Opportunities for Computing Technologies to Support Healthy Sleep Behaviors

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ABSTRACT
Getting the right amount of quality sleep is a key aspect of good health, along with a healthy diet and regular exercise. Human-computer interaction (HCI) researchers have recently designed systems to support diet and exercise, but sleep has been relatively under-studied in the HCI community. We conducted a literature review and formative study aimed at uncovering opportunities for computing to support the important area of promoting healthy sleep. We present results from interviews with sleep experts, as well as a survey (N = 230) and interviews with potential users (N = 16) to indicate what people would find practical and useful for sleep. Based on these results, we identify a number of design considerations, challenges, and opportunities for using computing to support healthy sleep behaviors, as well as a design framework for mapping the design space of technologies for sleep.

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Sleep, health, health informatics, persuasive technology, qualitative study, design, wellness.

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design, Human Factors.

INTRODUCTION
Eating a nutritious diet, exercising regularly, and getting adequate sleep are three important activities that people can do to support a healthy lifestyle. The first two have been the focus of many new technologies designed to promote good health. For example, mobile and sensing technologies have been used to encourage healthy eating and exercise habits, track progress over time, and help people set and meet health-related goals [5,16]. However, while *sleep* has been the subject of rigorous scientific research in the medical community, the HCI community has placed considerably less attention on ways that technology can support sleep.

Designing technologies to promote healthy sleep behaviors is a worthwhile goal for numerous reasons. Chronic sleep deprivation is common in the developed world, with 28-29% of all young adults reporting only 6.5 hours of sleep each night [3]. Getting the appropriate amount of sleep has been correlated with numerous health benefits, including reduced fatigue and stress. Likewise, when people regularly get less than 6 or 7 or more than 9 hours of sleep per night, there is a correlation with an increase in a number of diseases, including diabetes [9] and heart disease [2]. In addition to one's physical health, there are other important consequences of poor sleep habits. When people do not get enough sleep, their alertness is greatly reduced [3], and they often put themselves at a greater risk of a car accident, with estimates of as many as 36% of all fatal car accidents resulting from driver drowsiness [13]. Finally, a poor night's sleep can affect memory [17,27] and cognitive functioning [7], which can result in poor work performance.

Similar to how technology has been used to improve other aspects of health, we believe there is an interesting research agenda surrounding the exploration of technologies for promoting healthy sleep habits. Tracking sleep habits can help bring an individual's awareness to the problem, as can persuasive technologies designed to motivate good behaviors [8]. Technology could also be used to help doctors detect and diagnose a number of sleep disorders, such as insomnia, sleep apnea, or delayed sleep phase syndrome, which often go undiagnosed [24]. In addition, designing for the promotion of healthy sleep behaviors presents a number of interesting design challenges. With respect to *when* a sleep technology would be used, technology designers need to consider different aspects of sleep, such as the state of mind and awareness of individuals just before or after sleeping. With respect to *where* a sleep technology might be used, privacy concerns around the bedroom, and different cultural interpretations of sleep need to be carefully considered.

To better understand how technology can play a role in improving sleep health, we conducted a triangulated formative study to help develop our proposed design

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framework. We conducted a literature review on existing sleep-related technologies, contextual interviews with domain experts (N = 4), a large-scale survey of peoples' attitudes toward sleep-related technologies (N = 230), and interviews with a subset of the survey respondents (N = 16). In this paper, we present results of this study and discuss opportunities for technologies to help people develop and maintain good sleep habits. The contribution of this in-depth, formative work is its explication of a design framework and opportunities for HCI in the domain of sleep. We hope this will provide HCI researchers and designers with a better understanding of *sleep* as an interesting research area.

The remainder of this paper is organized as follows. First, we provide a brief background on sleep and discuss existing research projects and commercial products in this area. Next, we describe our study procedure and data analysis methods. We provide results focusing on current practices, factors affecting sleep, sleep-related goals, and peoples' attitudes toward technologies for sleep. Based on our findings, we propose a design framework for developing technologies to support healthy sleep behaviors. Finally, we conclude with future directions for this area of research.

BACKGROUND ON SLEEP

In this section, we provide background on the nature of healthy sleep behaviors, including sleep hygiene, types of sleep, and different sleep disorders. This section is intended to help readers better understand important aspects of sleep.

Sleep Hygiene

Sleep doctors and the sleep research literature make consistent recommendations to maximize one's chance of getting a good night's sleep [26]. Called *sleep hygiene*, these recommendations help people prepare their sleep environment and engage in behaviors that prepare them physically and mentally for sleep. According to the sleep literature [21,23,26] and recommendations from the sleep center involved in our research, basic sleep hygiene recommendations consist of the following:

- Sleep only as much as you need to feel refreshed during the following day
- Keep a consistent wake time and amount each day, seven days per week
- Do not eat or exercise within three hours of bedtime
- Make sure your bedroom is comfortable, free of light and noise, and is at a comfortable, cooler temperature
- Eat regular meals and do not go to bed hungry
- Avoid excessive consumption of liquids and alcohol in the evening
- Reduce the consumption of all caffeinated products
- Avoid smoking during the night when you have trouble sleeping or quit smoking entirely
- Do not attempt to sleep while stressing about problems
- Position the clock so that you cannot see it
- Do not use your bed for anything other than sleep or sexual activity (e.g., do not read or watch television, etc. in bed)
- If you do not fall asleep within 30 minutes of going to bed, get out of bed and engage in a quiet activity (e.g., reading, watching television)
- Avoid napping during the day

