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Developing the 'Fatigue Impairment Prediction Suite'

An R Package for Implementing Bio-Mathematical Models

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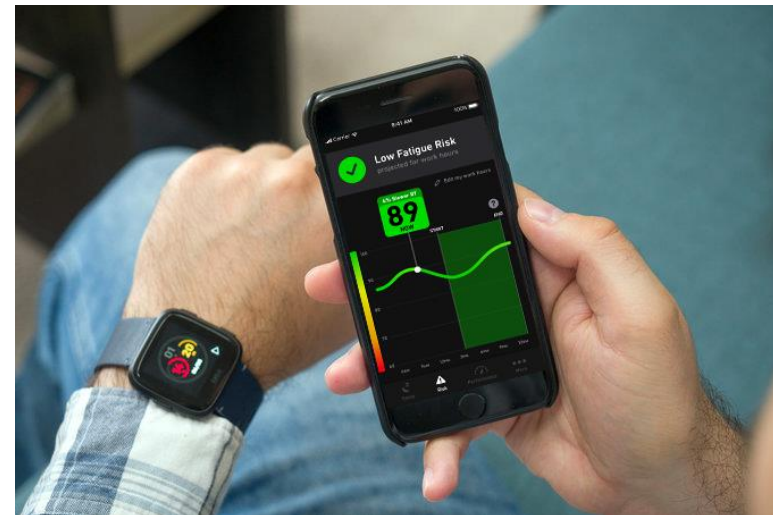
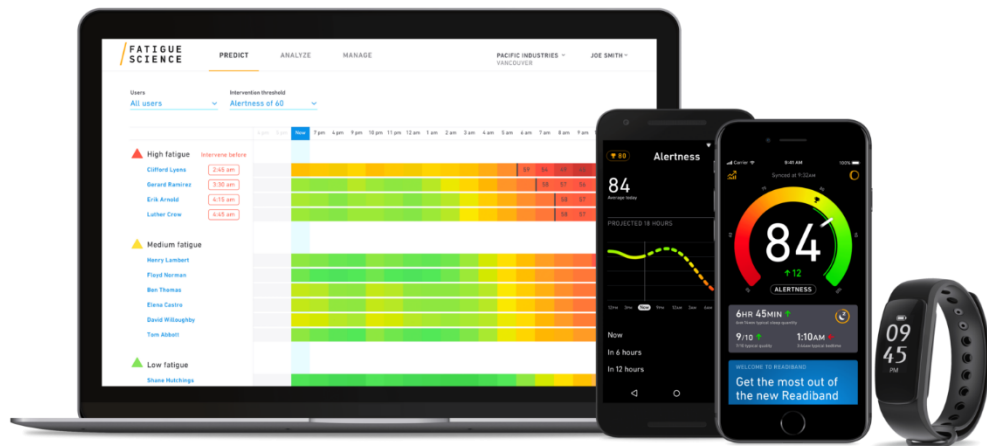
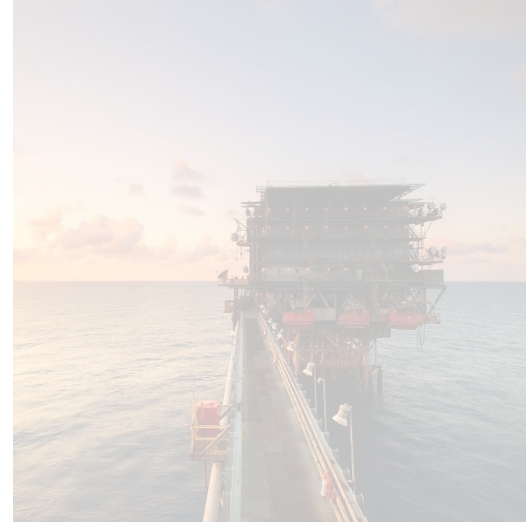
Outline

1. Brief overview/refresher on fatigue research
2. Introduction to biomathematical model mechanics
3. *Fatigue Impairment Prediction Suite* (FIPS)

Endurance and Fatigue

- Fatigue is a crucial factor underlying endurance
- A physiological state of reduced mental or physical performance capability
- **Fatigue** arises from multiple often interacting factors
 - Endogenous biological processes – circadian rhythm.
 - Sleep deprivation (acute and chronic)
 - Task factors and motivation (Hockey & Earle, 2006)
- Significant research has associated fatigue with
 - **Neurobehavioral deficits**, posing risks to operational safety and effectiveness.
 - **Decision-making capabilities** (Killgore, Balkin, & Wesensten, 2006)
 - **Increased risk of human error**, including in military settings (Miller, Matsangas, & Shattuck, 2008)
- *Terminology: Fatigue; Sleepiness; Fatigue-related performance; Alertness*

