ISYS90044 Minor Research Project in Information Systems

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Sleep with Technology: Challenges and Opportunities for Sleep Tracking

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Declaration

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person where due reference is not made in the text.

The thesis is 6750 words in length (excluding text in images, table, bibliographies and appendices).

Wanyu Liu

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Abstract

Prior work has examined how single computing system can support sleep and how potential users view sleep technologies. Tracking sleep can help users better understand their sleep patterns and even assist in improving sleep quality. With the emergence of a growing number of commercial sleep tracking products, yet how current users interact with these technologies remains unknown in HCI community.

I conducted a qualitative study aimed at understanding how current users of sleep tracking technologies practice sleep tracking, with a focus on what are the challenges they have encountered. I examined three types of sleep tracking technologies: Mobile applications, wearabales and embedded sensors, and collected fifty-one threads from five online forums mixed with personal informatics enthusiasts and general users. Twenty-two single challenges were identified under four themes: Tracking continuity, Trust, Data manipulation, Making sense.

Based on these results, I proposed six design opportunities and considerations targeting each of these challenge themes: Balancing Engagement and Automation; Ensuring Tracking Continuity; Explicating Technology Transparency; Empowering Data Ownership; Allowing Data Flexibility; Providing Feedback Instructiveness. These implications provide further insights for both researchers and practitioners to further improve sleep-tracking technologies.

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Introduction

Researches have shown that even a few nights of poor sleep can have severe effects on aspects of daily life: alertness, memory, mood and cognitive function (Altena et al., 2008; Chandola et al., 2010). Chronic sleep problems are often related to several other health conditions (Mai & Buysse, 2009). Tracking sleep habits can help raise individual's awareness to the problem, as can persuasive technologies designed to motivate good behaviors (Fogg, 2002).

Traditional clinical trials, such as Cognitive Behavioral Therapy (CBT), to deal with sleep problems are relatively obtrusive, costly and inaccessible for daily users (Morin et al., 2009). With the development of technology, movement of Quantified Self (QS), an international collaboration of users and makers of self-tracking tools, researches in personal/health informatics, sleep tracking became more usable and acceptable for everyday use. Currently, a large number of sleep monitoring and tracking technologies are accessible for general public who either desire to solve sleep problems or are curious about their sleep patterns. These technologies can be roughly categorised into three types based on their platform and tracking nature: mobile applications, wearables, and embedded sensors.

Some of those mobile applications are barely more than digital dairies (Sleep Journal); others, however, use accelerometer and microphone in mobile phones to monitor movement and sound respectively during the night (SleepBot). More sophisticated wearable systems track sleep through various built-in sensors. It is worth noting that there are currently three sub-categories that can be considered as wearables as they all require users to wear the technology on them. Firstly, Fitness trackers such as Fitbit[1] and SleepTracker[2]; secondly, a specific headband sleep tracker Zeo[3]; thirdly, smart watches such as Microsoft Band[4]. Technologies in new forms, though still in infancy, for example, Withings Aura[5], Beddit[6], and Hello Sense[7], provide an unobtrusive way to combine sleep behavior tracking and environment monitoring. Apart from these three types, new generation of technologies keep emerging. For instance,

[1] http://fitbit.com

[2] http://sleeptracker.com

[3] http://myzeo.com

[4] http://microsoft.com/Microsoft-Band/en-us

[5] http://withings.com/us/withings-aura.html

[6] http://beddit.com

[7] https://hello.is

ResMed S+[8] adopts a contactless method to measure sleep quality; Luna[9] introduces a smart mattress that can not only track sleep but also allow smart home integration.

Although various sleep-tracking technologies are widely available and new technologies keep emerging, how users interact with these technologies has barely been studied systematically in HCI community. To explore current users' experience and practices of using sleep-tracking technologies, particularly the challenges they have encountered, I conducted a qualitative study to explore challenges and opportunities for sleep tracking. I begin by going through existing relevant research, demonstrating research gap, illustrating research question and defining research scope. I go on to describe research design, including data collection and analysis method. I then present findings and implications that can be drawn from the results. I finally conclude the future directions for this area of research.

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[8] https://sleep.mysplus.com

[9] http://lunasleep.com

Related Work

Sleep Measurement

Sleep and sleep quality have a strong connection to healthcare but measuring sleep is a complex process as it involves various determinants. The gold standard of evaluating sleep is polysomnography (PSG), which combines a person's physical measurements all night yet requires a large amount of well trained specialists and specific equipment. A simpler approach is to use Actigraphy, which captures a person's movement through an accelerometer. Both of them are used in clinical settings thus unsuitable for daily use. Although being less accurate than polysomnography, Actigraphy still precisely measures sleep efficiency (SE), which is determined by the time a person goes to bed, the time he or she gets up, the time taken to fall asleep initially (sleep onset latency, SOL), time awake over night after sleep onset (WASO), and total sleep time (TST) (Ancoli-Israel, 2003).

Commercial sleep tracking products adopt simplified strategy to measure sleep and sleep quality. Though being built on different platforms, most of them are movement based. Mobile applications use built-in accelerometer and microphone to track movement and to record sound respectively while in bed (e.g., SleepBot). Most wearables, such as Fitbit, often determine users' stages of sleep throughout the night as well as the quality of their sleep through wearable sensors. Being attached to users, they are suggested to be more accurate than mobile applications. Embedded sensors, being tucked under mattress, provide a less obtrusive way to monitor sleep as well as to examine the sleep environment. However, all these systems' hardware design tends to be significant different and many are closed-source systems that have not been clinically tested (Borazio et al., 2014).

