Wearable Sensors in an Extreme Work Environment: Applying Computational Modelling

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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
Measuring and Assessing At-Sea Endurance
Current Research: Navy Endurance Project

• Ongoing project: operational endurance in **naval teams** (RAN)
• Three field studies conducted: 1-2 weeks of *in-situ* data
• **Highly unique context**
  • No wireless-enabled technology permitted (phones, Bluetooth, wifi).
  • Artificial sleep/wake patterns
  • No access to natural lighting
  • Safety-critical, protected and sensitive
• Establish accurate ambulatory assessment protocol?
• Moderating factors underlying fatigue – workload?
Measurement Protocol

Begin trial

**Pre trial**
- Surveys
  - Mood
  - Sleep quality
- Personality
- Burnout
- General well-being

**Start trial**

**Before on-watch**
- Surveys
  - Mood
  - Sleepiness
  - Workload
  - If waking up
  - Sleep quality
  - Recovery

- Diary
  - Off-watch activities
  - Cognitive test
    - Psychomotor vigilance test

**After on-watch**
- Surveys
  - Mood
  - Sleepiness
  - Workload
  - If waking up
  - Sleep quality
  - Recovery

- Diary
  - Off-watch activities
  - Cognitive test
    - Psychomotor vigilance test

Heart rate variability monitor
Wrist worn actigraphy

Repeat measures daily for duration of trial

**Post trial**
- Surveys
  - Mood
  - Sleep quality
  - Burnout
  - General well-being

Survey 1

AFTER ON-WATCH

- Time of Survey:
- Date of survey:

**Workload – PART A**

- Please rate your perception of overall workload for the watch period just completed by circling a number for each dimension of workload.

<table>
<thead>
<tr>
<th>Low demand</th>
<th>High demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental Demand</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Physical Demand</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Time Demand</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Performance</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Effort</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Frustration</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
</tbody>
</table>

**Workload – PART B**

- Rate how much underload or overload you experienced during the watch you have just completed. Circle a score on the scale below.

<table>
<thead>
<tr>
<th>Underload</th>
<th>Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
</tbody>
</table>

**Workload – PART C**

- How often did you experience the following during the watch you have just completed?

<table>
<thead>
<tr>
<th>Not at all</th>
<th>Sometimes</th>
<th>Very Often</th>
</tr>
</thead>
<tbody>
<tr>
<td>I struggled to remain alert and vigilant</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>I found it difficult to concentrate</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>I found work boring and monotonous</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>Time passed slowly</td>
<td>1 2 3 4 5</td>
<td></td>
</tr>
</tbody>
</table>

Your Performance

- What, if anything, prevented you from performing to your best ability over the last work period?

Survey 1

AFTER ON-WATCH

- What is your current level of sleepiness? Circle a number.

<table>
<thead>
<tr>
<th>Very Alert</th>
<th>Alert</th>
<th>Neither alert nor sleepy</th>
<th>Sleepy, but not fighting sleep</th>
<th>Very sleepy, fighting sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7 8 9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After On-watch survey continued on next two pages
Compliance and Resulting Data

• Compliance was acceptable.
• Sufficient data achieved for complex modelling procedures
• Entirely self-initiated measurement
• Extensive data cleaning was conducted prior to modelling, 26 of 68 participants excluded from sample for sleep-related analyses.
  • Incomplete diaries
  • No datetimes recorded
  • No actigraphy data
## Manifest Fatigue Analyses

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Estimates</th>
<th>CI</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>4.81</td>
<td>4.47 – 5.14</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Post-Work</td>
<td>0.80</td>
<td>0.62 – 0.98</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sleep Duration (L1)</td>
<td>-0.11</td>
<td>-0.18 – -0.03</td>
<td>0.008</td>
</tr>
<tr>
<td>Time Awake (L1)</td>
<td>0.03</td>
<td>0.01 – 0.04</td>
<td>0.011</td>
</tr>
<tr>
<td>Days into Mission</td>
<td>-0.07</td>
<td>-0.10 – -0.05</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

### Random Effects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^2$</td>
<td>2.17</td>
</tr>
<tr>
<td>$\tau_{00}$ Subjects</td>
<td>0.82</td>
</tr>
<tr>
<td>ICC</td>
<td>0.27</td>
</tr>
<tr>
<td>N Subjects</td>
<td>42</td>
</tr>
<tr>
<td>Observations</td>
<td>1430</td>
</tr>
<tr>
<td>Marginal R² / Conditional R²</td>
<td>8.6% / 33.7%</td>
</tr>
</tbody>
</table>
## Underload Overload Effects