Fatigue Risk Management Systems



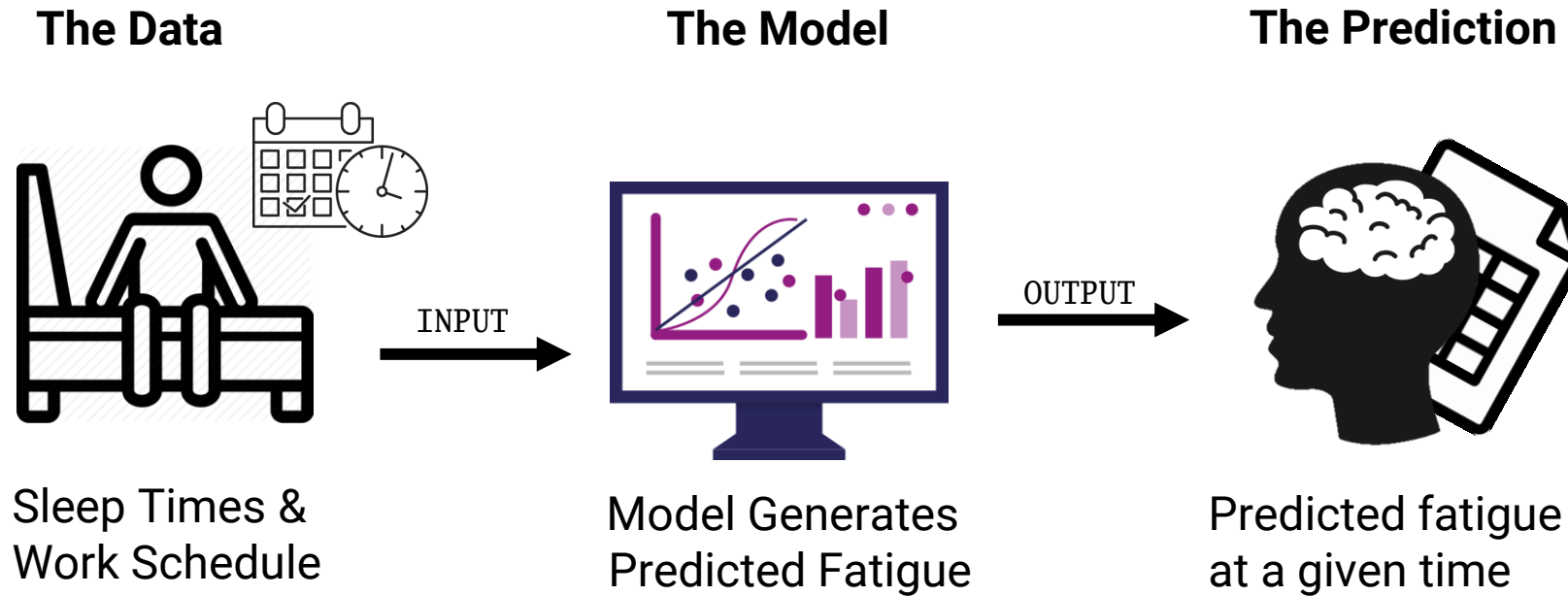
A photograph of a vast ocean with dark blue water and white-capped waves crashing over dark rocks. The sky is a pale, hazy blue. A white rectangular box is superimposed over the center of the image, containing the title text.

Biomathematical Models

What are BMMs?

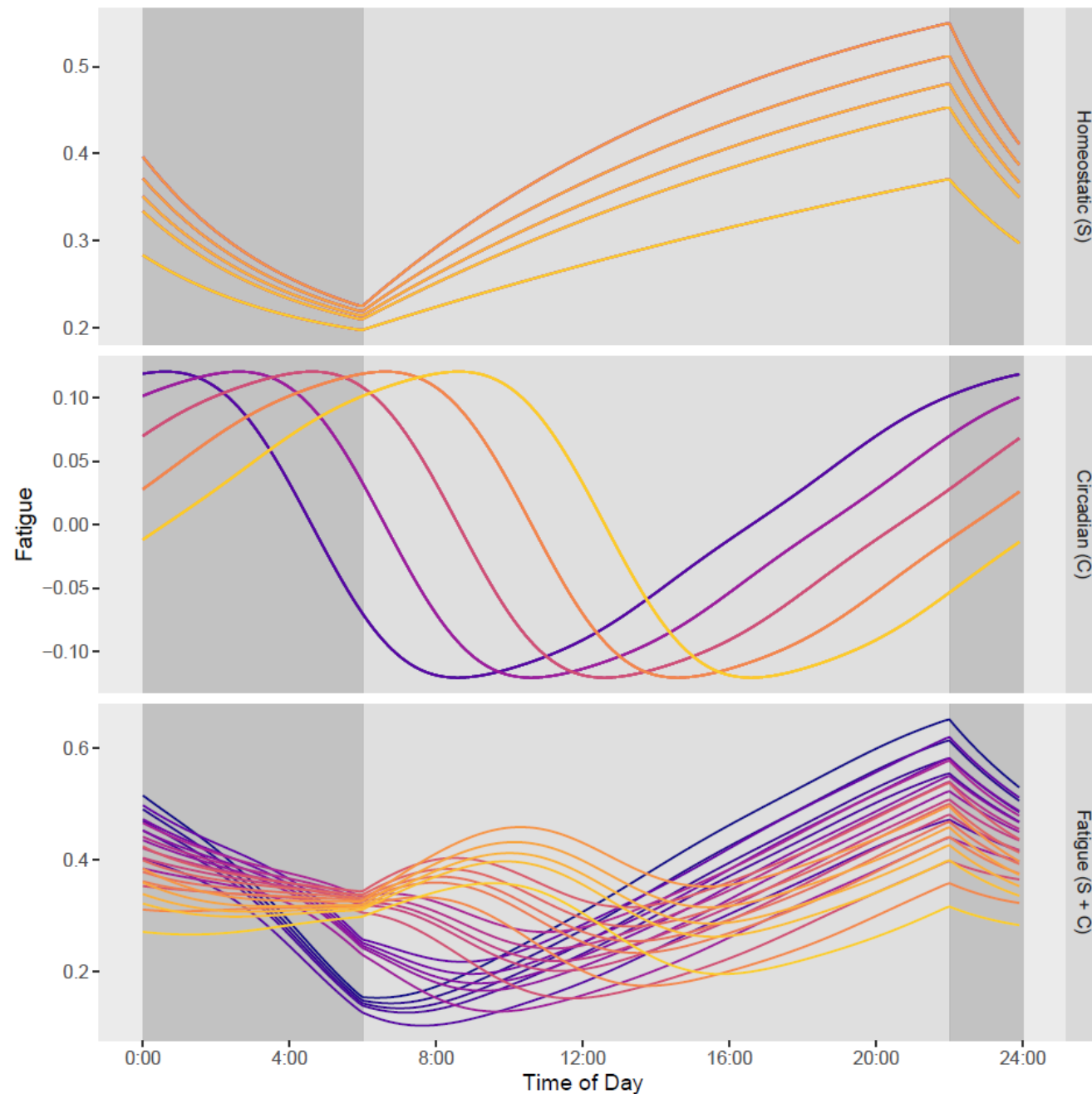
- Biomathematical Models of Fatigue
- Dynamic models for predicting “fatigue-related impairments”
- Take in sleep schedule, output predicted fatigue [or equivalent].
- Several peer reviewed and publicly available models:
 - Two & Three Process Models of Alertness (Borbély, 1982; Ingre et al., 2014)
 - Unified Model (Rajdev, Ramakrishnan at colleagues., 2013, 2015, 2016)
- Many commercialised ‘black-box’ proprietary tools in circulation:
 - SAFTE-based model (note some model formulations published)
 - *FAID* model
 - *CAS*, *BAM*

Basic Mechanics of Fatigue BMMs



Two Process Model: Basic Mechanics

- Majority of BMMs derived from Borbély's (1982) - '*Two-Process Model*'
 - Two core functions/processes
 - $S + C = \text{Alertness/Fatigue}$
- Parameters normally fixed, but variation shown in plots.



