Circadian Computing: Sensing, Modeling, and Maintaining Biological Rhythms

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Abstract Human physiology and behavior are deeply rooted in the daily 24 h temporal structure. Our biological processes vary significantly, predictably, and idiosyncratically throughout the day in accordance with these circadian rhythms, which in turn influence our physical and mental performance. Prolonged disruption of biological rhythms has serious consequences for physical and mental well-being, contributing to cardiovascular disease, cancer, obesity, and mental health problems. Here we present *Circadian Computing*, technologies that are aware of and can have a positive impact on our internal rhythms. We use a combination of automated sensing of behavioral traits along with manual ecological momentary assessments (EMA) to model body clock patterns, detect disruptions, and drive in-situ interventions. Identifying disruptions and providing circadian interventions is particularly valuable in the context of mental health—for example, to help prevent relapse in patients with bipolar disorder. More generally, such personalized, data-driven tools are capable of adapting to individual rhythms and providing more biologically attuned support in a number of areas including physical and cognitive performance, sleep, clinical therapy, and overall wellbeing. This chapter describes the design, development, and deployment of these "circadian-aware" systems: a novel class of technology aimed at modeling and maintaining our innate biological rhythms.

Introduction

Like that of nearly every terrestrial organism, human physiology has adapted to the 24 h pattern of light and darkness. Within our bodies there are hundreds of biological clocks, controlled by a "master clock" in our brain—the Suprachiasmatic Nucleus or SCN [32]. These body clocks control oscillations in our biological processes and

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drive our circadian rhythms. “Circadian” means about (*circa*) a day (*diem*), and our circadian rhythms reflect any biological cycle that follows a roughly 24 h period such as regular changes in our blood pressure, cortisol, and melatonin levels.

Biological rhythms vary between individuals. *Chronotype* represents one’s unique circadian profile and lies on a spectrum from proverbial “early birds” (early types) to “night owls” (late types). Beyond just influencing one’s preferred sleep time, these individual differences also impact our daily trends in mental and physical performance.

Living against our innate biological rhythms can result in *social jetlag*—a chronic jetlag-like phenomenon that stems from persistent misalignment between a person’s biological clock and “social” clock, the latter of which is based on social demands such as those from evening social schedules or the need to adhere to work schedules [89]. Such circadian disruption, which often results from waking up earlier than our internal clock dictates, is becoming increasingly widespread. Indeed, a large-scale study from Roennberg et al. found that more than 70% of the population suffers from significant social jetlag, with individuals’ biological and social clocks differing by more than 1 h [85]; and the U.S. Centers for Disease Control (CDC) now report that sleep pathologies, often indicative of circadian misalignment, are reaching epidemic levels, with sleep disorders affecting 50–70 million people in the U.S. alone [70].

Persistent disruptions to our innate biological rhythms can have serious consequences for physical and mental well-being [32]. Shift workers, who often suffer from chronic chronotype misalignment, are more likely to experience type 2 diabetes, coronary heart disease, cancer, and obesity compared to day-time workers [78, 96]. For younger populations, disruption can increase the risk of drug and alcohol use [97, 104] and produce cognitive impairments and learning deficits [15]. Circadian disruption has also been associated with neuropsychiatric illness. Around 30–80% of patients with schizophrenia report sleep and circadian rhythm disruption, making it one of the most common symptoms [79], and circadian instability has also been identified as a contributing factor behind the development of schizophrenia in susceptible individuals [48]. Compelling evidence also establishes a link between circadian disturbances and the onset of relapse for patients with bipolar disorder (BD) [8, 36].

This widespread impact that misalignments can have on our well-being helps illuminate an ever-increasing need for computational approaches that factor in considerations of the internal body clock. While recently there has been a consistent focus on making devices and technologies more personalized, such approaches do not yet support or adapt to individualized variations (e.g., in sleep onset, cognitive performance, working memory, alertness, or physical performance) that result from our personal circadian rhythms. The aim of *Circadian Computing* is to provide technology that can play to our biological strengths (and weaknesses), instead of making incomplete assumptions about the steady capabilities and fixed requirements of its users throughout the day.

Towards that goal, we focus on developing technologies for detecting circadian rhythms and disruptions and providing in-situ interventions. Our approach draws on techniques from mobile sensing, machine-learning, ubiquitous computing, and chronobiology in order to (1) develop low-cost and scalable methods that can cheaply, accurately, and continuously collect real-time behavioral data to identify biological rhythm disruptions; (2) design and build novel computing systems that help people realign with their individual rhythms by employing circadian interventions that support "fixing the broken clock"; and (3) deploy and evaluate these systems among target populations.