Sleep Research in HCI

In addition to a large number of commercial sleep trackers, researchers in HCI have placed more attention on ways that technology can support sleep. Mhóráin and Agamanolis (2005) developed an eye mask, Aura, to detect eye movements during sleep; Lawson et al. (2011) came up with a mobile application, Sleepful, which emitted low frequency noise to track and analyse people's sleep quality; Kay et al. (2012) designed a system called Lullaby to track and to better understand how sleep environment can affect sleep; Shirazi et al. (2013) presented a bedside device Sleep Compete for promoting healthy sleeping habits in children; Chen et al. (2013) introduced a novel model, Best Effort Sleep (BES) to measure sleep duration; Min et al. (2014) adopted a smartphone system, Toss 'N' Turn, to detect and determine sleep quality; Nagata et al. (2015) presented a nap supporting system by using a heart rate monitor; Kaur et al. (2015) designed Sleepstellar that includes a safety kit to protect sleepwalkers and a platform to encourage digital storytelling for overcoming embarrassment issues.

A comprehensive review work can be found in Choe et al. (2011). Several design opportunities and insights for technologies to encourage and support healthy sleep behaviors have been demonstrated based on literature review and formative study with sleep experts and potential users. Choe et al. (2011) explicated that participants who suffered from various sleep disorders were more interested in using technologies for sleep and would like to adopt a technology that is simple and unobtrusive to improve sleep health. Sleep technologies are also suggested to be persuasive in order to promote healthy sleep behaviours.

Personal Informatics and Quantified Self

The concept of personal informatics has recently emerged as a research topic within HCI community (Li, Dey & Forlizzi, 2011). It emphasises people's desire to obtain personally relevant information for promoting self-knowledge and self-reflection. Personal informatics systems provide an advantage to facilitate collection and storage of personal information, and to help individuals explore as well as reflect on the information more insightfully (Li, Dey & Forlizzi, 2010).

There are five phases involved in the stage-based model (Li, Dey & Forlizzi, 2010) as shown in Figure 1. Individuals firstly decide what information they are going to collect and what tool they are going to use in preparation stage. They then collect data during collection stage, integrate data for reflection, and take corresponding actions based on reflection.

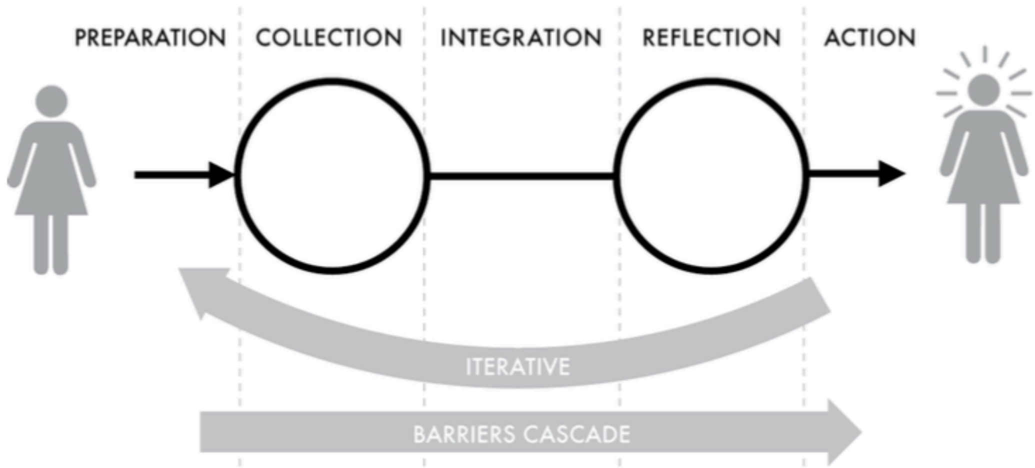

Figure 1. A stage based model of Personal Informatics Systems. (Source: Li, Dey & Forlizzi, 2010)

Being a community where self-tracking enthusiasts and technology early adopters gather, Quantified Self has received significant attention within HCI community. The prevalence of understanding Quantified Self tools and exploring how Quantified Selfers (Q-Selfers) practice self-tracking has accelerated personal informatics research.

Li, Dey and Forlizzi (2010) proposed the five-stage personal informatics systems design model based on the data partially collected from Q-Selfers. In the follow up research, they (Li, Dey & Forlizzi, 2011) recruited participants, a portion of whom were from Quantified Self website, and examined collection and reflection stages in particular. Choe et al. (2014) and Whooley, Ploderer and Gray (2014) examined Quantified Self videos to understand how Q-selfers practice data collection and integration respectively. Oh and Lee (2015) collected data from Quantified Self forums and explored UX issues in Quantified Self technologies. Researches focusing on this group are suggested to generate valuable insights for personal informatics at large.

Gap Analysis and Research Question

Gap Analysis

Since sleep involves unconscious experience, applying personal informatics systems in sleep provides a favourable way to obtain personal sleep knowledge and thus gains more popularity from general public. Prior work (Mhóráin & Agamanolis, 2005; Lawson et al., 2011; Kay et al., 2012; Shirazi et al., 2013; Chen et al., 2013; Min et al., 2014; Nagata et al., 2015; Kaur et al., 2015) has proposed various novel ideas to support sleep and conducted user test based on their own prototype. With the emergence of a large number of commercial products and the prevalent adoption of sleep tracking technologies, yet how users interact with these technologies remains unknown.