Limitations of BMMs

- Fixed model parameters derived from populations/averages
- Average model may not be representative of any individual within the sample (Ly et al., 2017)
- Conventional BMMs developed using short-term sleep deprivation studies
- Parameters rarely estimated in practice

Closed Source!

Most proprietary tools are closed source

*“Why **exactly** did a model make a particular prediction?”*

“How can I conduct independent model validation?”

“What normalisation was conducted on predicted values?”



Introduction to FIPS Package

- *Fatigue Impairment Prediction Suite* (FIPS)
- Implemented in R.
- Aims to provide a comprehensive set of functions for estimating and applying bio-mathematical models (BMMs) of fatigue.
- Open Source (likely GPL v3.0)



Planned 0.1.0 Release: Q1 2020
Planned 0.2.0 Release: Q2 2020

FIPS Feature Comparison

- FIPS is a **framework** for BMM
 - Implements *multiple* models
 - Supports parameter estimation
 - Allows simulation and prediction
 - Extendable and introspectable (to be built upon)
- Alternatives (e.g., FAID, SAFTE):
 - Provide modelling tool
 - Implements single model
 - Prediction only

Simulation Interface: Run Simulation

la	2.4000
ha	14.3000
d	-0.0353
g	-0.3814
bl	12.2000
Cm	0.0000
Ca	2.5000
p	16.8000
Um	-0.5000
Ua	0.5000
Wc	-5.7200
Wd	-1.5100
S0	7.9600

Parameter vector

+

	sleep.start	sleep.end	sleep.id
1	2018-05-21 01:00:00	2018-05-21 08:00:00	1
2	2018-05-21 18:00:00	2018-05-22 01:00:00	2
3	2018-05-22 11:00:00	2018-05-22 18:00:00	3
4	2018-05-23 04:00:00	2018-05-23 11:00:00	4
5	2018-05-23 21:00:00	2018-05-24 04:00:00	5
6	2018-05-24 14:00:00	2018-05-24 21:00:00	6
7	2018-05-25 07:00:00	2018-05-25 14:00:00	7
8	2018-05-26 00:00:00	2018-05-26 07:00:00	8