Thus, by modeling body clock patterns and identifying circadian disruptions through passive and automated sensing of behavioral traits, we aim to support users' varying needs over time. Specifically, the predictive ability of these models enables us to develop tools that can adapt to our individual rhythms and provide more biologically attuned support in the areas of sleep, cognitive and physical performance, and overall well-being—for instance, by suggesting schedules for daily activities that align with one's natural oscillation of alertness throughout the day. Such tools also have application in the context of mental health, where identifying disruptions and providing circadian interventions can help prevent relapse for patients with bipolar disorder and schizophrenia and, overall, serve to transform existing approaches to mental health care from being reactive to preemptive.

Background

As the Earth rotates around its axis approximately every 24 h, most organisms are subjected to periodic changes in light and temperature that result from exposure to the Sun. Given the constancy of this phenomenon over the course of evolution, nearly every living creature has developed internal biological clocks to anticipate these geophysical fluctuations. Jean-Jacques d'Ortous deMairan first reported the endogenous nature of these biological processes after observing daily leaf movement in heliotrope plants in 1729 [56].

Over the years, chronobiologists have continued to identify such endogenously generated rhythms in cynobacteria [37], insects [90], birds [38], and mammals [82]. The existence of circadian rhythms in humans was first reported by Jürgen Aschoff who noted that "whatever physiological variables we measure, we usually find that there is a maximum value at one time of day and minimum value at another" [6]. Since then, a number of studies have identified underlying biological explanations, including evidence that rhythm generation for different organisms has a genetic basis [4, 29].

Franz Halberg first coined the term "circadian" to emphasize the self-sustaining nature of these biological clocks [16]. That is, these biological rhythms continue to have a period of nearly 24 h even without external stimuli (e.g., in constant light or darkness). Under such constant conditions, the time it takes for a circadian process to complete oscillation is known as the *free-running* period. Our biological processes are usually not free-running because they are synchronized with the external environment. The process of synchronization is called *entrainment*, and environmental cues for entrainment are known as *zeitgebers* (zeit: time, gebers: givers). A number of environmental factors such as food intake and exercise can work as zeitgebers, but light (and darkness) is the most dominant cue. In mammals, light is transduced through the retina to a group of nerve cells in the hypothalamus known as the Suprachiasmatic Nucleus (SCN), which acts as a circadian pacemaker. The SCN uses these environmental cues to coordinate and synchronize our cellular circadian clocks to periodic changes in the environment.

Humans also show inter-individual differences in the phase and amplitude of circadian rhythms even in entrained conditions with the presence of external time cues. Biochemical processes (e.g., the timing of hormone secretions like melatonin) as well as sleep timing preferences reflect these differences. The phase difference between individual internal time (i.e. the timing of an individual's biological clock) and time cues from the environment (e.g., the cycle of the sun) is known as the *phase of entrainment*; and when individuals vary in this trait, they are referred to as different *chronotypes*.

Chronotype is a phenotype—a characteristic that results from genetic factors interacting with a person's environment. Vink et al. reported that approximately 50% of chronotype features are heritable [102]. Other demographic and developmental factors such as age, ethnicity, and gender might also influence chronotype [86]. Children are generally early chronotypes, but they transition to become increasingly later types during adolescence. After reaching a maximum lateness around 20 years of age, chronotype then begins shifting earlier once again. In general, people over 60 years old have an early chronotype. The shift to a later chronotype begins sooner for females than males, which is in accordance with the general biological phenomenon that females tend to mature earlier. This means that men are relatively later chronotypes compared to females of same age for most of adulthood [86], until the chronotype phases for men and women coincide around age 50, the average age of menopause.

Light exposure can also affect the phase of entrainment; longer exposure to daylight advances the sleep period and results in an earlier chronotype [89]. Specifically, Roenneberg et al. found that spending more than 2 h outside correlates with chronotype advancing by more than an hour [88].