These recommendations are seemingly straightforward, but can be difficult to follow. For example, people might engage in an activity for entertainment (e.g., reading or watching TV in bed), to be social (e.g., drinking alcohol), or because of other responsibilities (e.g., calming a crying baby or working toward a deadline), even if they know that it is not good for sleep. Even for those who are determined to change their behavior, some recommendations do not provide concrete and actionable information as to exactly what to do (e.g., How much liquid consumption at night is too much? What should you do if you need to get some sleep but are stressed out?). At the same time, sleep requirements are highly *individualistic*. For example, some people may feel rested after having 5 hours of sleep while others may need 8 hours of sleep to have the same restful feeling. For this reason, sleep hygiene recommendations tend to remain as high-level suggestions. While sleep hygiene is a good place to start thinking about the design space, sleep experts and HCI researchers can work together to explore ways to customize sleep hygiene recommendations and develop actionable goals.

Sleep Deprivation and Sleep Disorders

Sleep consists of varying phases throughout the night, including two broad types—*Rapid Eye Movement* (REM) sleep (when most people dream) and *Non Rapid Eye Movement* (NREM) sleep. The NREM sleep phase is further broken down into N1, N2, and N3; N3 is also referred to as the *deep sleep* phase [10], which is the most important contributor for people waking up feeling refreshed and restored. Bad sleep environments (e.g., an uncomfortable mattress or pillow, noise, light, too high or low temperature level), stress and anxiety, and consuming food and drinks before going to bed can have a negative impact on deep sleep, which may cause sleep deprivation—even for people who seem to be sleeping for an adequate period of time. People need varying amounts of sleep, but most sleep professionals, as well as the National Sleep Foundation (USA), recommend that adults need eight hours of sleep each night to feel rested and have full cognitive functioning during the day, with younger individuals tending to need more [21]. The 2009 Sleep in America Poll, however, indicates that on average, adults in the U.S. sleep 6.7 hours a night on weekdays and 7.1 hours a night on weekends, which can result in sleep deprivation. The problem has only gotten worse. People's reported average sleep hours for both weekdays and weekends have been continuously decreasing since the Sleep in America Poll was first undertaken in 2001 [21]. This indicates that regularly getting 8 hours of quality sleep has become a luxury for many people these days.

Sleep doctors work with patients to diagnose and treat a number of different sleep disorders. Sleep disorders include

not being able to sleep (insomnia), difficulties in breathing during sleep (sleep apnea), sleepwalking or talking (parasomnia), falling asleep uncontrollably (narcolepsy), and circadian rhythm disruptions (delayed and advanced sleep phase syndromes) [4,21]. There are also several other conditions or disorders that can negatively impact sleep, such as depression, obesity, or chronic pain [4]. Clinical sleep centers have sleep labs with beds and a number of sensing technologies, known as polysomnography. Patients suspected of having a sleep disorder spend a night sleeping at these centers while doctors and technicians monitor the patients' sleep using night vision cameras and a variety of measurements, including EEGs, EKGs, pulse oximetry, and respiration [21]. This highly studied night is then used in conjunction with manual sleep diaries completed by patients in their own homes to diagnose a variety of sleep disorders and recommend treatment.

LITERATURE REVIEW

Our first step in this research was to conduct a review of existing research and commercial products that use computing technology to support sleep. The main themes we identified were: applications that track sleep; technologies that help people wake or fall asleep; and sleep-related technologies that are social in nature.

Tracking Sleep

A number of research projects and commercial products exist for the purposes of tracking aspects of sleep, including the frequency, duration, or quality of sleep. Tracking is done by automatic sensing, manual input, or both. For example, the wristwatch-like *Actigraph*, which is often used in clinical settings, uses accelerometers to sense basic sleep patterns, such as the amount of hours in sleep, sleep efficiency (i.e., the percentage of time spent in bed that is asleep), and number of awakenings [1]. WatchPat[1] is a wearable device used at home for screening and detection of sleep apnea. Similarly, some other products require the use of wearable sensors, such as a wristband in the case of *FitBit*[2] and *SleepPhase*[3] or a headband for the *Zeo Personal Sleep Coach*[4]. These wearable sensors often determine the user's stages of sleep throughout the night as well as the quality of her sleep. Some other applications are built for use on existing devices, such as mobile phones. A number of applications for the Apple iPhone either provide journals to help users track their sleep manually (e.g., *Tylenol PM SleepTracker*[5]) or use the iPhone's accelerometers to track movement while in bed (e.g., *Sleep Cycle*[6]). Other tracking applications include the *YawnLog*[7], which allows the user to manually keep track of sleep online, the *Dream Recorder*[8], which allows users to record dream descriptions using a video camera, and the *Wellness Diary* [18], a research prototype on a mobile phone that allows manual input of sleep data as part of an overall wellness measure.

Waking and Sleep Inducing

Another category of sleep-related technologies helps people wake up in the morning or go to sleep at night. The most popular technology to help people wake up is the alarm clock. Many different waking sounds for alarm clocks exist, from basic buzzing or beeping, to radios, CDs, mp3 players, nature sounds, or customizable sounds. Many alarm clocks are appliance-based, but they are also standard on most modern mobile phones and computers. More creative alarm clocks use alternate senses to wake a person, such as through the gradual brightening of light as with the *BioBrite Sunrise*[9] product or through tactile feedback, such as vibrating beds for individuals with hearing impairments.

