Lullaby: Capturing the Unconscious in the Sleep Environment

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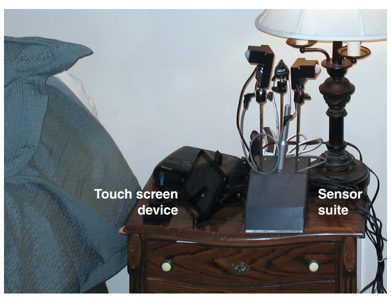

Figure 1. Lullaby deployed in a bedroom. Visible here are the touchscreen tablet mounted in a stand for easy access from the bed and the sensor box with pivoting sensor enclosures. The sensor suite itself is about the size of a bedside lamp.

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Abstract
Research has shown that environmental factors can be one of the major causes of poor sleep quality and interrupted sleep [8], which can contribute to daytime sleepiness and fatigue. In particular, a room that is too warm [11], has improper lighting [10], or is noisy [1] can have a negative impact on sleep. While some of these environmental factors are observable, others may be subtle. Individuals who have poor sleep quality can often have difficulty evaluating the cause or severity of their sleep difficulties [3]. We present preliminary results of an ongoing study of Lullaby, a capture and access system for the sleep environment, and discuss some aspects of designing capture and access for unconscious experience.

Keywords
Personal informatics, sleep, environmental sensing.

ACM Classification Keywords
H5.m. Information interfaces and presentation

Introduction
Clinical sleep centers can easily evaluate an individual's sleep quality [4], but because these tests do not occur in the individual's actual sleep environment, they cannot help individuals identify factors in that environment that might contribute to reduced sleep quality. A varie-

Figure 2. The Lullaby home screen with recording controls. Each sensor has a sparkline of recent readings, along with an indication (red or green) of whether those readings are outside recommended ranges for a good sleep environment. The sensors are: an infrared camera, two passive infrared (PIR) motion detectors, a light sensor, a microphone, and a thermometer. Previous versions had an air quality monitor, but piloting revealed its fan was noisy enough to potentially disturb sleep.

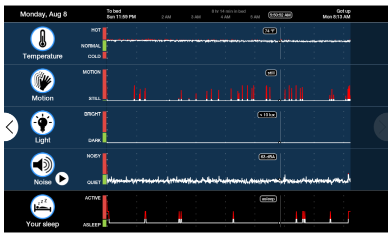

Figure 3. The history screen, showing readings previous nights' sleep (one night at a time), combined with sleep data from the sleep tracking device. This unified approach This approach follows from Li *et al.* [9]'s recommendations for visualizing multi-faceted personal informatics data. Touching on the graph shows the numerical readings taken at that point. Readings that are outside recommended ranges are highlighted in red.

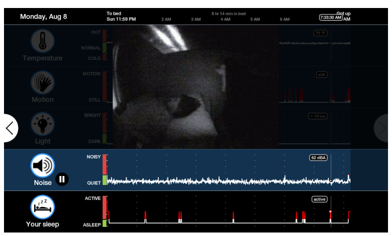

Figure 4. To give more concrete context on the history screen, users can play back the recorded images and audio corresponding to the data. Touching and/or dragging on the timeline scrubs playback. Due to space constraints, these are streamed from a lightweight HTTP service on the data collection computer rather than downloaded in advance.

ty of consumer-grade personal informatics devices—e.g. Zeo (http://myzeo.com/), Fitbit (http://fitbit.com/)—are now available for home sleep monitoring. They generally report measures like *sleep efficiency*, the proportion of time in bed actually spent asleep. This provides an indication of sleep quality, but gives little concrete guidance for sleep improvement.

Access to environmental data might help a person identify *why* their sleep was interrupted, not just *when*, allowing them to better understand their sleep conditions and make improvements in their sleep habits. To help address this need, we have developed Lullaby, a suite of environmental sensors—including sound, light, temperature, and motion—that helps users assess the quality of their sleep environments. Using a tablet device, 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.

Lullaby opens new possibilities for studying capture and access of an unconscious experience, such as sleep. That users do not consciously experience much of the data collected by Lullaby creates new challenges in creating an effective way for people to access captured data, and affects how they conceptualize privacy—the notion of what is private changes when the person involved was not conscious of their actions. We are exploring these issues through an in-home deployment of Lullaby, and present our preliminary results here.

Design

Our previous work [6] outlines our design. Summarizing, Lullaby tracks environmental factors associated with sleep disruption, chosen by examining the important components of *sleep hygiene* as identified by sleep doctors (see Choe *et al.* [3]). It is bedside a device about the size of a lamp (Figure 1) that collects data with little or no user intervention, and consists of four components: the sensor suite, a data collection computer, a sleep tracking device (currently a Fitbit), and a touchscreen interface (An Android tablet) for control and feedback (Figures 2-4). The tablet communicates with the data collection computer over Wi-Fi.