A More Complex Sleep Model

The sleep and wakefulness cycle is a ubiquitous process among both invertebrates and vertebrates, including humans [99]. In fact, sleep-wake patterns are among the most prominent biological rhythms in humans. Sleep occurs as a result of complex interactions between a number of biochemical processes (see Fig. 1). Borbély et al. first proposed that sleep results from two interacting and counterbalancing processes—a homeostatic process and a circadian process [10]. Homeostatic sleep pressure (the need for sleep) builds during wakefulness in accordance with the

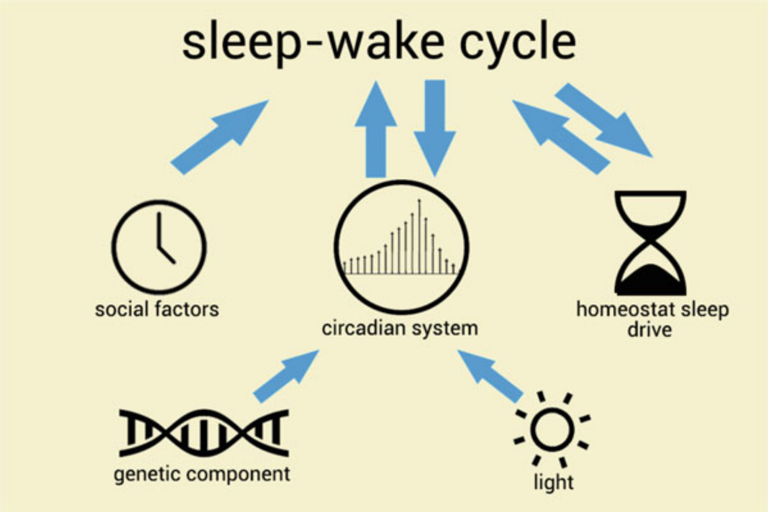


Fig. 1 Sleep and the human circadian system

duration of time spent awake and then dissipates during the sleep episode. Simultaneously, the circadian process maintains the rhythm of sleep propensity with peaks and troughs throughout the 24 h period. Thus, as the homeostatic sleep pressure increases with wakefulness, if sleep propensity is low from the circadian process, then wakefulness is maintained. Similarly, as sleep pressure dissipates during sleep, a stronger sleep propensity from the circadian process helps to maintain the sleep phase [71].

Though, while we are circadian creatures, whose numerous physiological, mental, and behavioral rhythms are driven by biological clocks, we are also social beings. As such, our behaviors and sleep patterns are additionally influenced by a "social clock" based on social responsibilities such as relationships and work schedules [89]. Overall, the timing and quality of sleep is therefore affected by three complicated and idiosyncratic factors: our circadian system, a homeostatic oscillator, and our social clock.

When we sleep and how we perform throughout the day is thus determined by multiple factors and contingent, in part, on each person's genetic makeup and age. Sleep advice, such as when we should sleep or wake, can therefore not be prescribed generically but rather must be tailored to each person's complex genetic and environmental conditions. In particular, not all of us can, or should, maintain a commonly promoted "early to bed and early to rise" lifestyle.

Circadian Disruption and Mental Health

As mentioned, the circadian system plays a crucial role in synchronizing our internal processes with each other and with external environments. However, a number of factors can disrupt an individual's circadian systems and, in turn, various aspects of functioning such as sleep-wake cycles, mood, and levels and timing of hormone secretions. These symptoms have been associated with a wide range of mental health problems including alcohol and substance abuse, anxiety, attention-deficit hyperactivity disorder, bipolar disorder, depressive disorder, obsessive-compulsive disorder, and schizophrenia. While in the past, biological rhythm disruptions have been attributed to the pathology of the given mental disorder, recent studies indicate that the circadian system may be more directly involved in disease etiology [53, 62].

In particular, the role of circadian disruption in schizophrenia and bipolar disorder has been well-studied. Sleep and circadian disruptions are the most common and consistent features of schizophrenia [79]. Abnormal phasing, instability, and fragmentation of circadian rhythms have been observed in patients with schizophrenia based on rest-activity rhythms assessed by actigraphy [58, 106]. Further, research finds that improvement in sleep regularity may lead to lower psychotic schizophrenic symptoms [74]. A number of studies have also reported associations between schizophrenia and the genes involved in the generation of biological rhythms ("clock genes") [52]. Similarly, a number of studies have linked bipolar disorder to genes that govern circadian rhythms [8, 57], and circadian disruptions are associated with onset of bipolar episodes. Sleep deprivation resulting from travel, shift-work, medication, or postpartum states can trigger mania; and a decreased need for sleep is considered to be a fundamental marker of the manic state [81]. As a result, interventions to effectively manage bipolar disorder often focus on maintaining sleep–wake rhythms, social rhythms, and light–dark exposure.

Measuring Circadian Rhythms and Disruptions

A number of methods exist to measure circadian rhythms and in turn circadian disruptions (e.g., see Table 1). Here we discuss the most commonly studied and used techniques, in the order of most to least invasive and burdensome for the individual being assessed.

