doses of modafinil (100 mg, 200 mg, and 400 mg) were compared to caffeine 600mg and placebo. Again for the first two hours the three doses of modafinil and one dose of caffeine substantially improved performance after roughly 42 hours without sleep.
54. Nil
55. Nil
56. In the crash of American International Flight 808 at Guantanamo, the flight crew had been awake for approximately 18 hours prior to the crash. The chose the more difficult approach (red arrow) "for the experience." The hard right banking turn was the more difficult because of the danger of stalling the right wing in the turn.
57. The plane did, in fact, stall and crash. But fortunately, all survived.

58. Depicted in the photos is the hard right banking turn. Note the black, burnt area, which is the crash site.
59. The figure above represents the reconstructed sleep wake histories of the flight crew by the solid blue bars. They had been up all night and were awake through the time of the crash a little after 1600 h. The time of the crash is indicated on the figure by the red arrow. The sleep wake histories were used as input to the SAFTE/FAST sleep performance prediction model and predicted the effectiveness of the flight crew at the time of the crash. For the Captain, who was the flying pilot, the predicted effectiveness at the time of the crash was 71%.
60. This is a transcript of the conversation from that crew as they approached the landing strip. The “strobe” light that the Captain is referring to is a marker on the ground that shows where the Cuban airspace starts. Actually, the strobe was not working on this day.

The Captain's dialogue is red. The Engineer and Co-Pilot's dialogue is in black. This transcript provides excellent insight into one of the cognitive deficits that characterizes sleep loss: Perseveration. Note that even though he was clearly warned that his airspeed was dangerously slow, the Captain kept looking for the strobe, rather than focusing on the primary task of keeping the aircraft aloft. The Captain persisted (perseverated in psychological terms) in searching for the strobe light ignoring the basics of aviation to in order of priority aviate, navigate, communicate. He was navigating and failed to aviate.

61. In the opinion of the NTSB, even when the aircraft had stalled, the Captain could have recovered the aircraft had he taken the appropriate action. Perseveration is characteristic of dysfunction of the prefrontal cortex, the brain area responsible for anticipation, judgment, and planning. As our imaging work has shown, the prefrontal cortex is deactivated more than other brain areas in sleep deprivation. Thus, the Captain's perseveration, his persistence in searching for the strobe beacon, is consistent with our understanding of the neurobiology of sleep loss.
62. Nil
63. The Harvard group studied physicians in post-graduate training (interns and residents) in the traditional schedule which allows for 36 hour shifts in the hospital and compared it to an intervention schedule in which in-hospital shifts were limited to a maximum of 16 hours.
64. The effect of the intervention schedule was to reduce the hours worked/week from 85 to 65 and increase average total sleep time from 6.6 to 7.4 hours/24 hours.

65. The intervention schedule had dramatic effects with serious medical errors reduced from 136/1000 patient days to 100/1000 patient days. There was an even more dramatic selective decrease in diagnostic errors which were reduced from 18.6/1000 patient days to 3.3/1000 patient days.
66. Others studies complemented with survey data the findings of the differences between the traditional and intervention schedule. In post-doctoral physicians working extended (greater than 24 hour shifts) vs. normal days shifts, there were more reported crashes, near misses, and fall asleep driving accidents, more reported significant medical errors, attentional failures, and fatigue-related preventable adverse events resulting in a fatality and, finally, more needle stick injuries.
67. Nil
68. In the Comair 5191 crash in Lexington, KY, flight crew became misoriented to the airport, were not corrected by the air traffic controller, and attempted take off from the wrong runway, a general aviation runway that was much to short for their aircraft. The plane crashed at the end of the runway killing all but one on board.
69. Comair 5191 crashed at approximately 0600 h. The Air Traffic Controller had worked an early morning shift the day before (0630-1430 h). He had the mandated by regulation 8 hours off and went back on duty at 2330 h. He was scheduled to work through to 0700 h the morning of the crash. Thus he was sleep deprived and working at an adverse circadian phase at the time of the crash. The Captain and First Officer had an early start restricting their total sleep opportunity and were also working at an adverse circadian phase. Thus the Air Traffic controller and the Captain and First Officer were sleep deprived and working at adverse circadian phase at the time of the crash. While we cannot say that fatigue played a role in the choice of the wrong runway, it seems likely that had the personnel involved been less fatigued (a function of sleep loss and adverse circadian phase) they might have realized their error in time to correct it.
70. Nil
71. We used the SAFTE/FAST performance prediction model to reconstruct an incident in which sleep deprivation-impaired judgment led to a catastrophic event. In this instance, the U.S. Army charged a Non-Commissioned Officer (NCO) with negligent homicide in the death of another soldier. The NCO faced a court martial on this charge. The figure shows the timeline of the events leading to the incident. Prior to the incident, the NCO was involved in a field training exercise (FTX). Going into the exercise, by his own self-report the NCO averaged about 6.5 hours sleep per night. During the training exercise, the NCO left the exercise to attend a funeral. He managed only a few hours of sleep before returning to the training exercise. Following his return to the exercise, the NCO volunteered to



take all-night duty. He was active all the next day and by evening was laying obstacles for the next day's training exercise.