Choe's et al. (2011) study with potential users painted a big picture of sleep technologies back in 2011 and revealed a number of opportunities for promoting sleep health in general. By the time Choe et al. (2011) conducted their research, there were only a few mobile applications and wearables available. Four years later, various sleep-tracking technologies built on different platforms are accessible for daily use. New generations also keep emerging, such as Beddit and Hello Sense, and provide an answer to one of Choe's et al. (2011) design considerations that sleep technologies are suggested to be unobtrusive. However, since embedded sensors are new to the market, few studies have been done to discover users' experience with them.

Research Question

Hence, this aim of this research is to explore:

How current users of sleep tracking technologies practice sleep tracking?

With a focus on:

What are the challenges they have encountered?

Scope

There are various elements involved in sleep and users might adopt sleep-tracking technologies for other purposes, for instance, sleep inducing or waking. To ensure the effectiveness of this work, I only focus on sleep tracking. Therefore, sleep technologies that are designed to provide white noise or to serve as smart alarm are excluded.

Research Method

Data Collection

To uncover the challenges that current users of sleep tracking technologies have encountered, I collected data from online forums where users talk about their own experience with sleep-tracking technologies. Unlike other platforms, online forums are often communities where people with same interests, though from different geographic locations, gather and exchange thoughts freely. Thus, I believe that the discussions they had and questions they asked are representative enough for sleep tracking at large.

It is worth noting that nearly all commercial products, particularly wearables and embedded sensors, have their own websites and forums where customers can raise questions about a particular product which will be answered by customer service staff. The 5 forums I selected are communities where users of various sleep tracking technologies gather: BulletProof Sleep, Lifehacker, Connectedly, Gizmodo, and Quantified Self Sleep. Since Quantified Self provides a platform for personal informatics enthusiasts and technology early adopters, I started from its Sleep forum to collect data, whose external links also led me to the rest four forums. As a whole, individuals from the first two forums are often keen to improve life quality while people from the second two forums are normally technology enthusiasts. Q-Selfers are considered both or either.

Forum threads are selected based on three criteria: 1. Individuals are current users of a certain type of sleep tracking technologies; 2. Users talk about their own experience interacting with technologies in terms of sleep tracking; 3. Users ask certain questions involving any aspect of sleep tracking by using technologies.

In the end, 51 threads (BulletProof Sleep: 18; Lifehacker: 6; Connectedly: 12; Gizmodo: 7; Quantified Self: 8) are selected, with total involved users of 287 and total replies of 1152. Users geographically spread out from North America, UK, Europe, and Asia-Pacific region. These forum threads started from 2011 till up to date. It is noted that discussions around mobile applications and wearables started from the beginning while embedded sensors discussions appeared only after 2013, which is in line with the emergence of sleep tracking technologies.

Data Analysis

There are three steps involved in data analysis. Firstly, all these forum threads were documented in Excel Sheet. Each thread was labeled with website link, technology type(s) mentioned, main topic(s) discussed, comments on copied actual data and some thoughts for later on. This helped me to form an overall perspective of all collected data. Table 1 summarises the technologies in my dataset. It is noted that the table may not be comprehensive as several users did not mention which technology they have been using but saying *"I use my phone to track sleep"* etc.

Technology Type	Technologies
Mobile applications	Sleep as Android; Sleep Cycle; SleepBot; Sleep Meister; Sleep Time; Smart Alarm Clock; Pillow; Sleep Better; Runner-up; Zeo Mobile
Wearables	Fitbit (One, Flex, Charge); Jawbone (UP move, UP 24); Pebble; Misfit (Flash, Shine); Withings Pulse; Garmin Vivosmart; Mybasis; Zeo; Microsoft Band; Razer Nabu; Runtastic Orbit
Embedded sensors	Beddit; Withings Aura

Table 1. Technologies examined.

Then detailed data were transcribed in online qualitative data analysis tool Saturate[10] along with user name and posting time. Paragraphs were segmented, scrutinised and coded. I did not define a coding schema beforehand but identified codes from actual data by repeatedly going through content in each thread, guided by the personal informatics stage based model (Li, Dey & Forlizzi, 2010). At least, 258 instances were identified under 22 codes, which also represent 22 individual challenges.

Lastly, after reviewing these codes multiple times, I used affinity analysis and grouped them in 4 different ways as shown in Figure 2 in order to think them through from different points of views:

1. Challenge themes: individual challenges were grouped into more abstract challenge concepts;
2. Design opportunities: individual challenges were grouped according to future design opportunities;
3. The stage-based model: individual challenges were grouped according to which stage(s) they affect in the stage based model of personal informatics systems (Li, Dey & Forlizzi, 2010);
4. Technology types: individual challenges were grouped according to which type(s) of technologies they affect.