### Predictors

<table>
<thead>
<tr>
<th></th>
<th>Estimates</th>
<th>CI</th>
<th>Statistic</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>5.65</td>
<td>5.16 – 6.14</td>
<td>22.39</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Under/Overload (Linear)</td>
<td>-3.45</td>
<td>-7.26 – 0.35</td>
<td>-1.78</td>
<td>0.076</td>
</tr>
<tr>
<td>Under/Overload (Quadratic)</td>
<td>3.46</td>
<td>0.06 – 6.85</td>
<td>1.99</td>
<td>0.047</td>
</tr>
<tr>
<td>Sleep Duration</td>
<td>-0.31</td>
<td>-0.47 – -0.16</td>
<td>-3.97</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Time Awake</td>
<td>0.03</td>
<td>-0.00 – 0.06</td>
<td>1.81</td>
<td>0.070</td>
</tr>
<tr>
<td>Time into Mission</td>
<td>-0.06</td>
<td>-0.10 – -0.02</td>
<td>-2.68</td>
<td>0.008</td>
</tr>
</tbody>
</table>

### Random Effects

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^2$</td>
<td>2.04</td>
</tr>
<tr>
<td>$\tau_{00 \text{ com_id}}$</td>
<td>1.35</td>
</tr>
<tr>
<td>ICC</td>
<td>0.40</td>
</tr>
<tr>
<td>N $\text{ com_id}$</td>
<td>32</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>525</td>
</tr>
<tr>
<td>Marginal R$^2$ / Conditional R$^2$</td>
<td>0.046 / 0.426</td>
</tr>
</tbody>
</table>
Forecasting Fatigue with 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
Two Process Model: Basic Mechanics

- Most BMMs derived from Borbély’s (1982) - ‘Two-Process Model’
  - Two core mechanisms (S & C)
  - \( S + C = \text{Alertness/Fatigue} \)
- Parameters normally fixed for simulation, but variation shown in plots.

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**The Data**: Sleep Times & Work Schedule

**The Model**: Model Generates Predicted Fatigue

**The Prediction**: Predicted fatigue at a given time
• **Fatigue Impairment Prediction Suite** (FIPS)
  • Functions for estimating and applying BMMs
  • Implemented in R.
  • Built-in visualisation methods
  • Summary statistics
  • Open Source (mid-2020 release)

• 1\textsuperscript{st} step: how well can a basic fixed parameter two-process model (1982) predict our known observed fatigue scores?
Two Process Model Performance

The diagram illustrates the distribution of correlation coefficients across different magnitude categories: Negative, Negligible, Small, Medium, and Large. The x-axis represents the correlation coefficient range from -0.2 to 0.8, while the y-axis shows the count of occurrences for each coefficient range.
Hierarchical Bayesian Parameter Estimation

- Ideally, model parameters should be trained based on data
  - E.g., unique circadian rhythms per person
- Allows individual tailored prediction models
  - Some parameters can be estimated at group level

<table>
<thead>
<tr>
<th></th>
<th>LOOIC</th>
<th>WAIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2PM Regression</td>
<td>1576.30 (25.73)</td>
<td>1576.29 (25.73)</td>
</tr>
<tr>
<td>2PM Group Estimates</td>
<td>1566.34 (25.54)</td>
<td>1566.30 (25.53)</td>
</tr>
<tr>
<td>2PM Individual Estimates</td>
<td><strong>1490.78 (29.64)</strong></td>
<td><strong>1480.32 (30.11)</strong></td>
</tr>
</tbody>
</table>
Classifying Sleep from ECG
• Ideally, sleep prediction should be automatic and accurate for BMM
• Exploratory ML investigation: can time in bed predicted from HR/HRV
• Models fit in Tensorflow with Keras
  • 11 participants from demanding mission
  • 80% set as training data.
• Started with a group classifier ANN, but as expected performed poorly (77.1%)
• Investigated at individual level
“The average accuracy of each classifier was 86.9%, with the lowest accuracy being 79.9% and the highest being 89.3.”
Immediate Outcomes

General Lessons
• Ambulatory assessment possible in demanding naval setting
• Requires novel approaches

Sleep Identification
• HR → activity detection, but only on an individual person level.
  • Operationally viable if models pre-trained to the individuals.
  • ‘Expensive’ studies would be required to cross-validate and train
• Ideally, sleep detection should be heuristically driven
• Part of closed-loop BMM predictions
Fatigue Measurement & Forecasting

• FIPS will enable researchers who have sleep data to calculate predicted fatigue estimates.

• Ultimate goal to develop tailored models, updated live.
  • ‘Model training’ prior to prediction (requiring measurement).
  • Domain / Watch / Job Role / Individual

• FIPS package release and optimisation
Summary

• Workload ⇔ Fatigue = Complex
• Naval measurement = Hard
• Biomathematical models enable fatigue forecasting.
• FIPS is a framework for developing & implementing BMMs.

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