A new trend uses more sophisticated alarm clocks that wake users when they are in the light sleep phase, which is presumed to be a more restful way of waking. The *SleepPhase*[3], *Zeo*[4], and *Sleep Cycle*[6] mentioned above attempt to wake the user at the most appropriate time within a 30-minute period. Another strategy employed by several new alarm clocks forces users to get out of bed to shut off the alarm, such as *Clocky*[10], which rolls off the nightstand and hides, and the *Flying Alarm Clock*[11], which rings until the small helicopter that it launches is put back into place. Finally, researchers have explored the use of alarm clocks as a way of conveying information at the start of the day, such as Landry et al.'s decision-making alarm clock [12].

Technologies that are designed to help users go to sleep typically focus on relaxing the user or minimizing distractions. White noise technologies, such as *aSleep*[12] for the iPhone and *SleepMate*[13] play soothing sounds, such as waves crashing on the shore or crickets chirping, which are intended to drown out distracting noise, such as a snoring roommate or busy street traffic. Other sleep inducing devices play relaxation or meditation sounds to help the user clear her mind in preparation for sleep. Portable biofeedback devices, such as *StressEraser*[14] and *emWave*[15], help people improve sleep by reducing stress through real-time biofeedback and guided breathing.

Social Applications

Many of the research-based applications focus on social aspects of sleep. For example, Kim et al.'s *BuddyClock* [11] and Schmidt's *Network Alarm Clock* [25] facilitate the sharing of sleep status within a social network as a tool for awareness. Two other research prototypes also focus on this aspect and use sensing and output to indicate presence to

[1] http://www.itamar-medical.com. {accessed Dec.28, 2010}.
[2] http://www.fitbit.com. {accessed Dec.28, 2010}.
[3] http://axbo.com. {accessed Dec.28, 2010}.
[4] http://myzeo.com. {accessed Dec.28, 2010}.
[5] http://www.tylenol.com/sleeptracker/index.jhtml. {accessed Dec.28,'10}.
[6] http://mdlabs.se/sleepcycle. {accessed Dec.28, 2010}.
[7] http://beta.yawnlog.com. {accessed Dec.28, 2010}.
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[9] http://biobrite.com. {accessed Dec.28, 2010}.
[10] http://nandahome.com. {accessed Dec.28, 2010}.
[11] http://www.hammacher.com/publish/73755.asp.{accessed Dec.28,'10}.
[12] http://signs-studios.com. {accessed Dec.28, 2010}.
[13] http://www.sleepmate980a.org. {accessed Dec.28, 2010}.
[14] http://stresseraser.com. {accessed Dec.28, 2010}.
[15] http://www.heartmathstore.com. {accessed Dec.28, 2010}.

people who are separated by space and time. *Aura* [20] uses an eye mask to detect eye movements and transmit musical signals of sleeping status to a remote device. Dodge's "*The Bed*" [6] uses different sensors to detect a sleeping partner at a distance and transmit signals back to the other person using a number of outputs, such as warmth, a heartbeat, or whispers. *Reverse Alarm Clock* [22] helps young children know whether or not it is a good time to get out of bed. Finally, the *Sleep Cycle*[6] product mentioned above allows users to upload sleep graphs to their Facebook accounts.

Summary

Although a number of sleep-related technologies already exist, there are plenty of opportunities and room for innovation. Much of the existing literature in HCI has not systematically looked at people's needs in regard to sleep and their current practices. Also, there appeared to be a lack of discussion around the design implications of technologies that are being used in a bedroom where people are often sleepy and groggy. Finally, we could not identify specific studies on the effectiveness or acceptability of many of the existing in-home sleep sensing products. This work endeavors to help identify and address these gaps, as well as lay the groundwork for future design opportunities.

STUDY PROCEDURE & POPULATION

To help uncover opportunities to support sleep, we used a mixed-method approach in our investigation. We began by conducting interviews with experts at the sleep disorders center affiliated with the University of Washington's medical school (N = 4). These interviews helped to inform the design of the remainder of our study elements, which included an online survey (N = 230) followed by in-depth, semi-structured interviews with a subset of the survey respondents (N = 16). In this section, we describe our procedure, populations studied, and the data analysis methods that we used.

Contextual Interviews with Sleep Experts

We interviewed four sleep experts. Our first interview was with the co-director of the sleep disorders center affiliated with our university, who has an M.D. in Neurology and is certified in Neurology and Sleep Medicine. During this interview, we learned about good sleep hygiene, different sleep disorders and their respective treatments, and existing sleep-related technologies. We were also given a brief tour of the sleep disorders center where overnight sleep studies are performed to diagnose different disorders. On a subsequent visit, we conducted a group interview with the co-director and three technicians. During this second visit, we were shown how a sleep study is conducted and reviewed anonymous data collected from patients during a sleep study. We collected artifacts that the center provides on good sleep health, forms used for sleep studies, and blank copies of the sleep diaries that patients complete at home to help doctors with the diagnosis of sleep disorders. The co-director then became a member of the design team and is a co-author on this paper, and thus that perspective is reflected throughout this work. The contextual interviews also informed the design of the online survey as well as our overall understanding of many aspects of sleep.