[10] http://www.saturateapp.com

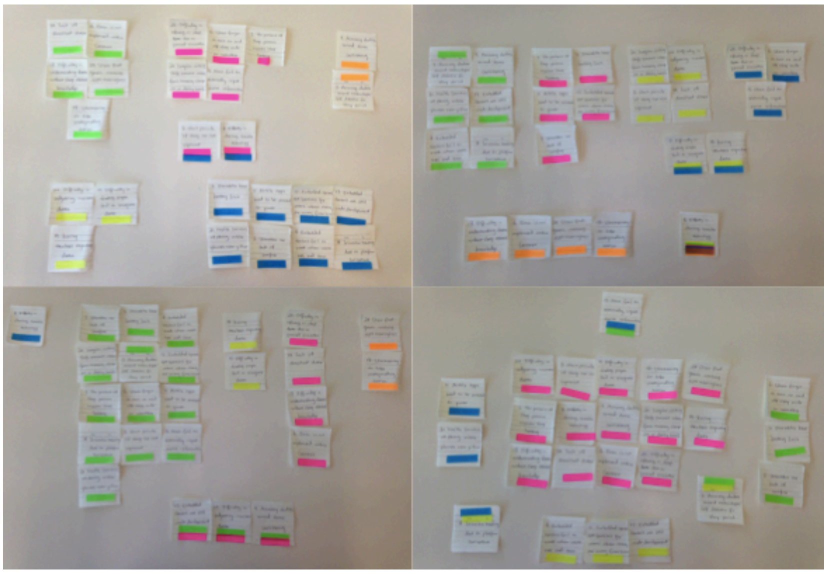

Figure 2. Affinity Analysis.

After gaining a better understanding of these challenges and discussing with supervisors, I eventually categorised them into four challenge themes. A detailed description can be found in the next section.

Findings

In my dataset, users expressed three motivations to adopt sleep tracking technologies: improve sleep quality when they have experienced sleep related problems; curious about their patterns; and desire to incorporate sleep tracking into daily activities, especially when they own a fitness tracker. In the following section, I present 4 challenge categories that current users of sleep tracking technologies have encountered (Figure 3). Under each category, detailed challenges are described along with an example from dataset.

Figure 3. Four themes to describe challenges that current users have encountered.

Tracking Continuity

There are 94 instances stated that users faced challenge of tracking sleep continuously. In order to generate valuable insights regarding sleep, it is necessary to collect data on a continuous manner. However, users articulated that it is difficult to track sleep continuously due to various reasons, either from technology side or from users' different lifestyles. I highlight these types in colors, as shown in Figure 4. It is noted that since embedded sensors are new to market and are relatively pricey, the number of early adopters is limited.

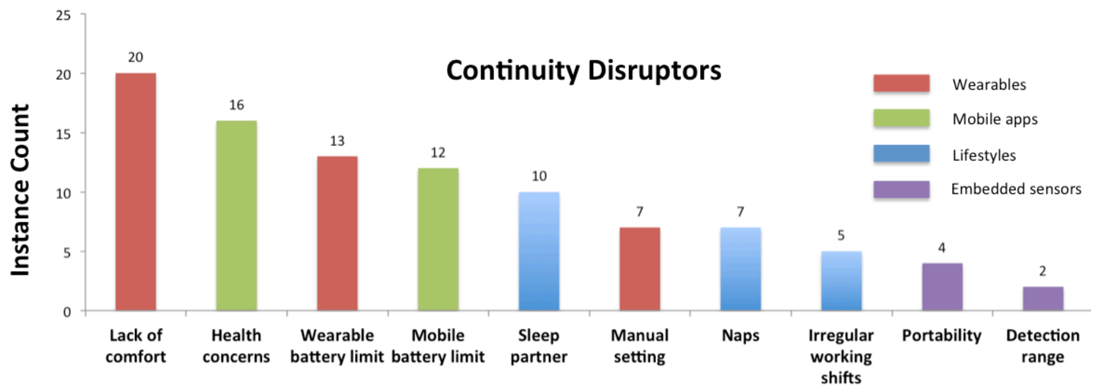

Figure 4. Tracking Continuity disruptors.

Challenge 1#: Lack of Comfort

Though wearables' design is getting better constantly by reducing the size and using skin friendly materials, 20 instances are found stating the uncomfortable characteristic of wearables for sleep tracking, which results in tracking discontinuity.

"Not really comfortable wearing watches to bed, so I sometimes take it (Jawbone) off." (#149592)

Challenge 2#: Health Concerns

Another noticeable challenge is that 16 users expressed health concerns regarding placing mobile phones near pillow to track sleep. Though there are different opinions about leaving mobile phones on bed at night, several users gave up sleep tracking due to safety reasons.

"I have been using the sleep cycle app for about a week now... My only concern is that I am putting my phone next to my head throughout the entire night, is this safe?" (#149922)

Challenge 3#: Wearable Battery Limit

The battery limit of wearables also inhibits users from tracking continuously. Though a number of wearables support long battery nowadays, especially fitness trackers, for instance, Fitbit Force's battery should last about 7 to 10 days, time takes to charge still disappoints users. Moreover, users who adopted smart watches to track sleep particularly have this problem. Since people often tend to do activities during the day, many users charge wearables during the night. Consequently, sleep tracking cannot be done continuously thus some days of sleep data is lost.

"I mean, you have to charge it anyway. So it's your choice to sacrifice activity (tracking) or sleep (tracking)" (#168849)

Challenge 4#: Mobile Battery Limit

Similar to challenge 3, running mobiles or tablets tracking sleep for the whole night requires powerful battery. Therefore, most mobile applications suggest to be connected to power when working. However, users find it difficult to use the application when they are in a situation where no plugs are available near bedside. One user complains that once he was in a hotel where there was no way to charge phone near bedside, the battery drained the next morning, as a consequence, he lost his sleep data due to tracking discontinuity.