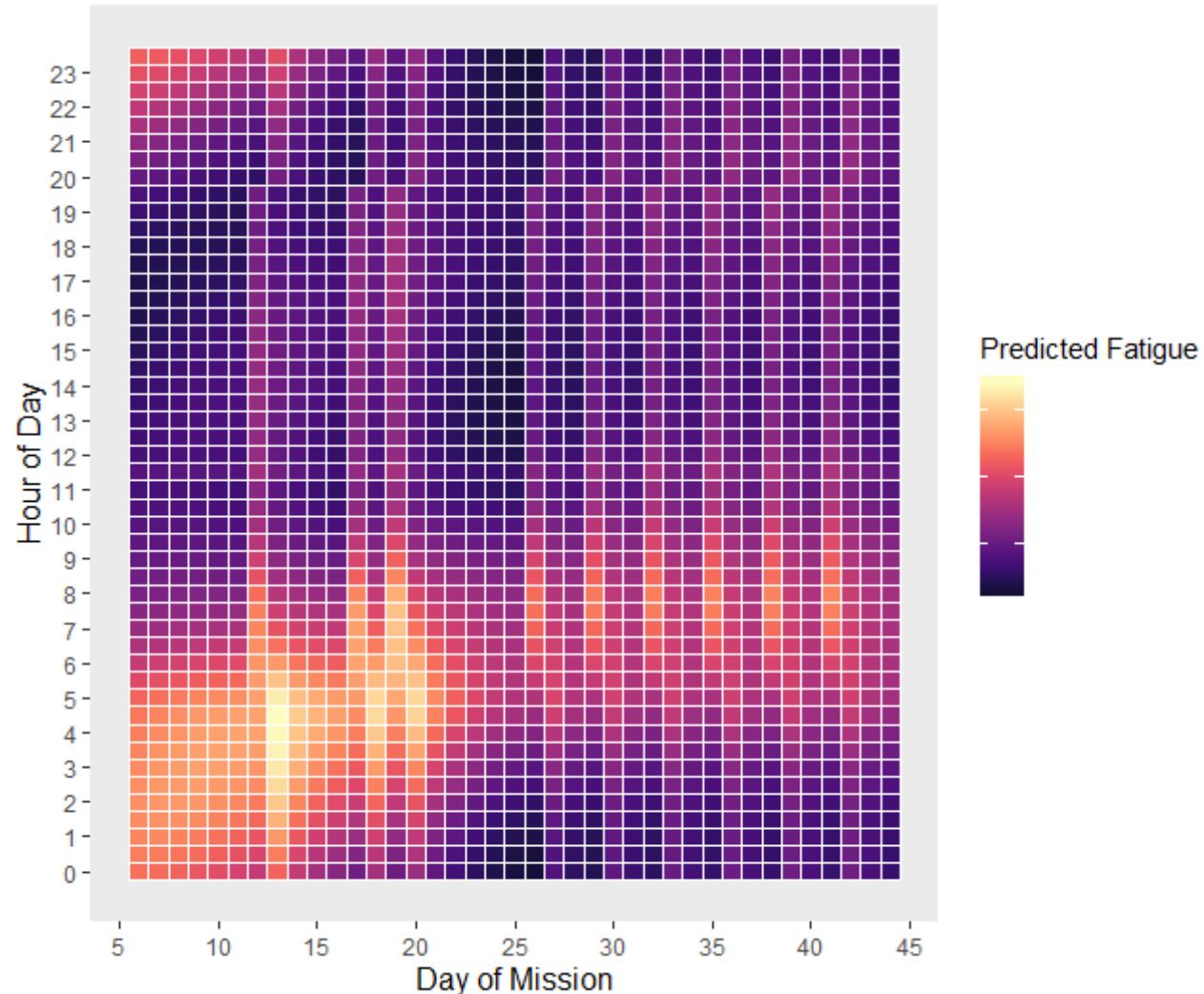
Sleep history information

Simulation Interface: Run Simulation

	datetime	s	l	c	w	u	alertness	KSS
1	2018-05-20 01:00:00	7.960	NA	-1.36160	-5.720e+00	-9.568e-01	5.642	7.215
2	2018-05-20 01:05:00	7.944	NA	-1.40701	-5.044e+00	-9.652e-01	5.571	7.257
3	2018-05-20 01:10:00	7.927	NA	-1.45176	-4.447e+00	-9.728e-01	5.503	7.298
4	2018-05-20 01:15:00	7.911	NA	-1.49581	-3.921e+00	-9.794e-01	5.436	7.338
5	2018-05-20 01:20:00	7.895	NA	-1.53915	-3.458e+00	-9.851e-01	5.371	7.378
6	2018-05-20 01:25:00	7.879	NA	-1.58176	-3.049e+00	-9.900e-01	5.307	7.416
7	2018-05-20 01:30:00	7.863	NA	-1.62362	-2.688e+00	-9.938e-01	5.245	7.453

Forecasting Fatigue with FIPS

- Built-in visualisation methods
- Summary statistics



Estimating the Parameters

- All simulations here used fixed parameters
- FIPS can perform parameter estimation
 - Additionally requires fatigue measurements (i.e., PVT)
- **Enables individualised and tailored predictions**

	LOOIC	WAIC
2PM Regression	1576.30 (25.73)	1576.29 (25.73)
2PM Group Estimates	1566.34 (25.54)	1566.30 (25.53)
2PM Individual Estimates	1490.78 (29.64)	1480.32 (30.11)



la	2.4000
ha	14.3000
d	-0.0353
g	-0.3814
bl	12.2000
Cm	0.0000
Ca	2.5000
p	16.8000
Um	-0.5000
Ua	0.5000
Wc	-5.7200
Wd	-1.5100
S0	7.9600

Performance Evaluation

- Data from 43 naval crew over 7-14 day periods (active mission)
 - Full sleep history information (objective)
 - Sleepiness 1-9 (KSS)
 - 10-40 observations per person.
- FIPS is not a model itself, it implements others.
- Two-process model in FIPS compared to SAFTE-FAST