Online Survey

Based on our literature review and interviews with the sleep domain experts, we developed an online survey to help define requirements for technologies to support sleep. Questions focused on what people perceived to affect their sleep habits, their needs for supporting healthy sleep, and what they believed they would be willing to use in terms of technology. The survey also asked about experiences with sleep disorders and current practices for inducing sleep or waking up. There were a total of 34 questions with a mix of open-ended, Likert, and multiple-choice types.

To recruit survey respondents, we posted paper flyers with the URL of the survey in public locations around the Seattle area, as well as posted a link to the survey on general purpose online discussion forums, websites for people with sleep disorders, and the researchers' social network pages. To encourage participation, each respondent was entered into a drawing to win one of three $50 USD Amazon.com gift cards. In total, 230 respondents completed the survey. Their basic demographics are provided in Table 1. There was a slight bias toward younger, college-educated females. Most respondents were from the United States.

Total Respondents = 230	
Gender	Female (57.8%), Male (41.7%)
Age Range	21 or under (18.7%), 22-30 (37.0%), 31-40 (21.7%), 41-50 (12.2%), 51-60 (7.4%), 61 or older (2.6%)
Highest Education Level Completed	Some high school (1.7%), High school (4.3%), Some college (20.8%), College degree (22.9%), Some graduate education (16.0%), Graduate or professional degree (31.2%), Training certificate (2.2%)

Table 1. Demographic information for survey respondents.

Semi-Structured Interviews

In the online survey, respondents were asked to provide their email address if they were interested in participating in a follow up interview. Among those who volunteered, we selected 16 interviewees (10 females, 6 males) based on diversity of demographics, interest in sleep technology, and experience with different sleep disorders. According to self-reported survey data, four participants had no sleep disorders, while 12 had experienced aspects of sleep disorders such as sleep apnea, insomnia, parasomnia, narcolepsy, and severe snoring. We conducted the semi-structured interviews in person or over the phone; interviews were audio recorded and transcribed. Each participant received a $15 USD Amazon.com gift card. The interview focused on the participants' sleep routines, factors affecting sleep, attitudes toward sleep technologies, and any sleep-related issues that may be addressed by technology.

Data Analysis Methods

To analyze qualitative data from the interview transcripts and open-ended survey responses, we segmented direct quotes that represented a single idea. Four researchers used affinity diagramming to categorize the segmented quotes

into similar themes. Some themes were structured around the questions (i.e., sleep aids and waking methods) while other themes emerged from the data (i.e., sleep related health goals, factors affecting sleep). From the initial grouping, two researchers independently re-sorted the ideas, and then compared their results. They discussed ideas upon which they did not initially agree (approximately 20% of the ideas) and came to a consensus after a series of refinements. For the quantitative data collected from the survey, we present descriptive statistics.

RESULTS

In this section, we present findings from our study with a focus on current sleep practices, factors affecting sleep, sleep-related health goals, and attitudes toward sleep-related technologies. Opinions from sleep experts are interwoven into each section to provide additional information in context.

Current Practices

Many survey respondents reported having inconsistent sleep schedules and sleeping for longer on the weekends (M = 8.97 hrs, SD = 3.58 hrs) than weekdays (M = 7.40 hrs, SD = 2.46 hrs). Moreover, 27% (n = 62) of the respondents reported that they did not have regular sleep habits where they slept for a continuous stretch; they instead slept in intervals using frequent naps. Nonetheless, many survey respondents were aware of the importance and benefits of establishing a healthy sleep routine and reported strategies that they had attempted to maintain a routine that they believed would make them feel less tired during the day.

Factors Affecting Sleep

Responses from the surveys and interviews suggested that numerous factors might have impacted an individual's sleep. Some factors were beyond their control whereas others were something that could have been corrected if they had adequate knowledge about sleep hygiene.

Commitments and Stressors

The survey data showed that sleep and wake times were often determined by external factors, especially job and school, which often competed with healthy sleep habits. Work- and school-related commitments were by far the highest number of all the commitments that may have impacted people's sleep patterns. Full time workers' sleep schedules tended to be more consistent compared to those of part time employees and students. People who reported having erratic sleep schedules included caregivers for babies, new mothers, graduate students, professors, medical students, and the unemployed. As shown in Figure 1, stress, fears, and worries that stem from work, school, or their personal life were common sleep disruptors as they caused racing thoughts and thus made it difficult to fall asleep. Other sleep disruptors that were beyond the respondents' control included side effects from other medical conditions, pain, needing to use the bathroom, pets keeping them up or preventing restful sleep, hectic lifestyles, nightmares, and family situations such as:

Survey Respondent (F, 31-40): *"Right now my life is chaotic! I use* [sic] *to have very regular patterns of sleep & wake but due to personal issues (divorce, relocation) I do not have a regular routine any more and typically use Tylenol PM to get to sleep."*

Environmental Factors

A number of respondents and participants noted that environmental conditions often made restful sleep difficult. This included too much light, street noise, loud neighbors, or the temperature of the room being too hot or too cold (Figure 1). According to the National Sleep Foundation, noise levels as low as 40 decibels or as high as 70 decibels can disrupt sleep, as well as the absence of a familiar noise, such as a fan or wind chime. Ideal temperature level is more individualistic although in general, temperatures above 75 degrees Fahrenheit or below 54 degrees Fahrenheit disrupt sleep. Other disruptors that are not listed in Figure 1 included guilty pleasures such as late night caffeine or alcohol, playing video games, or surfing the web.