"My phone was off the next morning, and guess what, it's all in vain" (#169757)

Challenge 5#: Sleep Partner

In contrast to other personal tracking activities such as fitness or diet, sleep sometimes is not personal. 10 users encountered difficulty in tracking sleep continuously if their sleep partner has negative attitude towards sleep tracking technologies.

"Sometimes if I think I might sleep through my alarm… when at the girlfriends house no (Pebble) as she hate touching watches in her sleep." (#149593)

Challenge 6#: Manual Setting

Most sleep tracking technologies require users to turn on and off sleep mode in order to start and end sleep period while few fitness trackers have introduced automatic sleep detection feature, such as Garmin and Mybasis. For wearables users, since the technology has always been on them, several explicated that they constantly forgot to do so, ending up in tracking discontinuity and data loss.

"You have to start and stop the sleep mode (Fitbit Flex) manually. This has to be done when you go to bed and also when you wake up.... My wife constantly forgot to do both." (#149585)

Challenge 7#: Naps

Since sleep is a highly individualistic activity, different sleep habits may also have influence on sleep tracking. Those users, who are used to take a nap during the day, or tend to get short but polyphasic sleeps, found it a challenge to track short period naps or to generate usual sleep pattern.

"It (Fitbit Surge) even tracks naps well as long as it is over an hour. The only thing it does not do well is track short naps. If I nap for less than an hour, it does not pick it up." (#149618)

Challenge 8#: Irregular Working Shifts

Five users also encountered the barrier of tracking sleep continuously due to irregular working shifts. For those who work during the day and night alternatively, having a regular sleep and generating a meaningful sleep pattern are difficult.

"It's not because I don't want to track (sleep), but I work irregular shifts and sometimes I can only allocate 4 hours of sleep per day." (#149925)

Challenge 9#: Portability

Four early adopters of embedded sensors encountered the barrier of using sleep trackers continuously when they are away from home. Embedded sensors provide users with a non-wearable solution by being tucked under mattress of users' bed. Being a sophisticated set, they also contain a bedside standalone device that is designed to track environmental factors and provide sleep-inducing light. However, they are not easily carried around due to their cumbersomeness. One user expressed the difficulty in carrying it around and setting it up when she was in another city for a conference.

"I just wouldn't bother to bring it (Withings Aura) with me. I already got a lot of stuff." (#149932)

Challenge 10#: Detection Range

Embedded sensors are currently designed to track one person's sleep. Therefore, the length of sensor only covers part of the bed. When users toss and turn around, sensors fail to track and thus prevent users from collecting data continuously.

"For example, I have a California King Bed. I almost always sleep on the right side of the bed but a few nights ago my fiance was away for the night and I ended up rolling over onto the left side of the bed where the sensor (Beddit) believed I had left the bed. I had a great nights sleep but woke up to a sleep score of 40!" (#155282)

Trust

There are 59 instances found regarding users' doubtful attitude towards sleep tracking technologies. Since nearly all technologies collect sleep data based on movement, users posed accuracy doubts and wondered whether these technologies can be trusted.

Challenge 11#: Tracking Reliability

Users (N=32) demonstrated doubtful attitude toward how sleep tracking technologies work. Nearly all commercial products decide sleep period and sleep quality according to movement tracking, except Zeo. Moreover, being placed on bed, mobile applications and embedded sensors consider any movement on bed or any sound they can record as users'. Therefore, for those who have pets, sleep partner, roommates, or live around noisy environment expressed the confusion caused by incorrect data collection.

"The quality of phones as sleep monitors is doubtful anyway. The fitness bands are more accurate (as they are strapped to your body), but even they are not perfect - I used one for a while (until it died) and it reckoned I was fast asleep when I know I was wide awake but lying very still." (#149944)

Challenge 12#: Results Congruency

Twelve users, who are using more than one sleep tracking technology at the same time, have doubts toward technology accuracy being given conflicting data from different technologies. The reasons of adopting more than one technology could be: curiosity of how different sleep tracking technologies work; desire to compare data from multiple sources; dissatisfaction with the data from single technology; try out new purchase.

"I use two apps at the same time and the one app gave a lower than normal score while the other gave me a high score. That is kind of a bummer.... Idk which one is right honestly...." (#146209)

Challenge 13#: Sleep Automation

Like Challenge 6, in order to reduce user involvement, several wearables and embedded sensors provide the function of automatic detection for sleep period. Embedded sensors start and stop tracking sleep when users are physically in and off bed respectively, while wearables, such as Fitbit Charge and MyBasis, detect whether users are in sleep or not automatically according to built-in sensors' calculation. Self-detection can reduce user involvement but also bring about accuracy crisis. 10 instances are found under this challenge.

"It (Mybasis) had the bad habit of thinking i was asleep whenever I don't move. So often when i'm watching a movie for instance, it considered I was asleep." (#146192)

"I've been on my way to work after a shower and it (Withings Aura) says I was still in bed. " (#149609)

Challenge 14#: Development Immaturity

Since embedded sensors' development is still in infancy, 6 early adopters lacked trust towards this new technology. They are frustrated when embedded sensor gave poorly presented data, false sleep detection or even data loss due to constant updates.

