Unobtrusive Sleep Monitoring using Smartphones

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About the Application

BeWell continuously tracks user behaviors along three key health dimensions (activity, social-interaction and sleep) without requiring any user input — the user simply downloads the app and uses the phone as usual.

BeWell promotes improved behavioral patterns via persuasive feedback as part of an animated aquatic ecosystem rendered on an ambient display on the smartphone’s wallpaper screen.

Let’s get started!

Welcome to BeWell

Set your BeWell active wallpaper

1) Tap and hold on the homescreen wallpaper
2) Select Live Wallpaper from the wallpaper menu
3) Select the BeWell Wallpaper

Use your own wallpaper with BeWell

If you don’t want to use the BeWell active wallpaper you can use your own. In this case BeWell will run in the background and keep your scores and site data up to date.

The orange fish represents your physical activity

Active!
When you are physically active, your orange fish will zip around the screen.

Not Active
If you haven’t been staying active, your orange fish will drift slowly around the screen.

• **Sleep quality and quantity impacts personal health.**
  -- blood pressure
  -- high stress
  -- anxiety
  -- diabetes
  -- high blood pressure

Motivation
Motivation

- Existing Sleep Monitor
  - A polysomnogram monitors

  Complexity

Cost

Not impractical

Motivation
Motivation

- Commercial Wearable Devices
  - Intrusive and cumbersome
Best Effort Sleep (BES) Model

Just Use a Single Phone!

Benefit:
--No interaction Need
--No wear or special manner
--Practical for large scale sleep monitoring

Wide-scale of smartphone make it feasible

Limit: only estimate sleep duration

Vision
Sleep-with-the-phone (SWP) model

12 Features:
(5 minutes long) four time-domain features

- minimum, maximum, root mean square
- \((x, y, z)\)

Each time window is classified using a C4.5 decision tree as implemented by Weka

Relate Work
● Jawbone Up
https://jawbone.com/up

Feature
Tracks not only sleep but also physical activity
Infers “light” and “deep” sleep

Limitation:
if the user fails to correctly toggle the device between sleep and wake modes the collected sleep data will be incorrect
To collect to review sleep data the user must connect it with either an iOS or Android smartphone

Relate Work
Zeo Sleep Manager Pro

https://www.youtube.com/watch?v=j3Y7PGhHR20

Feature
Monitor the electrical signals of the brain, muscle contractions and eye movement.

Limitation:
Must put on the headband during sleep
Pair it with a smartphone via bluetooth
Stay in place during sleep
Battery need recharging everyday

Relate Work
**BEST EFFORT SLEEP (BES) MODEL**

The BES model is statistical and has multiple features:

- **Phone Usage features.**
  - phone-lock (F2)
  - phone-off (F4)
  - phone charging (F3)

- **Light feature (F1).**
  - phone in darkness
  - phone in a stationary state (F5)
  - phone in a silent environment (F6)
BEST EFFORT SLEEP (BES) MODEL

BES combines these 6 features to form a more accurate sleep model and predictor.

- BES assumes that the sleep duration of a person (Sl) is a linear combination of these 6 features:

\[ Sl = \sum_{i=1}^{6} a_i \times F_i, \quad a_i \geq 0 \]

- Using 8 subjects for one week to train the BES model.

- BES formalizes the model training process as a nonnegative least-squares regression problem. Specifically, by solving:

\[
\min_{a_i} \sum_{j=1}^{4} (Sl^j - \sum_{i=1}^{6} a_i \times F_i^j)^2
\]
<table>
<thead>
<tr>
<th>Feature</th>
<th>Coefficient</th>
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<td>Light ($F_1$)</td>
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<tr>
<td>Phone-lock ($F_2$)</td>
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<tr>
<td>Phone-off ($F_3$)</td>
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<tr>
<td>Phone-charging ($F_4$)</td>
<td>0.0469</td>
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<td>Stationary ($F_5$)</td>
<td>0.5445</td>
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<td>Silence ($F_6$)</td>
<td>0.3484</td>
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</table>

**TABLE I**: Weight coefficients for each feature in BES

**Fig. 2**: The reduction in sleep duration error for BES by incrementally adding stationary, silence, phone-lock, phone-charging, light and phone-off features, respectively.

**Results**
Fig. 3: Overall sleep duration error for BES compared to the three alternative sleep monitoring systems (SWP, Jawbone, Zeo).

Fig. 4: BES sleep duration error when users behave as expected (“regular”) compared to three examples of atypical sleep behavior (i.e., corner cases). Specifically, these behaviors are: Case1 – user sleeps with the room lights on; Case2 – user has a prolonged nap during the day; Case3 – user fails to recharge their phone.

Results
**Results**

*Fig. 5:* Comparison of estimated and actual sleep duration under BES for one representative study subject.
Results

Fig. 6: Comparison of estimated and actual sleep duration under SWP for one representative study subject.

Fig. 7: Comparison of estimated and actual sleep duration for one representative study subject while using the Jawbone Up device.
Fig. 8: Comparison of estimated and actual sleep duration for one representative study subject while using the Zeo Sleep Manager Pro device.
### Results

<table>
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<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
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</table>

**TABLE II:** Summary of User Experience Survey
On-body Sensors vs. Smartphone Sensing

1) User Burden
2) Sleep Data
3) User Feedback
4) Cost

Conclusion
Thanks!