Lullaby: Environmental Sensing For Sleep Self-Improvement

Matthew Kay
Computer Science &
Engineering
University of Washington
Seattle, Washington, USA
mjskay@uw.edu

Eun Kyoung Choe
The Information School
University of Washington
Seattle, Washington, USA
eunky@uw.edu

Jesse Shepherd
Computer Science &
Engineering
University of Washington
Seattle, Washington, USA
zelgadis@uw.edu

Benjamin Greenstein
Intel Labs Seattle
Seattle, Washington, USA
bengreenstein@gmail.com

Sunny Consolvo
Intel Labs Seattle
Seattle, Washington, USA
Sunny.Consolvo@intel.com

Patrick Gage Kelley
Intel Labs Seattle
Seattle, Washington, USA
patrickgage@gmail.com

Julie Kientz
The Information School,
Human-Centered Design &
Engineering
University of Washington
Seattle, Washington, USA
jkientz@uw.edu

CHI 2011, May 7–12, 2011, Vancouver, BC, Canada.
ACM 978-1-4503-0268-5/11/05.

Abstract
We are developing a system to help users improve the quality of their sleep by monitoring environmental factors that disrupt sleep and providing feedback. This system, called Lullaby, has several design goals. Lullaby's sensor suite should be practical for deployment into bedrooms: it must be unobtrusive, inexpensive, and respect users' privacy in this sensitive context. Lullaby should identify relationships between sleep disruptions and environmental factors and reflect those back to the user. Finally, Lullaby should provide concrete recommendations for addressing the identified sleep disruptors. In this paper, we describe the design of Lullaby's sensor suite and user interface, and how it will support personal use in the home.

Keywords
Personal informatics, sleep, environmental sensing.

ACM Classification Keywords
H5.m. Information interfaces and presentation

Introduction
Getting quality sleep is an important aspect of a healthy lifestyle [2]. Clinical sleep centers can easily evaluate an individual's sleep quality, but this is an expensive procedure that requires the participant to stay overnight [3]. Additionally, because such testing occurs at a clinic, it does not help participants identify any disruptors within their natural sleep environments.

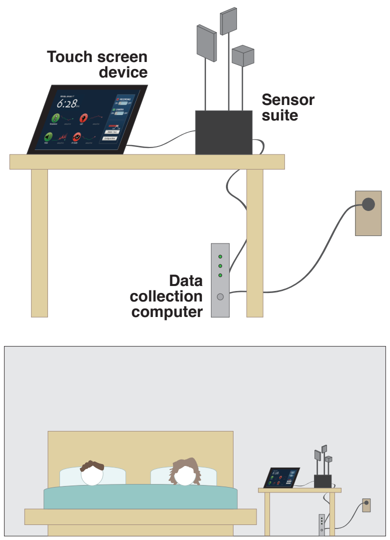

Figure 1. The Lullaby device concept, with closeup. The current iteration has multiple sensor pods, each of which can be oriented independently.

A variety of consumer-grade personal informatics devices (e.g., Zeo[1], Fitbit[2]) are now available for home sleep monitoring. These systems help identify when a person has had poor sleep and even specific times during the night when they have been awakened. However, none of these devices provide information about the user's sleep environment. Previous research has shown that environmental factors, such as sound and light, are a major cause of poor sleep quality [1,4,7]. Access to environmental data might therefore help a person identify *why* their sleep was interrupted, not just *when*. In addition, Choe *et al.* [2], in a survey of 230 individuals' attitudes towards personal sleep technology, found that assistance in creating an optimal sleep environment was one of the most requested features.

To address this issue, we are developing Lullaby, a suite of environmental sensors—including sound, light, temperature, and air quality—that can assess the quality of a user's sleep environment. Using a touchscreen interface, Lullaby presents this environmental data together with data from an off-the-shelf sleep tracking device to help people determine what is disrupting their sleep and how they can improve their sleep environment.

We are currently in the design and implementation phase of the collection system for Lullaby. In the rest of this paper, we describe the design of the sensor suite and user interface, and how we intend Lullaby to help users improve their sleep environments.

Lullaby Design

Lullaby consists of four components: the sensor suite, the data collection computer, a sleep tracking device, and a tablet interface for control and feedback. We will focus our discussion on the sensor suite and interface.