**Human
Neurobiology**

© Springer-Verlag 1982



A Two Process Model of Sleep Regulation

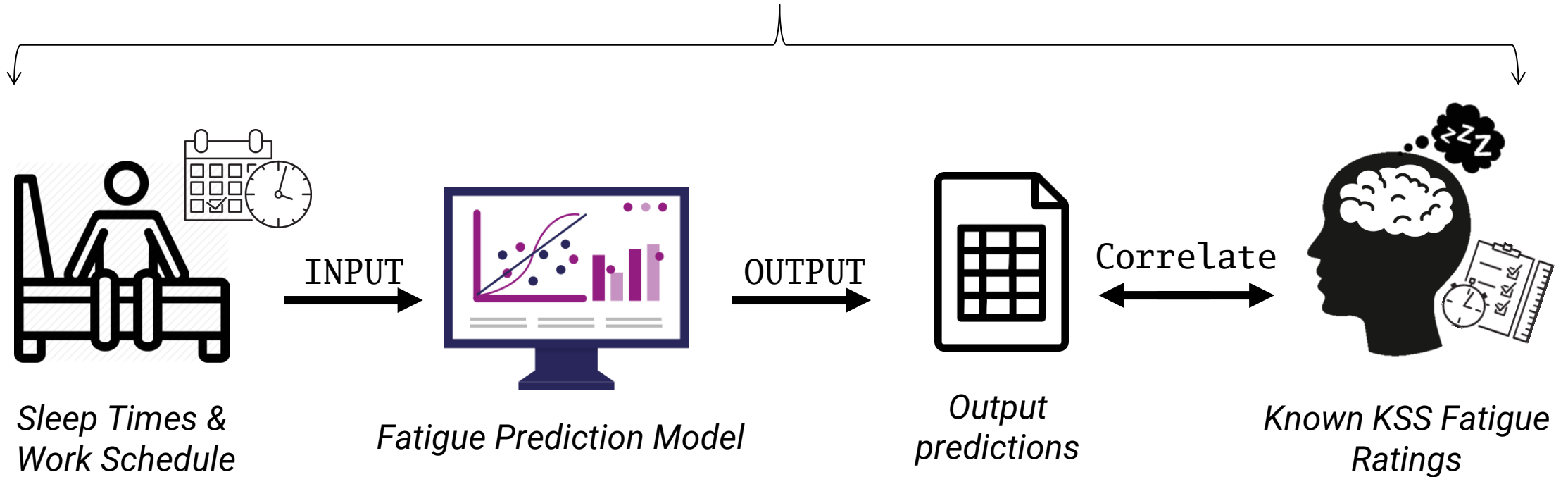
A.A. Borbély

Institute of Pharmacology, University of Zürich, Zürich, Switzerland



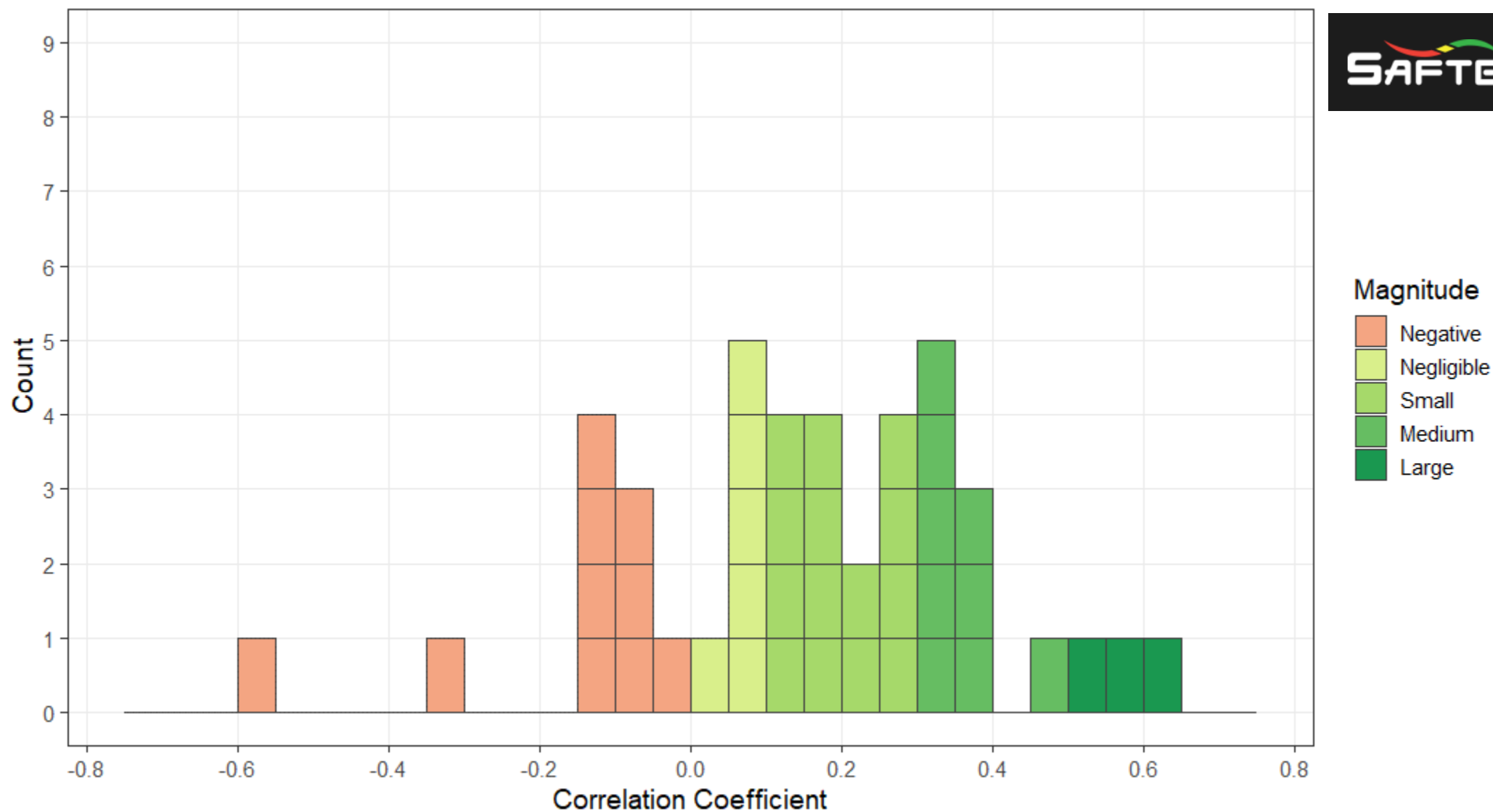
Step 1: Generating Model Predictions

For each participant & each model



1 correlation per person and model

SAFTE-FAST Performance

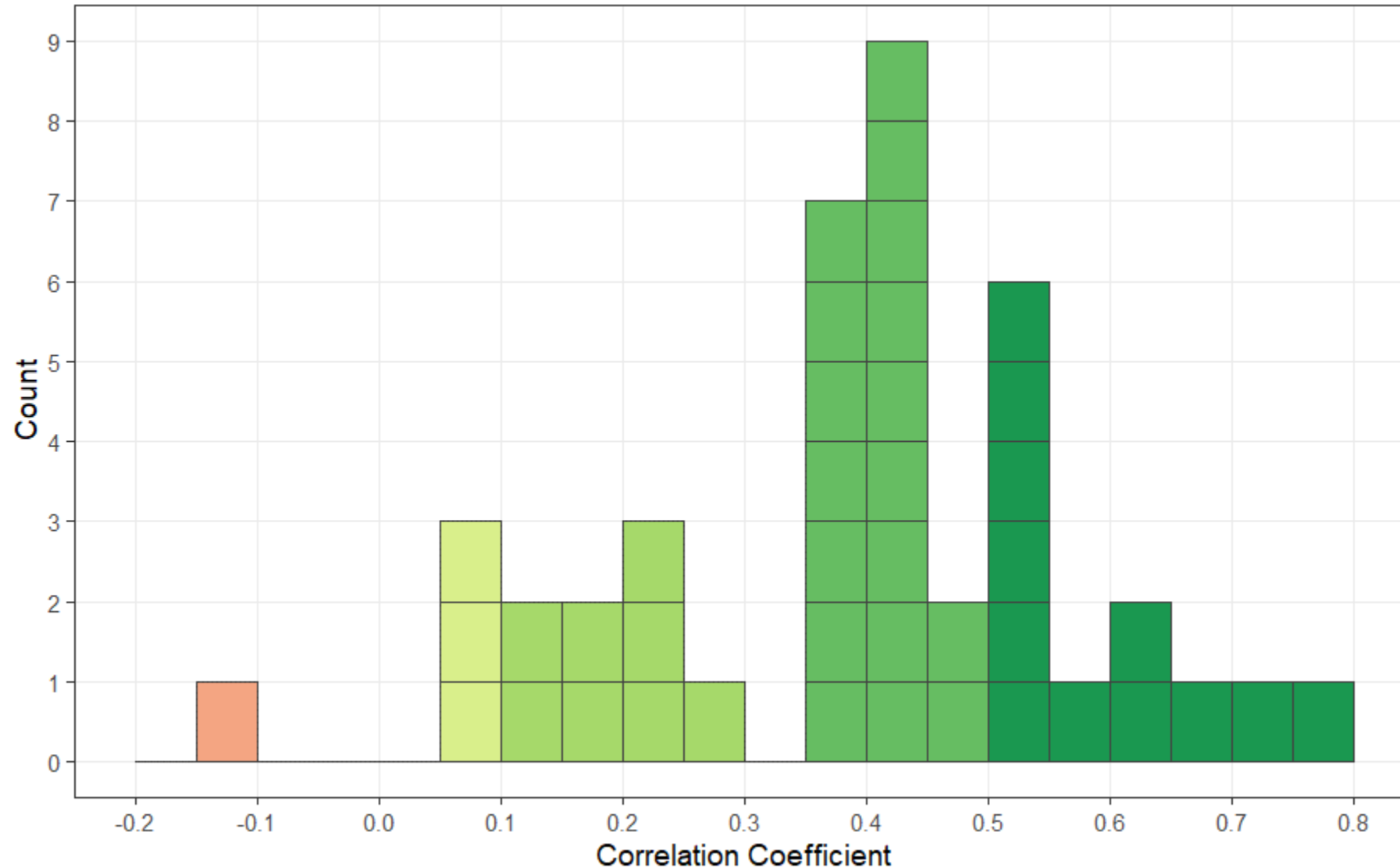


Two Process Model Performance



**Human
Neurobiology**

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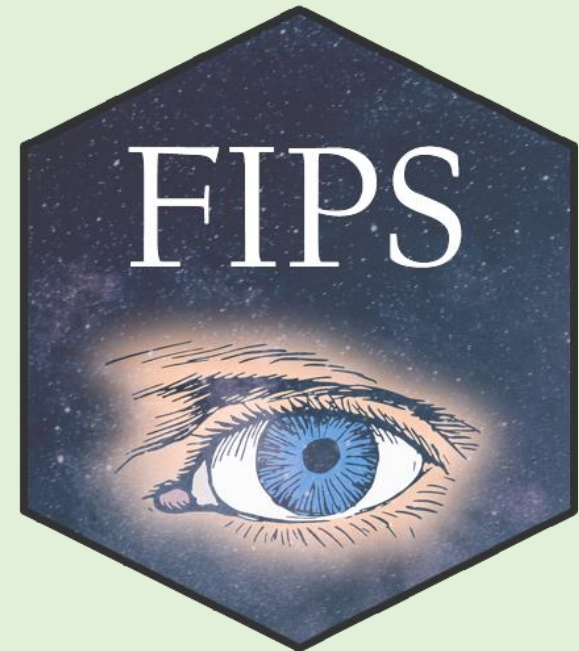


Immediate Conclusions

- Proprietary models are seriously limited by their closed nature
- BMMs must be **introspectable** and **transparent** if we seriously want to **depend** on their predictions in novel contexts
