Exploring the Design Space of Chronobiology-Aware Health Tools

Elizabeth L. Murnane[1], **Saeed Abdullah**[1], **Mark Matthews**[1], **Matthew Kay**[2], **Dan Cosley**[1], **Tanzeem Choudhury**[1], **Geri Gay**[1], **Julie A. Kientz**[3]

[1]Information Science
Cornell University
Ithaca, NY, USA

[2]School of Information
University of Michigan
Ann Arbor, MI, USA

[3]Human Centered Design & Engineering
University of Washington
Seattle, WA, USA

Abstract
Today, the swift spread and rapid technical evolution of computing technology, together with a growing engagement from individuals interested in using such tools to improve their health and quality of life, creates unprecedented opportunities for HCI researchers to develop tailored health applications that can be deployed on a broad scale. However, to build effective solutions in this space, researchers must accommodate the behavioral, environmental, social, and ***biological*** idiosyncrasies of users. In particular, there is a need to create technologies that account for individuals' innate biological rhythms, which govern numerous aspects of health, can be the underlying root of illness if disrupted, and are known to impact symptom testing and treatment efficacy for a variety of conditions. In this workshop paper, we discuss design opportunities for "chronobiology-aware" health technologies: a novel class of biologically-personalized tools aimed at helping people monitor, stabilize, and optimize their personal rhythms and, in turn, enhance overall wellness.

Author Keywords
Circadian Rhythms; Self-Monitoring; Sleep; Performance

ACM Classification Keywords
H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous; J.3 [Life and Medical Sciences]: Health

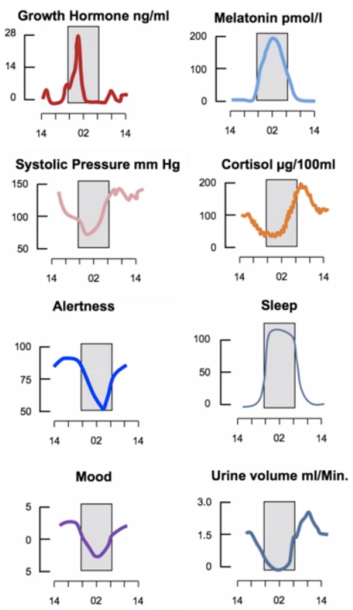

Figure 1: Circadian rhythms are central in regulating numerous aspects of our physical, cognitive, and psychological functioning. (Image from [4]).

Introduction

Like that of nearly every organism, human physiology has adapted to the periodic environmental changes that occur as the Earth rotates around its axis approximately every 24 hours, with our biochemistry varying in significant and predictable ways over the course of a day. These changes follow what are known as ***circadian rhythms***, a term that refers broadly to any self-sustaining diurnal biological cycle that keeps a roughly 24 hour period. ***Chronobiology*** is the field of study concerned with these rhythms, which regulate nearly all aspects of physiological and neurobehavioral functioning including sleep patterns, concentration, mood, athleticism, digestion, pain sensitivity, and much more [4].

Further, people display individual differences in the phase and amplitude of their circadian rhythms, from the timing of sleep-promoting hormone secretions, to the duration of sleep needed to maintain both short and long term health, to the times when alertness peaks and dips each day. ***Chronotype*** reflects a person's unique circadian profile, which manifests in such biological and behavioral differences and lies on a continuous spectrum from extreme early to extreme late types [6] ("early birds" and "night owls").

In addition, disruption to these rhythms can have detrimental physiological, cognitive, and psychological consequences and is linked to a number of serious illnesses such as cardiovascular disease, diabetes, cancer, and psychiatric disorders. Unfortunately, 70% of people are reported to suffer from circadian disruption [5], producing healthcare costs in the billions of dollars.

Considering the importance of biological rhythms when it comes to health and well-being, we see a compelling need to incorporate a greater awareness of these characteristics into the designs of tools to support care. Motivated by this opportunity and our recently published studies that suggest the feasibility of assessing circadian factors via low-burden methods, this paper explores the design space of chronobiology-aware tools across a variety of application areas including sleep, daily performance, and medical diagnostics and treatment delivery. Our presented designs range from speculative implications, to mid-level mock-ups, to informally evaluated prototypes. Regardless of fidelity, they demonstrate how design choices informed by the chronobiology literature can advance the development of personalized technologies that target significant health determinants and supply effective interventions.

Chronobiology-Informed Sleep Support

Given the prevalence of sleep problems and comorbid conditions, HCI researchers are keen to develop technology to help improve sleep habits. However, systems that do not consider circadian factors are missing the full picture, plus interventions that only target sleep disturbances may be treating the symptoms of a misaligned biological clock rather than addressing the roots of circadian disruption. These issues stand out as design directions to push on.