The sensor suite

This is an unobtrusive device that sits on the user's night stand and consists of several sensors, each of which can be oriented independently in order to best capture its data (Figure 1). It has the following sensors:

- *Infrared (IR) camera.* The camera will be pointed towards the user's bed to collect images that a sleep doctor could use to help users diagnose sleep problems.
- *Two Passive Infrared (PIR) motion detectors.* One of these sensors will be used to detect motion in the bed, such as movement of a partner or a pet. The other will be used to detect movement elsewhere in the room (e.g., a child moving in or out of the bedroom).
- *RGB light sensors.* High levels of light—particularly blue light—negatively impact sleep [4]. Two light sensors will be pointed upwards, with a combined field-of-view of 180°. This will capture a range of lighting conditions, from sunlight to the dull blue light of a TV.
- *Air quality sensor.* This is a consumer-grade ($200) air quality monitor that gives data approximating the PM_{10} measure (quantity of particulate matter of less than 10 microns in size). PM_{10} has been associated with instances of sleep apnea (interrupted breathing) [7].
- *Sound sensor.* Abrupt changes in sound pressure can disrupt sleep [1], as can persistent loud noise [6]. We use a calibration microphone with flat frequency response that can characterize different types of noise, from an annoying tapping sound to an ambulance siren.
- *Temperature sensor.* The National Sleep Foundation recommends temperatures between 54°F and 75°F for a comfortable sleep environment [6]. We will include

1 http://www.myzeo.com/
2 http://www.fitbit.com/

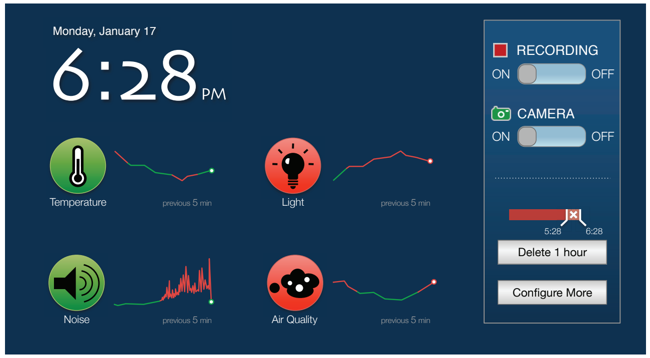

Figure 2. The Lullaby home screen, with clock, current sensor state, and controls. Each sensor has a sparkline of recent readings, along with an indication (red or green) of whether those readings are outside recommended thresholds for a good sleep environment.

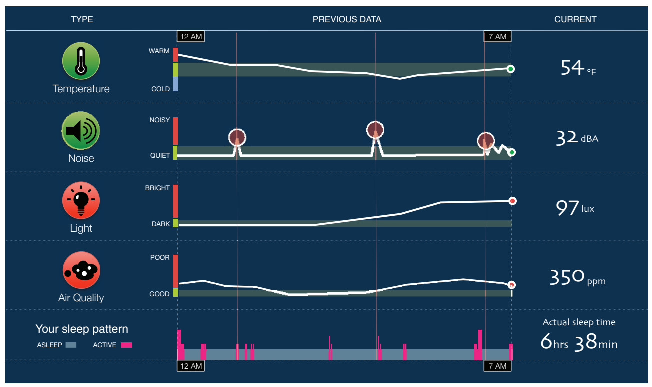

Figure 3. The details screen, showing readings from the previous night, combined with sleep data from the sleep tracking device (e.g., Fitbit).

a temperature sensor in the base of the sensor suite, positioned at approximately the same level as the user.

The touch screen device (an Android tablet)
This device communicates with the data collection computer over WiFi, allowing the user to both control the Lullaby sensor suite and see visualizations of the data it collects. See Figure 2/Figure 3.

We recognize that using a backlit tablet interface has the potential to disrupt sleep. We are exploring ways to mitigate this affect, for example, by providing auto-dimming functionality and a quick gesture to dim the screen, such as that used by the Nightstand Central iPad app[1]. We are also using a fan-less mini-PC as the data collection computer so that we do not introduce additional noise into the environment.

Support for Personal Use

Our system aims to be usable by individuals within their own homes to track their sleep environments. Li *et al.* [5] developed guidelines for building successful personal informatics systems; these guidelines break such systems into five stages: preparation, collection, integration, reflection, and action. To motivate our design, we describe how Lullaby supports each stage of use.