- Parameter estimation not just scientific
- Ultimate approach involves tailoring parameters
 - 'Model training' prior to prediction (requiring measurement).
 - Domain / Watch / Job Role / Individual

FIPS Moving Forward

- **Attract industry, researcher, and practitioner interest.**
- Refine Bayesian parameter estimation procedures
- Improve GUI version of application (stretch goal)
- Increase validation datasets with industry samples



Thankyou – Question Time

Summary

- Biomathematical models enable fatigue forecasting
- Widely implemented, but limited.
- FIPS is a framework for developing these models.

Contact Information

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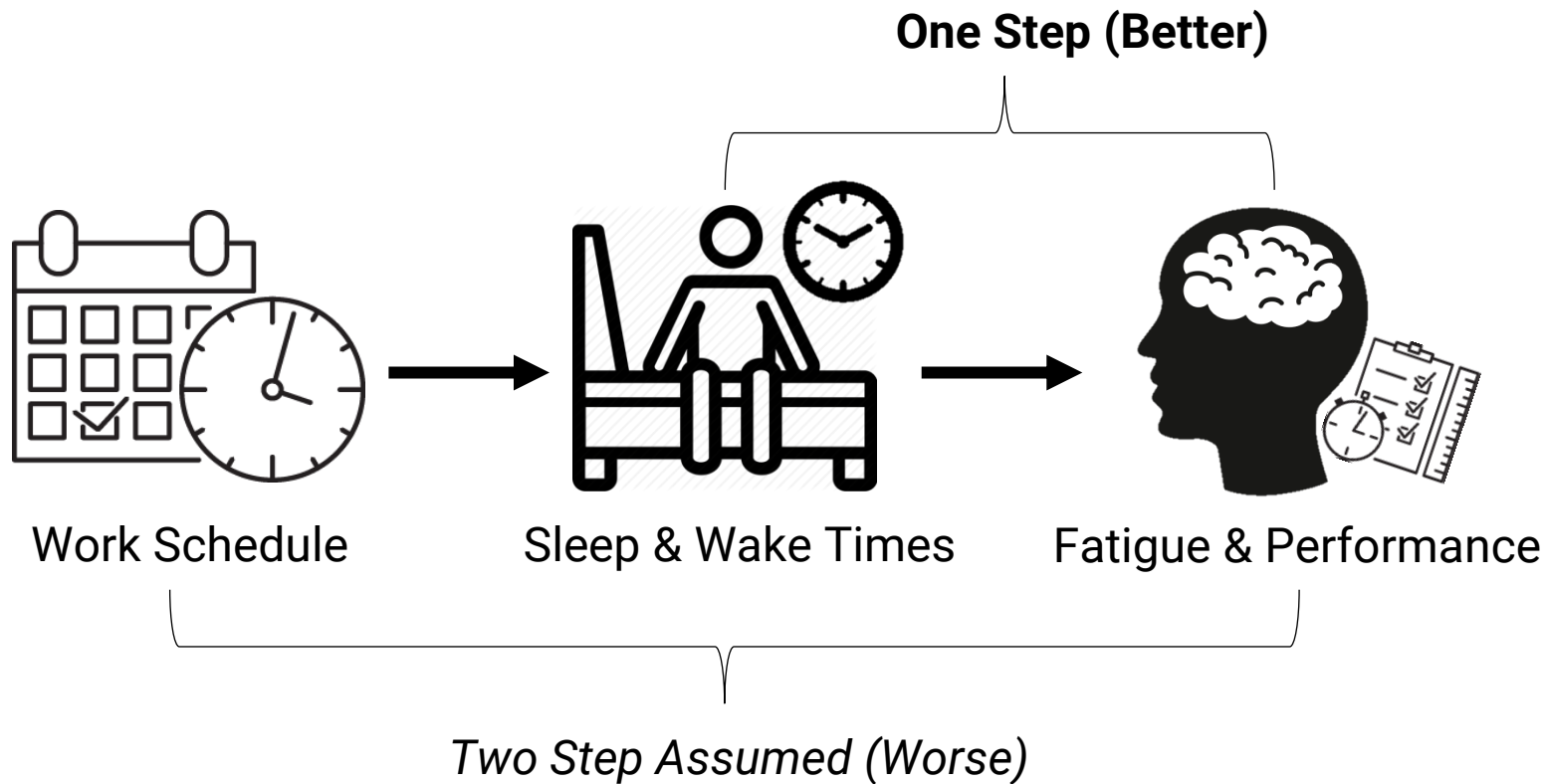
 @humanfactorsio