Personalizing Sleep Hygiene Recommendations

Doctors often recommend that patients with sleep problems work to improve their "sleep hygiene", defined by the National Sleep Foundation as the "practices that are necessary to have normal, quality nighttime sleep and full daytime alertness". Examples include getting 7–8 hours of sleep per night, avoiding exercise within 3 hours of bedtime, and generally limiting caffeine especially within 4–6 hours of sleep.

Most of today's sleep self-monitoring technologies are built with some subset of these sleep hygiene recommendations in mind, though they tend to take a relatively generic perspective. In this case, generic advice is likely better than no advice at all; but it would be desirable to make these recom-

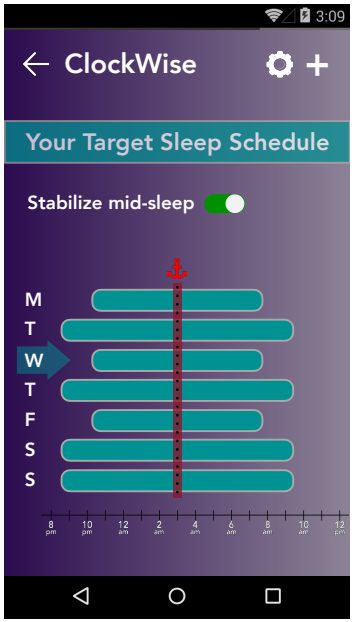

Figure 2: Our smartphone-based tool provides personalized sleep schedules where onset, duration, and waking are chronotype-tailored and maximize circadian stability.

mendations more biologically-personalized, given the highly individualistic nature of sleep requirements. Specifically, how we sleep is contingent, in large part, on biological attributes like genetic makeup, gender, and age. For instance, genetics play a role in determining the effects caffeine has on a person, including the time at which intake will affect sleep; women's circadian clocks tend to run earlier and shorter than men's; and, as mentioned earlier, every person has a distinct chronotype, with many individuals (especially young adults) at the late end of the spectrum [6].

After capturing such information, chronobiology-aware sleep hygiene tools could tailor recommendations to better fit an individual's unique needs instead of providing blanket recommendations (e.g., to end caffeine consumption 8–14 hours before bedtime or avoid any napping more than 8 hours past waking). By translating personal data streams into behavioral biomarkers of caffeine-related traits, future systems could provide a genetically-appropriate caffeine cut-off window tuned to a user's predicted genetic response to caffeine intake and its personal impact on sleep. Or, users could be provided with chronotype-tailored napping schedules, given their benefits found in prior chronobiology studies [3], thereby making sleep hygiene guidelines for napping less brittle by supporting naps during later portions of one's day, as long as they are timed in a biologically suitable way to stabilize rather than disrupt sleep.

Moving beyond timing and duration, systems' sleep quality metrics could also be improved. Chronobiologists agree that other indicators like severity of sleep inertia, social jet lag, and sleep debt (defined in the following subsection) are equally important to assess when it comes to evaluating sleep and its impact on overall wellness. Furthermore, such indicators are often symptoms of a misaligned biological clock, which intervention tools could help to stabilize.

Stabilizing Circadian Disruptions

As mentioned, disruption (or "misalignment") of the human circadian timing system is associated with a wide range of negative health impacts. One immediate design strategy is to create applications that facilitate the broad-scale, real-world deployment of lifestyle interventions that have shown promise in small lab-setups or in animal studies.

One set of such interventions focus on adjusting sleep schedules to reduce social jet lag (the discrepancy between patterns of undersleep on workdays and oversleep on free days) or sleep debt (the accumulation of undersleep) and their misaligning effects, which are similar to crossing time zones and linked to fatigue, confusion, mood disturbance, tension, and stress. Another effective way to support healthy circadian rhythms is to maintain regularity in certain sleep-related "anchors" — particularly mid-sleep, the halfway point between sleep onset and waking. Based on the current time, the user's past sleep-wake data, and her known future schedule constraints, an adaptive system could provide optimal sleep schedules to maximize mid-sleep stability, as seen in Figure 2.

Tools can also help people temporally structure activities beyond sleep in ways that reduce circadian misalignments. Circadian rhythms are maintained by a process known as entrainment, whereby a group of nerve cells in the brain use external information to keep body clocks synchronized with environmental changes referred to as ***zeitgebers***. Light is the most dominant one; but a number of external factors including temperature, food intake, and exercise work as zeitgebers too — cues technology could schedule to minimize disruptions and promote stability.