Due to the sensitive nature of recording bedroom activity, Lullaby includes several privacy controls: recording control (turning all recording on/off), targeted deletion (deleting 15-minute chunks of data), and recent deletion (deleting the most recent hour of data).

Evaluation

To understand how Lullaby would be used in real world settings and to test its feasibility and usefulness as a feedback device, we are conducting an in-home evaluation of Lullaby. We present the preliminary results of

Participants

Dianna is a female in her 30s. She does not typically sleep with a partner. Dianna has noticed a decline in her sleep quality over the past 5 years. She has noticed some coughing in her sleep, which she attributes to allergies. As a result, she started using an air purifier in her bedroom. Previously she also made use of a white noise machine.

Nathan is a male in his 30s. He does not typically sleep with a partner, but shares his apartment with two cats, who regularly sleep with him. Nathan has made some effort to adjust his sleep environment in order to improve sleep, e.g. by using (at times) an eye mask to block morning light, and through occasional use of a white noise machine.

P	Home	History	Delete
Dianna	53min	35min	75min
Nathan	26min	26min	<1min

Table 1. Time spent by each participant on each screen over the entire study period.

the two deployments run so far. Each deployment consists of an initial interview, 14 nights' use of Lullaby (the same length of time used to collect baseline data in insomnia treatment [12]), and an exit interview.

We recruited participants via Craigslist. Our primary criterion for inclusion was an interest in improving sleep quality. We are currently recruiting additional participants through flyers in a sleep clinic. We compensated participants up to $200 USD in gift cards, pro-rated based on the number of nights of use. Our two participants so far, Dianna and Nathan[1], are described at left.

Results

In total we collected data from 31 sleep periods (15 for Dianna, 16 for Nathan) over approximately 40 days. Some gaps in continuous use were caused by participants forgetting to use one of the sleep tracking devices, technical issues, or other sleeping arrangements. In total, Dianna used Lullaby for 164 minutes over the study period, and Nathan for 53 minutes (see Table 1).

Deleting Private Moments

Neither of our users made use of the deletion functionality to delete data from when they were sleeping. Instead, they were more concerned about private activities surrounding (but not during) sleep, such as sexual activity or changing their clothes. This result confirms Choe *et al.*'s study on private moments in the home [2], in which participants predicted that intimacy and self-appearance (including changing clothes) were the most sensitive activities they would not want recorded. It may be that some of the other activities reported in Choe et al.'s study were not deleted because the data was simply too overwhelming—that finding an instance of picking one's nose, for example, is the proverbial needle in the haystack, and the reward for sifting through the entire data set for a small privacy invasion does not outweigh the time taken to do so.

Capturing Unconscious Experiences

While previous work has looked at automated capture of spontaneous or unplanned events [5,7], there are additional challenges to capture and access when the events captured occur while the user is *unconscious*. When capturing spontaneous events, arguably users are aware of the occurrence of the event as it happens or shortly after. In contrast, the domain of sleep is one where events of interest are not known by users until well after their occurrence, when the user goes looking for them. We have tried to provide guidance in this process by highlighting data that is out-of-range (and thus possibly of interest), and by showing all collected data together, chunked by sleep period, to give users a framework from which to approach the data (with image/sound playback to give a more concrete context).

Both of our participants found this unconscious data compelling. Dianna discovered that she moved more than she thought in her sleep, and that she coughed more frequently than she thought (an important finding, as coughing can be symptom of sleep disorders). Nathan was able to identify a sleepwalking event in his data stream, which he found compelling.

While unconscious events can capture user interest, it is clear from our results that further work is needed to help users approach these events. The sheer volume of data collected by Lullaby is often overwhelming, despite our efforts to provide a framework for understanding

[1] Names have been changed to preserve anonymity.

that data. We are currently developing higher-level summaries of the data to help users navigate the volume of data collected by Lullaby.

Drawing Inferences from Data

One of the goals of Lullaby was to help people to identify the sleep disruptors. Some disruptors might be easy to see just by looking at graphs and verifying them using the audio/visual stream, such as a co-occurrence between awakenings and motion caused by cats entering or exiting the bed; this was also a compelling aspect of the data for Dianna: "'I was curious about what matched up with what." However, more subtle causes may be difficult to determine just by reviewing the data manually. For example, a user may want to know if they awaken more frequently while the temperature is warmer over a period of several nights. With enough captured data, Lullaby could help with identifying these things by running statistical analyses on the data to determine if there are any significant correlations. This type of inference might be useful for other types of self-monitoring applications, such as determining the cause of increases in blood sugar levels for diabetes patients or determining causes of headaches for a headache diary tool.

Conclusions and Future Work

We have described preliminary results of an on-going evaluation of Lullaby, including interesting aspects of the system that arise from capture and access of unconscious events. Our future work will involve continuing our in-home study of Lullaby with more participants to assess its usability and usefulness in order to generalize on people's receptiveness to environmental sleep data collection, privacy issues, and whether users find Lullaby's data and visualizations to be useful.

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