72. Upon returning to training, the NCO helped lay two obstacles across a road, about a mile apart, and separated by a hill. After the second obstacle was laid, a couple of soldiers asked the NCO to ferry them to Obstacle 1 by motorcycle. The sleep-deprived NCO took off with one of the soldiers. He navigated the incline of the hill without incident. However, rather than anticipate the obstacle ahead and appropriately adjust his motorcycle speed, he was looking for this path off to the left which he was going to use as a shortcut back to Obstacle 1. It turns out he missed the path without realizing it, and continued to barrel forward toward the obstacle. He finally either realized or saw the obstacle ahead of him, and tried to stop the motorcycle. However, this realization came too late, and the motorcycle, the NCO, and his passenger ploughed into the obstacle. One of the stakes used to secure the concertina wire was pulled free and hit the passenger on the back of the head, killing him.
73. Here we illustrated the NCO's predicted performance across the 3 days preceding the incident, based on his sleep/wake history. This is compared to a performance prediction had he been obtaining 8 hours of sleep per night. By the time the accident occurred, the NCO's predicted mental performance was 14% below where he was on the previous day, and 24% below where he would have been with 8 hours sleep per night. This incident demonstrated a failure in the highest-order mental capacities, due to lack of sleep. In this instance, the ability to anticipate and adjust behavior accordingly was severely impaired, this time with devastating and fatal consequences. The NCO was acquitted on charges of negligent homicide, and the incident went down as a training-related accident.
74. Nil
75. There are clear trait-like, enduring individual differences in sensitivity to sleep loss. In the left hand figure shows the average performance over 40 hours of wakefulness of 8 less vulnerable individuals (in green) and 7 more vulnerable individuals (in blue). Demonstrating the persistence (and hence trait-like) of either sensitivity and vulnerability, the right hand figure the consistency in sensitivity/vulnerability (compare the dark blue diamonds to the turquoise squares) from one sleep deprivation bout to one months later.
76. Despite the differences in individual vulnerability of performance to sleep loss (left figure), this is not reflected in self-perceived subjective sleepiness (right figure). Thus one's own subjective sense of sleepiness is no predictor of how one is actually performing.
77. U.S. Air Force F-117 Stealth Fighter Bomber pilots are both highly selected and highly self-selected and yet they also show the same range of individual

differences in performance vulnerability/sensitivity to sleep loss (left figure and right figure).

78. Using Bayesian statistical techniques it is possible to transform a group average model (green curve in left two figures) into an individualized prediction for a given individual (red curves in right two figures).
79. The figures shows an actigraphically recorded continuous activity record (gray lines), the actigraph record scored for sleep/wake history (red lines), and the performance prediction (blue curve) when the sleep/wake history is used as input to a sleep/performance prediction model. Note the actigraphically-recorded nap (break in gray lines) and the increase in the predicted performance subsequent to it (blue curve).
80. This is the circadian rhythm in core body temperature. Performance follows this curve, rising as body temperature rises and falling as body temperature falls. It is the mirror image of sleep propensity, which rises as body temperature falls and falls as body temperature rises.
81. The top figure represents the normal hypnogram of sleep stages with sleep onset at approximately 2330 and awakening at approximately 0730. The lower figure (on the same horizontal scale) shows a shift worker's sleep/wake cycle with split as opposed to consolidated sleep. There is some napping sleep while on shift, a main but truncated bout of sleep in the morning hours and a late afternoon nap. Since it is total sleep time in 24 hours that largely determines performance a napping strategy entailing split sleep can sustain reasonable performance in the face of shift work, extended work hours, and back side of the clock operation.
82. Nil
83. We are entering an age of personal biomedical status monitoring in which we will be embedded in robotic systems that will monitor us, assist us, and sustain us. The flight deck of a modern commercial jet aircraft is just such an environment.
84. Such monitoring will include actigraphic assessment of sleep/wake history and assessment by some technology as yet to be determined of circadian rhythm phase angle and amplitude. These quantitative assessments will be used as input to mathematical models instantiating sleep science and predicting performance. Such models will be validated against metrics of operational performance including both embedded (e.g., FOQA) and added metrics (e.g., PVT). Validated model predictions for individual pilots can be integrated into the optimization function of rostering and scheduling software optimizing against other constraints (e.g., flight duty time limitations, labor management agreements, etc.) providing in effect turnkey fatigue risk management.