For example, chronobiology-aware light therapy tools could assist users in getting exposure to outdoor or artificial light at the times that would help restabilize their circadian sys-

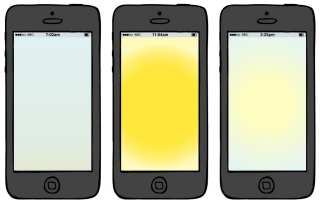

Figure 3: To provide peripheral self-awareness, this live wallpaper's color transitions in real-time with the user's alertness levels at that moment. By default, brighter yellow saturation corresponds to higher alertness while faded blue-gray corresponds to lower alertness. From left to right, these images illustrate an individual's early morning low alertness, late morning alertness peak, and mid-day alertness dip.

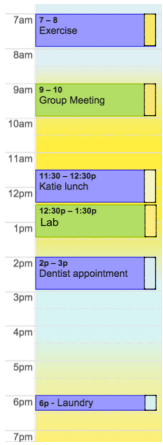

Figure 4: Our chronobiology-aware calendar background scaffolds self-awareness of alertness with a customizable color scale. Visual indicators on events provide an at-a-glance sense of whether scheduling aligns with personal alertness at that time.

tems. Advances in screen hardware on personal devices (e.g., smartphones, tablets) could even allow applications to deliver clinically-robust light therapy sessions without the use of specialized equipment. Similarly, homes and offices might adapt the intensity and wavelength of lighting settings to cue exposure at opportune moments for restabilization.

Regarding temperature, existing tools often do encourage users to keep their bedroom "cooler", though the suggested range is a bit loose (e.g., 60–75°F). Instead, a chronobiology-aware heating system could more closely simulate the nightly temperature fluctuations experienced in nature, which recent research suggests can greatly benefit circadian stabilization [9]. Additionally, smartphone notifications or calendar tasks might remind a person to adhere to a personalized meal schedule based on timings chronobiology studies have found improve sleep quality, while chronobiology-aware fitness tools could provide advice about the optimal type, intensity, and duration of exercise to perform at a particular time of day to achieve the circadian stabilization benefits found in prior work [7].

Optimizing Daily Performance

Increasingly, cognitive performance is coming to be seen as a critical component in the overall notion of wellness; and as performance optimization emerges as a new frontier in health, there is a growing interest in developing technology to facilitate performance monitoring and improvement [8]. In doing so, it is important to take into account a user's innate biological rhythms, which influence nearly all aspects of cognition (e.g., alertness, attention, reaction time, response inhibition, short-term and working memory, and higher executive skills including creativity). In our work to-date, we have focused on alertness, a cornerstone of cognitive performance that correlates with a number of cognitive functions but that can be difficult to self-assess [2].

Self and Social Awareness

To begin, chronobiology-aware tools can help people gain a better sense of personal performance rhythms. Such self-knowledge could empower a person to make biologically-informed decisions when it comes to productively managing activities or increase personal empathy and the capacity to understand, accept, and even embrace performance dips.

For example, using a peripheral background with a customizable color scale, the following designs convey a user's alertness levels in an open-ended way that leaves room for interpretation and self-driven decisions. Based on preliminary evaluations, we use a brighter, more yellow saturation to represent higher alertness by default and a faded blue-gray color for lower alertness. Figure 3 shows the smartphone version, a live wallpaper that displays the user's real-time moment-to-moment alertness; and Figure 4 shows a chronobiology-aware calendar that provides a more holistic overview of days, weeks, or longer time periods including archives of past patterns.

This same information can also be communicated in ways that more intentionally expose it to other people, for instance through personal beacons (e.g., a desk ornament, room light, etc.) or wearable charms (e.g., a necklace, pin, etc.) Such displays not only increase self-awareness but also communicate normally invisible characteristics to create a shared awareness among co-workers, family, or roommates. Along related lines, a "family portrait" interface, viewable from a digital display in the home and synced to personal devices, could show the performance and sleep-wake patterns of each household member as a way to coordinate scheduling and foster empathy (e.g., improving a family's understanding that its teenager's late wake schedule is driven by biology, not laziness).

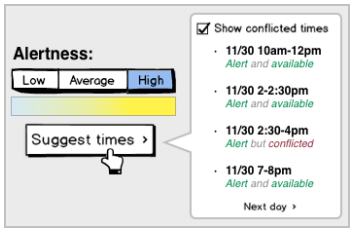

Figure 5: Specifying performance related parameters (e.g., alertness, as shown here) enables scheduling recommendations that align with personal rhythms.