"I installed the new iOS 8 beta on my iPhone and unfortunately lost all of my Beddit data!" (#149901)

"One odd caveat is that the Beddit app says that I fall asleep in 8 minutes every single night without exception, which was really frustrating." (#149902)

Data Manipulation

There are 35 instances found involving lacking of data manipulation. Current users illustrated the desire to manipulate their sleep data under three circumstances: to amend incorrect data; to export data; and to integrate data.

Challenge 15#: Data Amendment

Users (N=9) are aware of technologies' incorrect tracking, and expressed the desire to amend incorrect data. However, since not many technologies provide this function, users face the difficulty in editing wrong data.

"Using this app (Beddit) for the first time I awoke at 7am … after looking at my data I fell back asleep for an hour and was disappointed when I could not edit my sleep to reflect this." (#155281)

Challenge 16#: Data Export

Another 16 users encountered the barrier when they tried to export their sleep data in order to combine it with data from other sources, or to save data due to other reasons, for example, Zeo was out of business. Current users found it difficult to export sleep data as many technologies only support email-based data (e.g., Runtastic), or users are not familiar with specific data export techniques due to the unique format of sleep data.

"I'm new to this forum and have some questions about Zeo. It's a real shame they've shut down... I'm not a programmer, so I wonder if you could point me to a step-by-step on how to get all my Zeo data to a spreadsheet." (#169791)

Challenge 17#: Integration Tools

Another challenge sets barrier for 11 users when they could not find a proper tool to integrate data.

Technologies provide certain ways to gather and visualise sleep data. Compared to mobile applications, wearables and embedded sensors take longer time for users to integrate data as for they are required to transmit data to mobiles or computers by blue booth or other kind of connection. Despite of automatic synchronization, users, particularly those who are keen to improve their sleep quality, encountered difficulty in finding proper tool to integrate data or to visualise data the way that is helpful for finding out the factors that affect their sleep. Since technologies fail to correlate factors with sleep data, users have put different levels of manual efforts to export, combine and correlate data to meet their own needs. A variety of methods have been tried, from Microsoft Excel to more advanced tools, for instance, Project R11. On this point, the most common challenge is to find a tool that is simple but sophisticated enough to integrate data and prepare for reflection. Therefore, they seek help online from experienced others.

"How are you inputting the data? What tool are you using to chart your data?" (#151930)

Data Interpretation

There are 98 instances found in respect to difficulty in sleep data interpretation. Current users explicated 5 reasons that prevent them from effectively reflecting on their sleep. Similar to Continuity, these challenges may come from technology side or due to users' different lifestyles, hence, I separate them in different colors, as shown in Figure 5.

[11] http://www.r-project.org

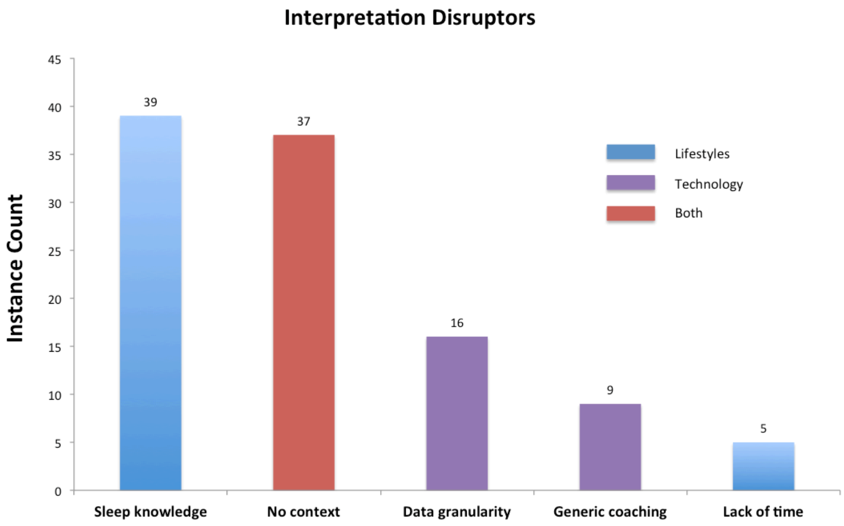

Figure 5. Interpretation disruptors.

Challenge 18#: Sleep Knowledge

Users (N=39) faced the challenge of making sense of their sleep data due to lack of sleep knowledge. Consequently, they inquired what does the data really mean to them. Technologies interpret sleep using both graphs and figures. Most graphs are binary when presenting sleep data, both detailed data, such as light sleep and deep sleep, and summarised sleep trend, for instance, sleep pattern, length, sleep time, wake time, etc. Figures could be in time set or in centesimal format when showing sleep quality or sleep efficiency. However, users have troubles understanding this information without sleep related knowledge. As a result, they questioned what is sleep score, how many hours of sleep they really need every day, how many hours of deep sleep and REM sleep they need respectively every day, etc.

"My deep sleep is usually much lower (~10%) and I have two deep sleep cycles. Is this normal?" (#146222)

Challenge 19#: No Context

Technologies, mostly mobile applications, allow users to take notes or manually input factors that affect their sleep, such as exercise before going to bed, caffeine consumption, alcohol consumption during the day, etc. Though several technologies do provide this function, they fail to correlate these factors with sleep data. Therefore, the data is not interpreted within context, which prevents users, particularly those who desire to find out factors that affect their sleep, from effectively reflecting on their sleep data. 37 instances are found under this challenge.