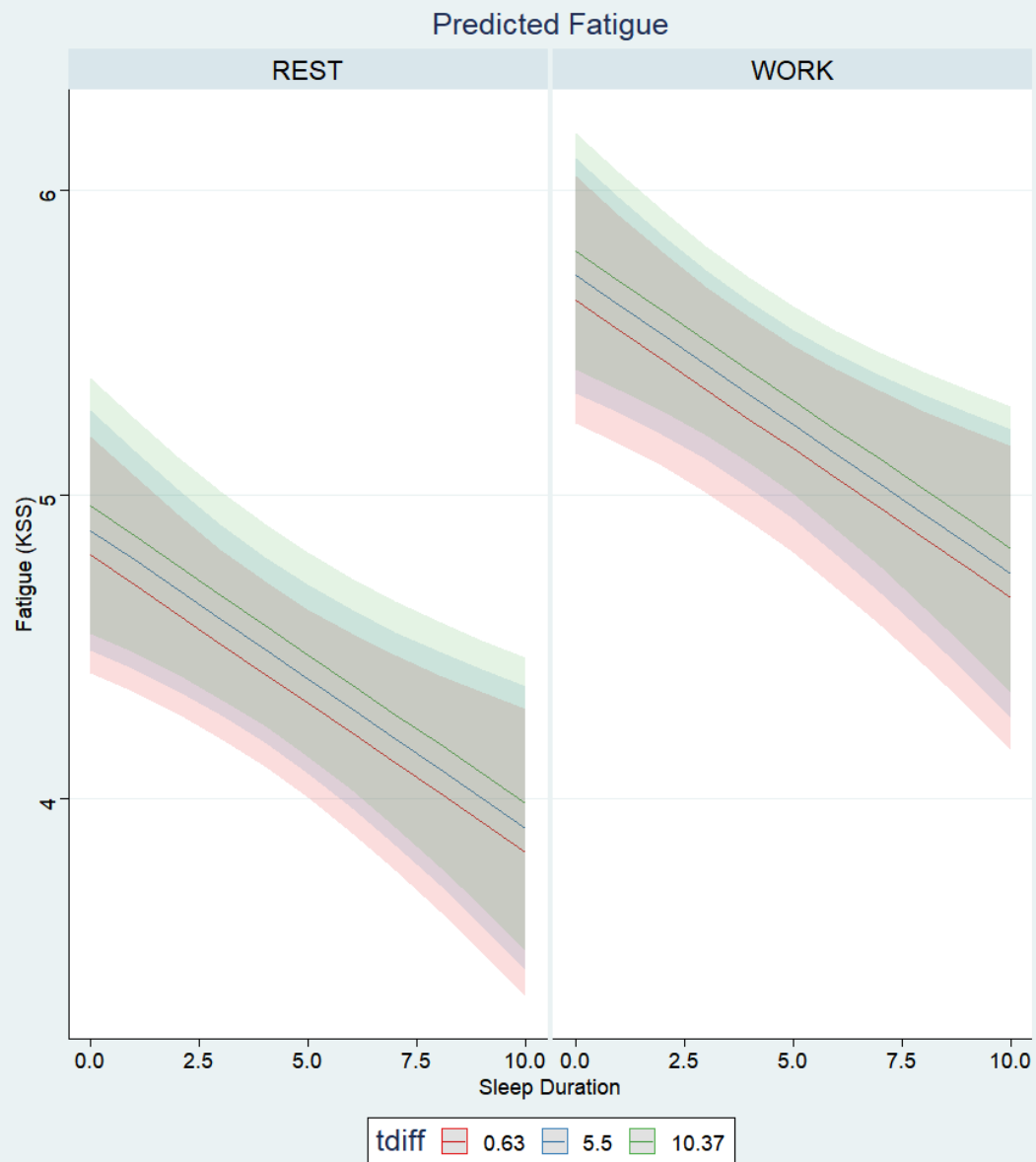
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Appendix: Types of Modelling Tools