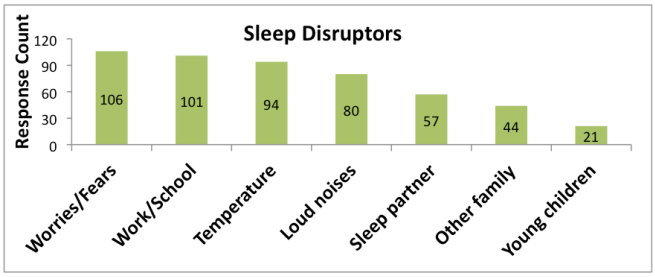

Figure 1. Frequent sleep disruptors from the survey. Participants could select more than one response.

Strategies for Aiding Sleep

Figure 2 shows survey responses on sleep aids. Interestingly, *temperature* was reported as one of the most popular sleep aids in addition to being a sleep disruptor. Uncomfortable sleep environments led people to devise strategies to control their environment. This included installing heavy curtains, using earplugs or blindfolds, covering up with a blanket, and using microwavable heat packs. Others attempted to relax or drown out unwanted noises with music, TV, fans, or white noise machines that play nature sounds. An interview participant explained:

Interview Participant (F, 31-40): *"I put the TV on the cartoon channel, and I have the volume on really low. It helps by being like white noise for me. I live on a fairly busy street and it helps to drown out the traffic noise from outside."*

Physical activity was another popular sleep aid, which participants thought to be helpful for their sleep. Sleep doctors, however, suggest avoiding intense exercise within three hours before sleep because it stimulates the heart, brain, and muscles, which makes it harder to go to sleep. This implies that the type of exercise people do and the time of day should be carefully chosen so that it does not impede having a good night's sleep. Other strategies people often used to help them go to sleep included: music; meditations; mental exercises; drinking warm milk, tea, or alcohol; taking a warm bath; listening to rain falling on the roof; reading; watching TV; surfing the web; and sex.

While many people mentioned lighthearted activities and mental relaxation methods to prepare for sleep, there were other extreme lines of thought such as staying up until feeling tired or exhausted and working hard until right before going to bed. Several interview participants and survey respondents used medication or diet to help them fall asleep, although most admitted that this was not a sustainable solution and had varying success. The sleep experts also stressed that sleep medications can become addictive; they typically do not recommend the use of medication except in extreme circumstances. The survey and interview results suggest that people often had misconceptions about what could help them to sleep better, and that there is room for technology to help bridge the gap by providing accurate and customized sleep hygiene information.

Technology to Help Waking

Survey respondents were asked to choose one or more strategies that help them to go to sleep. Most respondents used some sort of alarm clock, the majority of whom used the alarm clock on their cell phone (60.4%) or a standalone alarm clock (50.9%). They had strong opinions about the use of alarm clocks, which ranged from a need to have soothing music or nature sounds to which to wake up, to as loud of a sound as possible, to the elimination of the alarm clock entirely. Some felt their alarm clocks gave off too much light or were overly complicated to use while groggy. Most felt their alarm clock needed to be as simple to use as possible. Many also made extensive use of the "snooze" feature, which delays waking by shutting off the alarm and ringing it again a set number of minutes later. Others used multiple alarms to ensure that they would get out of bed. However, the noisy alarm was more or less seen as a necessary evil.

Interview Participant (F, 51-60): *"I try and turn off the alarm before it goes off. That noise will just ruin my whole day."*

Some participants had success with gentler methods of waking, such as the use of a "dawn simulator" that gradually brightened the room, for example,

Interview Participant (F, 22-30): [on success of dawn simulator] *"I think it was just something about waking up more gradually just felt more natural, like I've been rested as opposed to just like being jarred awake by a loud noise."*

As such, participants seemed to have an inner tension between wanting to wake up gently and yet a need to use one or more clamorous alarm clocks to awake on time. Interestingly, sleep experts typically do not recommend using an alarm clock because in an ideal world, people would not need them, and rather they would just wake up when they were rested. However, in some patients with idiopathic hypersomnia where rising in the morning can be particularly problematic, sleep experts recommend multiple alarm clocks, some placed away from the bed, to facilitate waking. The experts also suggested turning the face of the clock away from the bed once the alarm is set so people do not see the time while in bed, as it can increase anxiety.

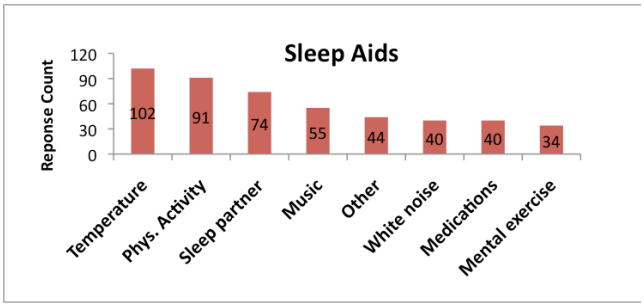

Figure 2. Strategies used by survey respondents to go to sleep. Respondents could select more than one response.

Sleep-Related Health Goals

Many survey respondents and interview participants wanted to become better educated on good sleep habits. This included improving the consistency of their sleep by going to bed and waking up at the same times everyday or becoming more of a "morning person" to synchronize with others around them.