"The problem I had was that I already knew I had a poor nights sleep, (Fitbit Flex) telling me exactly how poor didn't seem to help... I can't really figure out why I am "restless" or awake, so the data is of less real use to me." (#168841)

Challenge 20#: Data Granularity

Sleep tracking technologies adopt different data interpretation and presentation strategies. Some of them show detailed information, for instance, the movement and clickable sound recording for the whole evening, others, on the other hand, summarise sleep data after calculation, such as sleep efficiency score. Since sleep is a complicated process, which involves various factors, 16 users expressed the desire to obtain more detailed data.

"I have a Beddit… although it does detect heart rate the only information I get about that heart rate is what the average for the night is which is very disappointing." (#146193)

Challenge 21#: Generic Coaching

A number of sleep tracking technologies provide some generic coaching tips to help users become aware of factors affecting sleep in general. However, 9 users expressed negative attitude towards these tips, as they are being meaningless for highly distinct individuals.

"Early adopters (of Beddit) don't need vacuous coaching tips like the one I received today ("Sensitivity to caffeine can increase with age...") or yesterday ("A small amount of alcohol may help falling asleep...") We want cold, hard data so we can see how something during the day (e.g., exercise, stress, alcohol or caffeine) impacts our breathing, heart rate, delta sleep, REM sleep, etc. " (#149907)

Challenge 22#: Lack of Time

Individual life styles and personal situations also inhibit effective reflection on sleep data. In this case, lack of time prevents 5 users from making sense of their sleep data.

"I currently use SleepBot for Android to track my sleep, but I'm notoriously bad for not looking at the graphs to actually quantify my sleep… Oh well, one thing at a time. I'll get the BP Diet nailed first." (#155279)

Discussion

My findings contribute a comprehensive list of 22 challenges under 4 themes that current users have encountered interacting with sleep tracking technologies. The challenges extend Choe's et al. (2011) work, which targeted potential users, by understanding current users' experience with technologies that have not been examined in their work, and by illustrating the new sleep tracking technologies landscape. In this section, I discuss a further exploration of these challenges and based on which, I propose six design considerations and opportunities for sleep tracking researchers and practitioners who are interested in working in the space.

Tracking Continuity

My findings have identified 10 barriers that prevent current users from collecting their sleep data in a continuous manner. These barriers vary from technologies to users' lifestyles, specifying Li, Dey and Forlizzi's (2011) work in personal sleep informatics.

From users' side, I found three possibilities that inhibit continuous sleep tracking. Firstly, sleep tracking is greatly influenced by sleep partner's attitude. If this attitude is negative, users chose to put technologies aside. Secondly, personal lifestyles and sleep habits also play an important role in sleep tracking. Particularly, irregular working shifts and naps have been demonstrated as high distinctions, which, as a result, build barriers for users. Thirdly, since the moment to bed and the moment to wake up are the time when individuals feel less conscious, technologies that require user engagement at this stage, e.g., turn on and off sleep mode, add burden to users.

Engaging users can raise users' awareness (Li, Dey & Forlizzi, 2011) and facilitate self-reflection (Choe et al., 2014). However, different from other activities, when users are fully sober, sleep often happens when individuals feel tired and less clear-minded. Moreover, having late night activities or being busy at various life events also prevent users from engaging in tracking sleep.

Opportunity 1#: Balancing Engagement and Automation

I suggest that sleep-tracking technologies need to provide a simple method to engage users at an appropriate level. Choe et al. (2014) demonstrated "intimacy with data" when users are involved in data collection, here I propose that for sleep tracking, it is desirable to reduce user engagement when sleep happens but flexible enough to allow manual data collection and data manipulation later on. Moreover, it is of great importance to take sleep partner into consideration when designing engagement mechanism, so is to support different life styles and personal sleep habits (naps). Yet how this information will be integrated into overall sleep data needs further investigation.

Technology problems have barely been discussed in prior work. In my findings, I identified a number of technology barriers for three platforms. These technology barriers are diverse from lack of comfort (wearables), health concerns (mobile applications), design defect (embedded sensors), battery limitation (mobile applications and wearables), lack of portability (embedded sensors) and incorrect tracking (all). They have strong impact on tracking sleep on a daily basis. On the other hand, in order to generate insightful patterns and trends, it is necessary to track sleep in a continuous manner.

Opportunity 2#: Ensuring Tracking Continuity

Therefore, besides the suggestions in existing literature that sleep tracking needs to be simple and less obtrusive (Choe et al., 2011), I argue that from the perspective of technology, sleep trackers are suggested to support tracking continuity. It should consider portability when users are in different geographical locations, technology battery limitation and material renew.

Trust

Commercial sleep tracking technologies provide a simpler way to support sleep tracking for everyday use. Compared to sophisticated clinical devices, these technologies adopt a less complex strategy to collect sleep data, thus, being less accurate. As described in Borazio's et al. (2014) work, sleep detection on most current sleep tracking technologies lacks clinical test. Based on movement tracking and adopting different detection algorithms, these technologies' accuracy is widely doubted by current users. When using more than one technology at the same time, several users have demonstrated conflicting results given by different technologies. Lacking of trust for sleep tracking technologies prevents users from taking them seriously and from using them in a long term.