Figure 6: Our chronotherapy-informed tools are designed to deliver personalized schedules for diagnostic testing, medication administration, and non-pharmacological treatments (e.g., physical therapy or positive psychology exercises).

Scheduling and Activity Management
If such designs are effective at improving people's awareness of personal rhythms and their impact on functioning, it will hopefully increase receptivity to more prescriptive forms of feedback. For example, the chronobiology-aware calendar can assist with scheduling performance-intensive versus lightweight tasks. Specifying an event's chronobiology-relevant information (e.g., required alertness in Figure 5), a user receives scheduling recommendations based on her circadian profile. Similarly, the calendar's "Fix My Day" feature analyzes events to offer rescheduling suggestions that optimize alignment with predicted performance levels. The calendar medium is also well suited to scheduling the aforementioned circadian stabilizers (i.e., delivering zeitgebers).

To afford more agency in decision-making, we are next prototyping smartphone and smartwatch clockface widgets that support more high-level activities and flexible timeframes (e.g., to "work" or to "exercise" during time windows with fuzzy boundaries). If more hands-on guidance is desired, a user can enable the tool to deliver notifications with specific directives (e.g., "go for a 30 minute brisk walk at 12pm on Stewart Avenue").

Performance-Predictive Systems
Another fruitful area is the development of adaptive tools that can automatically alter system behavior (e.g., notification delivery or restricted usage times) based on the user's current or predicted performance. Systems could also help individuals make more informed choices for themselves. For instance, when pondering whether an all-nighter will either be productive in the long run or instead lead to diminishing returns, a sleep-decision-support application can provide feedback about the net gains (or losses) of staying awake, in terms of the impact the system predicts potential sleep choices will have on performance the next day.

Finally, impaired alertness performance can be a serious issue when it comes to safety, increasing the risk of occupational injury, industrial disasters, and vehicular crashes. Chronobiology-aware technology might help prevent such accidents by delivering just-in-time interventions. For instance, a driving application could apply our predictive models about a user's alertness [1] in order to determine whether to deliver a recommendation to avoid the road until resting, while an instantiation in a smart car might exert more control in extreme situations, locking the car's doors to prevent driver entry or automatically pulling over.

Diagnostic Testing and Treatment Administration

An individual's biological rhythms can impact her diagnostic test results for a range of health items (e.g., allergies, blood pressure, glucose tolerance, hematology, and hormone levels); and symptom intensity also follows rhythmic patterns for a number of medical conditions (e.g., asthma, gout, and peptic ulcer attacks worsen during night while the risk of heart failure or stroke peaks during the morning). In addition, the outcomes of taking medication can be markedly different depending on the patient's circadian phase, with the effectiveness, safety, and side effects of a given medication changing at different times of day.

By considering characteristics of the medication, the taker's circadian phase, and rhythms of disease pathophysiology, ***chronotherapy*** aims to deliver medications at biologically opportune times (e.g., research finds chronotherapy-based cancer treatment is 50% more effective). Chronobiology-aware tools informed by these procedures could improve the efficacy of medications by providing recommendations about delivery times, as seen in Figure 6. Further, by suggesting the best times to attempt a diagnosis, such systems could also enhance the accuracy of diagnostic tests that assess that treatment's efficacy.

Significance to WISH and Participation Goals

Chronobiology plays a pivotal role in our health, directly and substantially impacting numerous aspects of our daily lives and overall wellness. As HCI researchers continue to investigate the promise of applying technology to healthcare challenges, this effort could benefit from an increased awareness of such biological factors. This paper is a step in that direction, aiming to promote a greater understanding of individuals' innate rhythms and start a conversation among the WISH community about how systems can be made more sensitive to them.

Through our participation, we aim to connect with interdisciplinary scholars working on related topics in order to exchange expertise, expand the scopes of our current research and practices (e.g., application areas, interaction paradigms), and chart design paths toward next generation healthcare technologies for assessment, monitoring, management, and intervention.

In exploring chronobiology-aware systems, we have so far pursued what we see as highly fertile spaces: (1) technologies to support sleep and stabilize circadian disruption via software that provides actionable advice tailored to each user's biology or home integrations that automatically adapt environmental conditions, (2) tools that can increase (inter)personal awareness of daily performance patterns and assist in scheduling, and (3) chronotherapeutic systems that facilitate diagnosis and treatment including of chronic conditions. Still, numerous other areas are ripe for attention too; plus it is necessary to examine recognized or unforeseen challenges, devise novel ways to capture chronobiological data, and determine apt evaluation strategies. Overall, we hope our work serves to spark contemplation about broad opportunities to build on chronobiology in order to personalize health technology in this innovative manner.

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