Interview Participant (F, 31-40): *"I'd definitely like to go to sleep earlier. (…) My sleeping schedule is horrible and I need to fix it….I might go to bed at 2 in the morning but I usually don't fall asleep until maybe 3 or 4… it's not that I'm lazy, it's just how my sleep cycle is. I'd like to be able to change that so it's a little more in sync with most of the people around me."*

Others were interested in breaking bad habits, such as a dependence on sleep medications and letting work, homework, or other distractions (e.g., books, television, the Internet) interfere with their sleep routines.

Survey Respondent (F, 21 or under): *"One of my goals is to be able to sleep through the night without the use of medication, but that has never become a reality."*

In some cases, participants who were already aware of their bad sleep habits suffered from a lack of motivation to do something about it. For example,

Interview Participant (F, 51-60): *"I have a tendency to read in bed, and if I'm in the middle of a good book, I'll read all night. I can't put it down... Or like last night there was a really great show about kamikazes. I was going to go to bed, but I started watching it… I was going to go to bed around 12, but I stayed up."*

Establishing consistent and healthy sleep patterns is another important sleep-related goal, but this is especially challenging for people with insomnia. When insomnia patients see a sleep doctor, the doctor first monitors patients' sleep patterns by keeping track of their sleep data for about two weeks using either a sleep diary or an actigraphy device. From this data, doctors calculate the patients' sleep ability—how many hours someone can actually sleep—and prescribe times they should go to bed. This is part of *Cognitive Behavior Therapy* (CBT) that has a goal of creating a consistent sleep cycle for insomnia patients. Doctors recommend creating a nighttime routine because it contributes to having a consistent sleep cycle—consistent to-bed and wake up times. The routine would include creating a suitable sleep environment (e.g., dimming the lights), and engaging in an activity that helps

people go to sleep. One interviewee illustrated the success of her pre-sleep rituals as a way to get prepared for bed and stated that if she did not do these rituals, she often had trouble sleeping.

Interview Participant (F, 51-60): *"I make my lunch, I pick out my uniform for the next day, I get everything ready by the door, I do my toiletries, I get my bed ready, it's quite a ritual, then I watch TV for awhile and do Sudoku."*

Attitudes toward Technologies for Sleep

The survey respondents were asked about their attitudes toward using technologies for sleep. Overall, 62.6% (n = 144) of survey respondents answered "Yes" or "Maybe" to the question on whether they would be interested in using a technology to help them sleep. We looked further into the characteristics of these people who were open to the idea of using technologies for better sleep. A chi-square test of independence was performed to examine the relation between attitudes toward using technologies and experience with sleep disorders. The relation between these variables was significant, χ^2 (1, N = 230) = 9.80, p = .002. This suggests that respondents who were interested in using technologies for sleep were more likely to have experienced sleep-related problems than those who were not interested. Those who were interested had experienced sleep-related problems such as having trouble waking up (54.2%) or falling asleep (40.3%), insomnia (51.4%), and mood disorders such as depression or anxiety (50%).

Of those who responded "Yes" or "Maybe," we asked them to report on their level of interest of different features for sleep technologies. Some popular features were recording sleep data automatically, assessing the quality of sleep, recommending optimal sleep conditions, and tracking and reviewing sleep data over time. Other features respondents would like to see included: screening for the presence of sleep partner's snoring; daylight simulation; recording dreams; and helping them set and maintain regular routines. Many were particularly enthusiastic about ideas that would help them fall asleep faster, help them have quality sleep throughout the night, and help them feel rested when they wake up. Some were interested in determining their optimal sleep cycle:

Survey Respondent (F, 31-40): *It would be nice to know how much sleep I SHOULD be getting and also why I don't crash the day after no sleep... knowing how long I have before that sort of thing catches up to me would be nice.*

Though not surprising, some of the main requirements included the ability to customize the alarm sound and bedroom light levels to cater to different preferences, augment existing technologies when possible (e.g., cell phone) rather than introducing new ones, and be cost effective. Several respondents recounted discarding poorly designed alarm clocks out of frustration.

Technology features that were the least popular included those that required manual input of data and those that shared data within a social network. When participants speculated about their attitudes toward wearable sensing technologies (e.g., *SleepPhase*[3]), they liked the idea of tracking sleep data, but were resistant to the thought of having to wear a special device every night.

Interview Participant (M, 22-30): *"I wouldn't like attachments to my body while I sleep. That would be uncomfortable. It would have to be something like you put it on your nightstand and records all that stuff. If you gotta attach something to your head or to your hands or something, I wouldn't want that."*

Many also emphasized that simplicity and unobtrusiveness were crucial. Although these are important qualities for many technologies, they are especially important for something used every day and at a time when people are typically sleepy or groggy, making them even less willing to deal with complex user interfaces than typical users.

Survey Respondent (F, 31-40): *"Minimal effort on my part. I wouldn't do something that takes a significant amount of time or thought, especially in the morning (I am not a morning person)."*

It is worthwhile to mention that 38.5% (n = 89) of survey respondents were not interested in using any technology for sleep. When we asked why, many remarked that they did not have anything they wanted to change about their current habits, did not see how technology could help them, or did not want "yet another technological intrusion" in their lives. Many people in this group reported that they were in control of their sleep patterns, and were able to fall asleep and wake up when they want to. Thus, if they were up late at night, it was usually by choice.