Opportunity 3#: Explicating Technology Transparency

Interviewing with sleep experts (Choe et al., 2011) has indicated that precise sleep measurements are not necessary to meaningfully understand sleep behaviors and trends. On this point, I agree with Choe et al. (2011) that reasonable trade offs are possible between technology accuracy and unobtrusiveness and possibly other features, such as portability. In order to solve users' trust crisis towards these technologies, I also suggest technologies to clearly clarify how they work. It does not mean that technologies need to provide specific algorithms of sleep detection, but to inform users to what extent their sleep is recorded and how their sleep data is interpreted. It is also worthwhile to help users have appropriate expectations for sleep tracking technologies and provide possible explanations for unusual data.

Data Manipulation

As owners of their sleep data, several users have expressed the desire to manipulate data whenever possible. However, current sleep tracking technologies only provide a simple method, if at all, for users to access their sleep data. In collection stage (Li, Dey & Forlizzi, 2011), users are unable to adjust incorrect tracking data; in integration stage (Li, Dey & Forlizzi, 2011), individuals faced the difficulty in exporting data since not many technologies support this function, or in integrating data with a proper tool. Lacking of data manipulation significantly impacts users reflecting on sleep data as well as taking actions.

Opportunity 4#: Empowering Data Ownership

Since users are the owners of their data, I suggest that sleep-tracking technologies grant full empowerment for users to access and manipulate their sleep data. In collection stage (Li, Dey & Forlizzi, 2011), it is suggested that users enable to edit incorrect tracking data and to input new entry if sleep is not captured. For those who desire to explore their data on different platforms and those who switch technology over time, which often happens as time goes by (Oh & Lee, 2015), it is also significant to provide a simple way to allow data export and integration from multiple sources.

Data interpretation

Prior work (Choe et al., 2011; Kay et al., 2012; Lawson et al., 2013) has outlined that privacy is considered as a major issue in sleep, in my dataset, users seemed to be willing to share their sleep data in online communities, particularly when they had difficulty in making sense of data given by technologies, as “understanding information” in reflection stage (Li, Dey & Forlizzi, 2011). These challenges may come from technologies or come from users when sleep related knowledge is missing or lack of time. Consequently, users are uncertain to take corresponding actions, either to improve sleep quality, or to better incorporate sleep into daily activities.

From technology side, technologies summarise some aspects of sleep that users are interested in exploring in detail. It is understandable that since various factors are involved in individual’s sleep, it is difficult to provide all information in equally exhaustive way.

However, the lack of detailed data frustrates users and impedes users' motivation to use technology in a continuous manner. Moreover, some technologies present data in a plain manner without providing context or trigger, or only offer generic coaching tips, which are not specific to users' unique situation.

Opportunity 5#: Allowing Data Flexibility

Technologies could provide both detailed data and summarised data to meet users' various tracking goals and to help users obtain better self-knowledge. Detailed data could provide information about what is going on when they are in bed through various factors (movement, sound, heart rate, etc.) while summarised data could paint a picture from higher level to support long-term reflection. Since users may wake up during the night, sleep-tracking technologies are also suggested to provide real-time data visualisation, either detailed or summarised, to show how well their sleep is before waking up.

From users' perspective, some found it difficult to reflect on their sleep data without adequate sleep related knowledge, which is understandable as sleep is a complex process that consists of professional medical knowledge. Additionally, as a matter of fact that individuals have unique lifestyles, which lead to different sleep conditions, they faced the barrier to understand their own sleep through mutually understanding conversations without scientific support.

Opportunity 6#: Providing Feedback Instructiveness

Since sleep is highly individualistic, in addition to generic sleep hygiene tips, sleep-tracking technologies are suggested to provide personal related feedback ideally. This requires correlation between factors that affect user's sleep and his or her actual sleep condition. Apart from graphs and charts visualisation, in order to provide insightful feedback, I suggest that sleep-tracking technologies could consider text-based instructions. Hard data is useful to explain the situation with no doubt, providing highly personal instructiveness could improve the close relationship between users and technologies as well as help users take corresponding actions.

To help users better understand their sleep, sleep-tracking technologies are also suggested to provide sleep related knowledge. This could be done by educating users with general sleep information, particularly by informing users that sleep is highly individualistic thus comparison with common standards is often less actionable; or by incorporating educations into instructive feedback with personal sleep data, which could be more desirable for long term reflection.

Conclusion

The work presented in this paper contributes twofold to sleep and HCI community: it outlined a comprehensive list of 22 challenges under 4 categories that current users have encountered, and it proposed 6 design opportunities and considerations to better design sleep tracking technologies and to support improved user experience. Sleep tracking technologies can help users better understand their sleep pattern, raise awareness of healthy sleep behaviours, and even support sleep related problems solving. I believe that the challenges and opportunities that are identified in this work could provide insights for sleep researchers and practitioners to further improve sleep-tracking technologies and benefit both current and future users.

It is noted that since I only focused on sleep tracking, more work could be done to understand how individuals interact with sleep technologies in general, e.g., sleep tracking, waking, sleep inducing, light, white noise, etc., and how people with sleep disorders interact with sleep technologies in particular. Moreover, although not many sleep-tracking technologies provide the function to share sleep data regarding privacy concern, users tend to share for various reasons. Therefore, I believe that future work could be done to discover sleep data sharing, for instance, how do they share sleep data, who do they share with and to what extend do they share.

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