- *Preparation.* This stage should allow users to tailor how much and what kind of data they wish to collect [5]. We carefully considered the privacy-sensitive nature of data collection within the context of sleep, allowing users to pause recording for either the camera or the entire suite. The sensors are on ball joints, allowing them to be oriented to collect the best data for their environment. Placement and orientation is always an issue, one of our next steps will be to provide concrete guidance to users in how to place the sensors.
- *Collection and integration.* These processes are automated by Lullaby, including integration of Fitbit data. Recognizing that users may wish to delete collected data if they believe it to be sensitive, data can be deleted in the main interface after it has been collected.
- *Reflection.* This is currently supported through the visualization of environmental sleep disruptors alongside Fitbit sleep data (Figure 3). The interface helps users to visually correlate sleep disruptions with

1 http://itunes.apple.com/us/app/nightstand-central-for-ipad/id392479477?mt=8

environmental factors. As an example scenario, imagine a user looking at the Fitbit data and noting a point where their sleep was disturbed. Then, looking at the sound data on the same time axis, they notice a spike in sound level at that time. Clicking on the sound graph, the sound at that time is played back—the sound of a garbage truck outside the user's window. The user has thereby identified the cause of the sleep interruption.

- *Action.* Continuing the example scenario from above, imagine that Lullaby determines that the user's sleep is often interrupted by sound. Lullaby then suggests that the user set up a white noise machine to lessen the impact of other sounds on their sleep. We believe this approach would generalize well: the system would detect long-term trends in sleep disruption and suggest concrete steps the user can take to improve their sleep environment.

Finally, we believe that use of a tablet/smartphone device fits well into many sleep environments if it is carefully designed. While we are using a tablet for the study, our software could be adapted for use on smaller smartphones. Many individuals already use phones in sleep contexts (e.g., as an alarm clock, or with apps like SleepCycle[1]), potentially making these devices a good fit for interacting with systems like Lullaby.

Conclusion and Future Work

We are in the process of completing the implementation of Lullaby. Following that, we will conduct an in-home study of Lullaby to assess its usability and usefulness One of the goals of the study will be to explore people's receptiveness to environmental sleep data collection, privacy issues, and whether users find Lullaby's data and visualizations to be useful. We also intend to use the sensor and sleep data collected from this study to develop more complex data analyses, e.g., for deriving recommendations or improved visualizations.

We have designed Lullaby to meet our initial goals. We have used inexpensive consumer-grade sensors, and believe that a commercial version of the device would be affordable. We have also considered privacy aspects of the design from the beginning, taking care to ensure users can pause collection or delete sensitive data. Our current design helps users identify correlations between sleep disruptions and environmental factors, and we have plans to provide concrete recommendations for addressing the identified sleep disruptors in the future.

1 http://mdlabs.se/sleepcycle/

References

[1] Basner, M., Müller, U. and Elmenhorst, E. Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep*, 2011, 34 (1).

[2] Choe, E. K., Consolvo, S., Watson, N. F. and Kientz, J. A. Opportunities for Computing Technologies to Support Healthy Sleep Behaviors. *CHI '11 (to appear)*, 2011.

[3] Douglas, N., Thomas, S. and Jan, M. Clinical value of polysomnography. *The Lancet*, Elsevier, 1992, 339.

[4] Kozaki, T., Kitamura, S., Higashihara, Y., Ishibashi, K., Noguchi, H. and Yasukouchi, A. Effect of Color Temperature of Light Sources on Slow-wave Sleep. *J Physiol Anthropol Appl Hum Sci*, 2005, 24 (2).

[5] Li, I., Dey, A. and Forlizzi, J. A stage-based model of personal informatics systems. *CHI '10*, 2010.

[6] National Sleep Foundation. The Sleep Environment. http://www.sleepfoundation.org/article/how-sleep-works/the-sleep-environment.

[7] Zanobetti, A., Redline, S., Schwartz, J., Rosen, D., Patel, S., O'Connor, G. T., Lebowitz, M., Coull, B. A. and Gold, D. R. Associations of PM10 with Sleep and Sleep-disordered Breathing in Adults from Seven U.S. Urban Areas. *Am. J. Respir. Crit. Care Med.*, 2010, 182 (6).