DISCUSSION

Our results uncovered a number of design opportunities and insights for technologies to encourage and support healthy sleep behaviors. To help identify new areas of exploration, in this section, we describe a design framework for sleep technologies. We also discuss a number of design considerations and opportunities for technology designers who are interested in working in this space.

Design Framework

Based on our literature review and formative study, we have mapped out a preliminary design framework for technologies to encourage and support healthy sleep behaviors. Our intent is to help technology designers, researchers, and clinicians in understanding the spectrum of possibilities and identify the current gaps in the design space. Our proposed design framework consists of six dimensions, within which are several elements. It is possible for a technology to have multiple elements within each dimension. The six dimensions are:

- **Goal:** What is the goal of the system relative to sleep habits? Elements include: diagnosis; treatment; monitoring; waking; and sleep inducing.
- **Features:** What are the primary features of the specified system? This includes features for: tracking sleep information; persuasion; education on aspects of healthy sleep habits; awareness; relaxation; social applications; and entertainment applications.

- **Source:** What is the source of the design or strategy used by the sleep technology? The sources include: sleep medicine community (e.g., clinically-validated sleep therapy, guidelines from the National Sleep Foundation, sleep experts, or doctors); peer-reviewed literature (e.g., general behavior change techniques from psychology, HCI, preliminary study); other literature (e.g., books about theory, design, sleep); popular media (e.g., news, magazine, blog post); folk wisdom; or none.
- **Technology Platform:** What technology form factor does the application use? This includes: wearable technologies; stand-alone appliances (e.g., an alarm clock); mobile applications; web applications; software running on a PC or laptop; or ubiquitous computing.
- **Stakeholders:** Who are the stakeholders of the specified application? This includes people with sleep disorders; without sleep disorders; indirect stakeholders (e.g., bedmate); sleep clinicians; and sleep researchers.
- **Input Mechanism:** How does the user interact with the application? This includes: manual input by user; automatic entry via sensors or some other mechanism; or none.

We have applied the framework to 10 existing sleep-related commercial products and research projects that represent a broad spectrum of goals (Table 2). To illustrate the framework, we characterize the popular Zeo Sleep Coach[4] appliance as an example: Zeo has the goals of *monitoring* and *waking*; the features of *tracking* and *education*; the sources of *peer-reviewed literature* (for example, see [15]); the technology platforms of *stand-alone appliance*, *wearable*, and *web;* the target users of those *without disorders*; and input mechanisms of both *input by user* and *automatic*. Table 2 shows that there is still room for opportunity to design sleep technologies that that have the goals of in-home *diagnosis* and *treatment*, the features of *persuasive* and *education*, and finally, the form factor of *ubiquitous* and the input mechanism of *automatic*.

The framework also reveals that not many of these technologies, including Zeo, have been validated nor recommended by the sleep medicine community although many have the source of peer-reviewed literature. We note that not many technologies have the luxury of undergoing a thorough clinical trial, which limits their ability to be recommended by the sleep medicine community. But at the same time, we do want to emphasize that clinical perspectives toward technology interventions may not always be straightforward. This is exemplified by the actigraphy device, which took 20 years of research before the American Academy of Sleep Medicine officially announced that the device "may be a cost-effective method for assessing specific sleep disorders" [1].

Considerations and Opportunities

In this section, we outline some additional considerations that we uncovered as a result of this research and how they impact design opportunities for technologies that support healthy sleep behaviors.

Tracking Sleep Trends over Time

Tracking sleep is an important feature for technologies that aim to help monitor or aid in diagnosis. For those without sleep disorders, tracking sleep is not necessarily required, but can help them increase their awareness and encourage healthy behavior change, similar to other health- and wellness-related applications (e.g., a pedometer). For those who have sleep problems, tracking sleep is helpful for both clinicians to diagnose problems with and for individuals to reflect on their sleep habits. However, most existing products rely on wearable sensors or continuous manual input, which many participants stated were undesirable. While highly motivated people who need to diagnose serious sleep problems may be willing to wear these devices for a short duration, wearable sensing solutions are often uncomfortable and people may simply forget to wear (or charge) them, making them unsuitable for long-term sleep tracking. This presents an opportunity to develop

	Goal	Features	Source	Technology Platform	Stakeholders	Input Mechanism
Actigraph	Monitoring, Diagnosis	Tracking	Sleep medicine community	Wearable, PC/Laptop	With Disorder, Clinicians, Researchers	Input by user, Automatic
WatchPAT[1]	Monitoring, Diagnosis	Tracking	Sleep medicine community	Wearable	With Disorder, Clinicians, Researchers	Automatic
BioBrite[9]	Waking	Relaxation	Sleep medicine community	Stand-alone	With / Without Disorder	Input by user
SleepMate[13]	Sleep Inducing	Relaxation	Peer-reviewed literature	Mobile	Without Disorder	Input by user
Zeo[4]	Monitoring, Waking	Tracking, Awareness	Peer-reviewed literature	Stand-alone, Wearable, Web	Without Disorder	Input by user, Automatic
BuddyClock [11]	Waking	Persuasion, Social	Peer-reviewed literature	Stand-alone	Without Disorder	Input by user
Reverse Alarm Clock [22]	Monitoring, Waking	Tracking, Persuasion, Education, Social	Peer-reviewed literature	Stand-alone	Without Disorder	Input by user, Automatic
Clocky[10]	Waking	Persuasion, Entertainment	Popular media	Stand-alone	Without Disorder	Input by user
SleepCycle[6]	Monitoring, Waking	Tracking	Popular media	Mobile	Without Disorder	Input by user, Automatic
Standard Alarm Clock	Waking	None	Folk wisdom	Stand-alone, Mobile	Without Disorder	Input by user

Table 2. Design framework of technologies for supporting healthy sleep behaviors

unobtrusive solutions that allow users to monitor their sleep schedules without requiring them to wear anything.