85. This shows an actigraph record that clearly demarcates periods of sleep from periods of wakefulness. One such period of sleep is marked by the red box with one such period of wakefulness marked by a blue box.
86. We show in this figure response-by-response performance on the 10-minute PVT. This subject manages to make roughly 70 responses on the 10-minute PVT. Note that even in the well-rested condition after 12 hours awake following a normal night of sleep there are still some slowed responses toward the end of the 10-minute test. A few of these are overt lapses (response time greater than 500 milliseconds (indicating a failure in attention)).
87. Here is an example of a sleep/wake history covering two weeks of the life and work of a Boeing 777 pilot obtained from the use of the sleep watch (wrist worn actigraph) to measure arm movement with the arm movement record then scored for sleep and wake by specialized software. Each horizontal block is noon from one day until noon the next day. Subsequent horizontal blocks are subsequent days. Waking is marked with red underscores to the activity record. Blue boxes are flight times and the red boxes are in-flight sleep opportunities. The sleep/wake history includes sleep at home, sleep on board the 777, sleep during layover for two pairings, one ultra-long range (ULR) and one long range (LR). By inspecting this record one can see that this particular pilot slept well at home and was able to take advantage of in-flight and layover sleep opportunities, maintaining respectable amounts of sleep in each successive 24 hours.
88. The graphic shows a schematic of a fatigue risk management mathematical model (alertness model) integrated into industrial strength rostering and scheduling software used in commercial aviation. Pilots available and flights to staff are brought together through software that optimizes assignments taking into consideration flight time limits, labor agreements, and other constraints, now with the addition of the alertness model to ensure that flight assignments are fatigue friendly in addition to meeting the other requirements. A series of scenarios based on the above are presented in the 4 following graphics.
89. In Scenario 1, flight time limits are applied but labor agreements and the alertness model are not to yield the base (reference) case.
90. In Scenario 2, flight time limits and labor agreements are applied but the alertness model is not applied to yield the current case - flight time limits and labor agreements enforced but no formal consideration of fatigue is undertaken. This yields a small improvement in alertness for the most fatiguing flights and reduces overall productivity of the schedule.
91. In Scenario 3, flight time limits, labor agreements, and the alertness model are all applied. This a further improvement in alertness for the most fatiguing flights and some improvement in alertness over all flights with a similar-to-Scenario 2 reduction in overall productivity of the schedule.

92. Scenario 4 is the most radical. In Scenario 4, neither flight time limits nor labor agreements are applied, just the alertness model. In effect, the model becomes the rule, replacing flight time limits and labor agreements. This yields a still further improvement in alertness for the most fatiguing flights, some small improvement in alertness for all flights, and a small improvement in productivity of the schedule over the base (reference) case
93. Making an analogy to managing fuel in a mechanized infantry battalion, sleep becomes an item of resupply. One can measure how much sleep is on hand, soldier by soldier, using actigraphy, match this against mission requirements, and plan for the intelligent and timely resupply of sleep.
94. Integrating fatigue risk management into rostering and scheduling software for its fullest implementation will likely depend upon the development of personal biomedical status monitoring. This would involve 1) the measurement of sleep and waking (sleep/wake history) to detect sleep loss and to total up sleep obtained in every 24 hours probably by means of sleep watch (actigraph; 2) the measurement of circadian rhythm phase and amplitude by some technology yet to be developed; and 3) the use of these metrics as inputs to a mathematical model predicting performance from these metrics. The predictions could be validated against measures of real world performance such as FOQA in commercial aviation or lane deviation in commercial trucking. These metrics and models would be integrated into the optimization function of commercially available rostering and scheduling software, e.g., Carmen, so schedules would be optimized against fatigue in addition to other constraints like flight time limitations.
95. Fatigue risk management should be embedded within the corporate structure of safety management, as it is a safety management system.
96. In one conceptualization, a fatigue risk management system (FRMS) is a multi-tiered, defense in depth against fatigue risk (Dawson and McCulloch, 2005). Tier 1 using computer-based rostering and scheduling with integrated predictive modeling ensures that there is adequate opportunity both in terms of duration and placement with respect to the circadian rhythm of sleep propensity. Tier 2 using self-report and the wrist-worn actigraph ensures that personnel make adequate use of the sleep opportunity available. Tier 3 using self-report, co-worker report, and added (e.g., PVT) and embedded (e.g., FOQA) objective performance metrics.
97. Nil