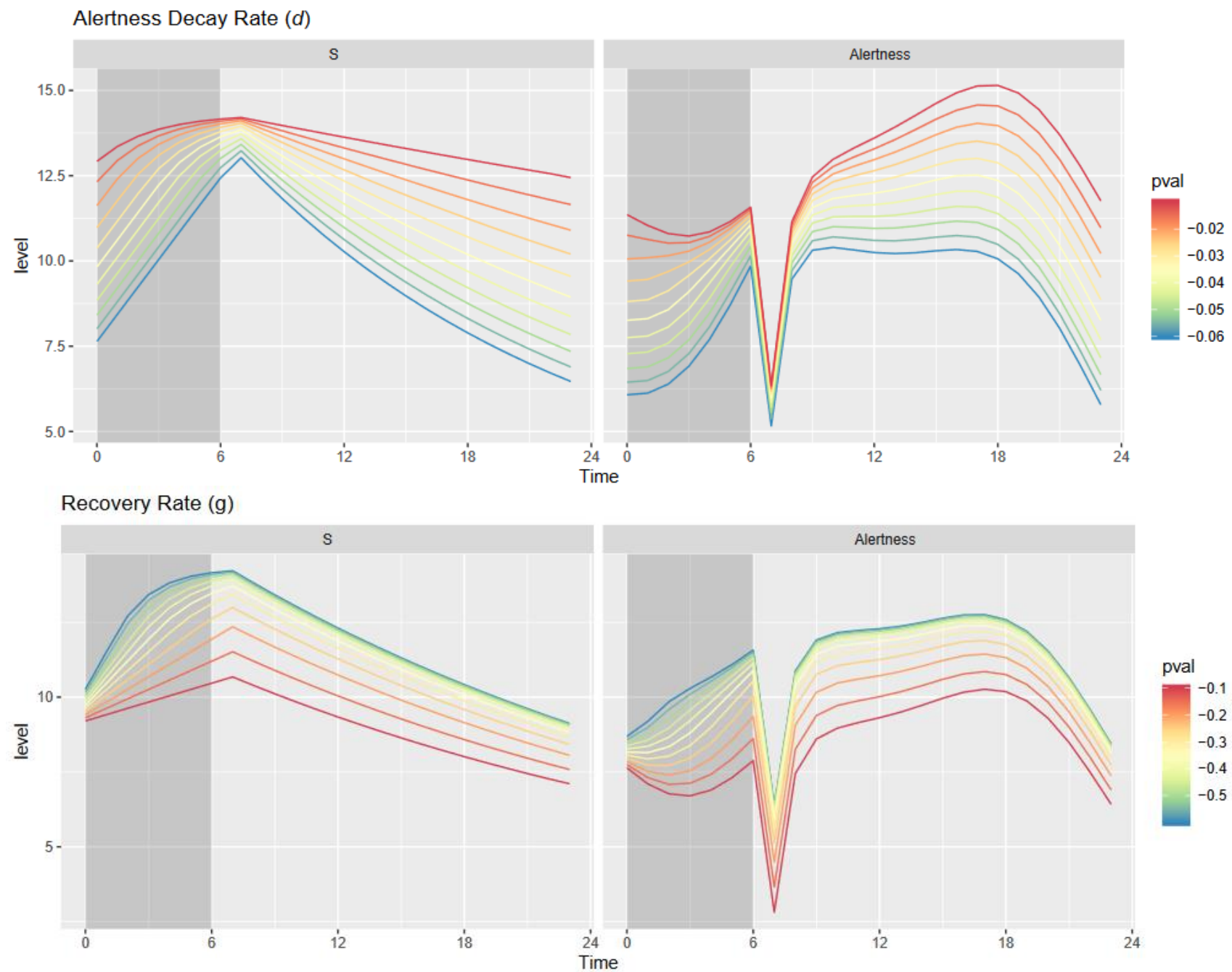
Appendix: Manifest Fatigue Analyses



<i>Predictors</i>	Sleepiness (Fatigue)		
	<i>Estimates</i>	<i>CI</i>	<i>p</i>
(Intercept)	4.81	4.47 – 5.14	<0.001
Post-Work	0.80	0.62 – 0.98	<0.001
Sleep Duration (L1)	-0.11	-0.18 – -0.03	0.008
Time Awake (L1)	0.03	0.01 – 0.04	0.011
Days into Mission	-0.07	-0.10 – -0.05	<0.001
Random Effects			
σ^2	2.17		
τ_{00} Subjects	0.82		
ICC	0.27		
N Subjects	42		
Observations	1430		
Marginal R^2 / Conditional R^2	8.6% / 33.7%		

Note the inversed scale!
(Alertness)

S Governing Parameters



Appendix: GUI Forecasting of Fatigue with FIPS

Data Upload Interface

Fatigue Simulation

?

Introduction

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Data Upload

⚙️

Model Setup

📊

Model Results

Simulation Start Date & Time:

2018-05-01 at 08:00 pm

📅

Simulation End Date & Time:

2018-05-01 at 08:00 pm

📅

File

Browse...

No file selected

Delimiter

Comma

▼

Decimal mark

Point

▼

Timezone to parse

▼

Timezone to display

▼

Please select a file

File not selected

File not selected

Data Pre-Processing

Transform Data

Working prototype of model setting interface

Fatigue Simulation

?

Introduction

■

Data Upload

⚙️

Model Setup

📊

Model Results

Widgets

Fatigue Startpoint

Initial Value of S

0

Lower Asymptote

Minimum level of sleepiness

0

Tau Wake

controls rate of rise in S during wake

18.2

Phi

phase at beginning of the simulation (I think this should be 0 if t = tod)

2.02

Sleep Inertia Initial

extent of alertness reduction at time of waking (typically = -5.72, but sign is reversed for 2PM)

5.72

Upper Asymptote

Maximum level of sleepiness

24.12

Tau Sleep

controls rate of decay in S during sleep

1

Tau Lambda

rate of change in lower asymptote

4.06

Kappa

influence of circadian process - represents A in this model

4.13

Sleep Inertia Recovery

exponential recovery of alertness (typically = -1.51)

-1.51

Appendix: FIPS Comparison Chart

	FIPS	Commercial Tools	Published Models
Expertise Required	✓ Any	✓ Minimal Expertise	☒ Experts only
Fatigue Forecasting	✓	✓	✓
Introspectable	✓	☒	✓
Modifiable/Tailorable	✓	☒	✓
Multiple Models	✓	☒	—
Parameter estimation	✓	☒	—
Cost	Free	Expensive	Free
Sleep Prediction	☒	✓	—