The sleep experts noted that precise sleep measurements were not necessarily needed to have a meaningful picture of sleep behaviors and trends. For this reason, we believe that a reasonable compromise can be made between accuracy of sleep data and unobtrusiveness of sensing. A remote sleep sensing tool that has one or more sensors (e.g., pressure, passive infrared motion) may provide a sufficient estimate of objective sleep data, such as frequency and duration of sleep, number of awakenings throughout the night, and sleep latency (the time elapsed from lights out until sleep onset). In addition, technologies could monitor sleep environments and create good sleep conditions with simple sensors such as light spectrum, light intensity, audio, and temperature sensors. Such tools can be incorporated into a smart home control system to assess the environment and automatically adjust the room temperature, for example, to prepare for bedtime.

Because much of the sleep-related sensing is likely to take place in the bedroom, there are often constraints such as other occupants in bed (e.g., a sleep partner or a pet). Not only can this create confusion for the sensors, but it can also raise privacy concerns. Technologies to support sleep should protect users' and any sleep partners' privacy by making it clear whose data the system is collecting, when the data is being collected, where the data is being saved, and who has access to it.

Persuasive Technology for Healthy Sleep Behavior

Interview participants had a wide range of goals for improving their sleep, such as improving the consistency of their sleep patterns, becoming a morning person, and breaking bad habits that affect sleep. To help people accomplish these goals, persuasive technologies may help encourage healthy sleep behaviors. Persuasive techniques could be incorporated into games, social support systems, goal-setting features, or timely reminders, all of which can motivate people to improve their sleep.

Keeping a consistent to-bed and wake time is an example of a sleep-related health goal. Many survey respondents and interview participants had good intentions for going to bed at a reasonable time, but would often lose track of time or become distracted by books, computers, video games, or TV. In addition, people with insomnia or delayed sleep phase syndrome often cannot go to sleep when they want to. One way to help people deal with this problem is to have them set healthy sleep goals (i.e., consistent to-bed and wake times) [14] and increase the visibility of these goals through visualization of the data and timely reminders.

To facilitate goal commitment, a persuasive sleep application may guide users to commit to an achievable goal through setting an alarm every day, with the default setting being the suggested wake time. The user's sleep goal can also be identified based on a prescribed sleep schedule from a sleep specialist. The sleep goals can then be added to other applications (e.g., an online calendar system, smart home control system) to provide ambient notice when bedtime nears to help users get ready for sleep.

Tensions between Technology and Sleep

While we explored design opportunities for technology to support people's healthy sleep behaviors, a number of study participants expressed their concerns toward the instrumental examination of sleep. Technology that suggests that a person should sleep more or less, should not drink coffee or alcohol at night, should turn off the TV or computer, and should go to bed at a certain time may be met with resistance. Thus, it is important to consider how to design the technology to help people become more mindful of their sleep and behaviors that affect sleep while not feeling as if their lives have been invaded by these devices.

In fact, it is conceivable that a user's sleep may be hampered by the use of technologies in the bedroom, and a sleep technology could be another entry in the long list of technologies that are already being used in the bedroom that disrupt sleep. For this reason, designing sleep technologies to not impede people's sleep quality is an important consideration and a topic that we intend to explore further.

Cultural Differences in Sleep

Across different cultures, interpretations of sleep and what constitutes "normal" sleep vary. Our study participants were primarily within the U.S., and thus the study results and discussion reflect U.S.-centric perspectives on sleep. We note that a study of the perspectives of people in countries with a *siesta* culture where taking an afternoon nap is prominent may have drawn very different design ideas. Similarly, cultural influences on infant sleep vary. Parents' co-sleeping with infants/children is practiced in Asian cultures where interdependence and group harmony are valued [19]. American parents, on the other hand, generally seek separateness through enforced solitary sleep of their infants/children. Design specifications of sleep monitoring may be much different depending on the target audience's family context and cultural background.

CONCLUSION AND FUTURE WORK

The work presented in this paper sought to uncover how computing technologies could be used to help people set and maintain healthy sleep behaviors. To understand the space, we conducted a contextual inquiry, online survey, and interviews on the opportunities for and feasibility of technologies to support healthy sleep. Based on our results, we proposed a design framework for technologies that support healthy sleep behaviors and discussed considerations and opportunities that can be used to develop further ideas in this domain. We are developing and evaluating technologies to support healthy sleep behaviors, and we encourage other HCI researchers and designers to use our findings to innovate as well. Finally, we would like to note that the work in this paper is focused on general sleep health for adults. There are several sleep disorders and different age groups that we did not explore fully, which could benefit from designs specific to the needs of those

particular disorders or age groups. In closing, we believe that the HCI community can make a meaningful impact in this relatively underexplored area that can potentially affect many people's quality of life.

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