Biological Markers

The core body temperature (CBT) of homeothermic organisms, including humans, is maintained by a complex thermoregulatory feedback system. Specifically, through mechanisms of heat-loss (e.g., conduction, convection, and evaporation) and

Table 1 Methods for assessing circadian rhythms and disruptions

Method	Instrumentation	Considerations
Core body temperature (CBT)	Rectal thermometer [69]	Not scalable and highly invasive
Melatonin	Blood (serum and plasma), saliva, urine [67]	Invasive and not suitable for longitudinal deployment
Cortisol	Blood (serum and plasma), hair, saliva, urine, feces [63]	Invasive and not suitable for longitudinal deployment
Heart rate	Electrocardiography (ECG) [45]	External factors (e.g., carbohydrate intake) can affect measurement [67]
Activity	Accelerometer based sleep and circadian rhythm monitoring (e.g., actigraphy) [5]	Not suitable for scalable deployment as it requires special devices
Sleep journal	Manual journaling of sleep onset and duration [109]	Can be unreliable due to potential non-adherence and unreliable recall
Self-assessment survey	MCTQ for assessing chronotype and social jetlag [89]	Not suitable for monitoring changes over long periods of time
Mobile sensing	Smartphone usage patterns and sensors [2]	Individuals must carry their phones consistently

heat-production (e.g., metabolic thermogenesis), the body maintains temperature at a stable level. A number of studies have found that core body temperature displays a circadian rhythm, with a period close to 25 h [24]. Trends in CBT are also associated with circadian sleep-wake regularization. Specifically, CBT reaches its maximum during the day, begins to decrease at the onset of sleep, and drops to a minimum (about 2 h before waking) during the major sleep phase [101]. Studies therefore widely consider core body temperature as a robust biomarker of circadian rhythms and circadian dysregulation.

However, current techniques for measuring core body temperature are highly intrusive. CBT measurement via rectal probes is the most accurate and widely used method in the scientific literature [69]. While consistent efforts have been made to perform less-invasive assessment through wearable devices that measure oral and skin temperature [76], such approaches can be unreliable across different environments and physical conditions (e.g., sweating) [107]. As a result, using core body temperature to assess circadian rhythms and disruptions in an unobtrusive, dependable, and scalable manner is still not feasible and is particularly unsuited to studies in naturalistic settings.

Several hormones in the human body are also used as circadian biomarkers. Two of the most studied are melatonin and cortisol. Melatonin, a hormone secreted by the pineal gland, plays a major role in regulating and reflecting circadian rhythms. Melatonin secretion essentially indicates the onset of night; circulating melatonin concentration is low during the day and higher at night [24], and a longer period of darkness correlates positively with a longer duration of melatonin secretion [19]. Compared to other biomarkers such as core body temperature and heart rate, melatonin is considered more robust against external influences and thus may provide a preferable form of circadian rhythm assessment [67]. Melatonin levels can also be used to evaluate the effects of bright light exposure, which is a key circadian synchronizer for humans [42].

Melatonin concentration can be measured from blood (serum and plasma), saliva, and urine. By taking melatonin samples at regular intervals (e.g., every hour), patterns of individual circadian rhythms can be reliability assessed. However, while a wide range of both laboratory and field based studies have used melatonin to measure circadian phases and disruptions, the burden of taking regular samples along with the required chromatography and/or mass spectrometry analysis makes it less desirable as a scalable instrument.

Cortisol is a hormone produced by the adrenal gland that has been shown to display circadian patterns [50]. Blood is considered the most reliable way to measure cortisol, though tests can also use samples of hair, saliva, urine, or feces [63]. Overall, cortisol is considered a less accurate circadian biomarker than melatonin [65].

Biophysiological Monitoring

Given that sleep is both a reflector and modulator of our latent circadian rhythms, tracking sleep-wake patterns can be useful in determining circadian patterns and disruptions. The gold standard for assessment is polysomnography (PSG), which monitors sleep and records a variety of biological measurements including brain waves, blood oxygen levels, blood pressure, breathing and heart rhythms, and eye and limb movements. However, the required setup, controlled environment, and specialized equipment makes PSG infeasible for longitudinal or in-situ tracking.

Instead, a wide array of studies use actigraphy, which measures body movement through the use of a wearable sensor (often on the wrist of a person's non-dominant hand) and can conveniently record sleep and activity patterns over spans of days, weeks, or longer. Accelerometry data captured by actigraphy is used to infer active and inactive status, which in turn can be utilized for detecting sleep-wake patterns. A number of studies have found sleep patterns inferred from actigraphy to be reliable and consistent with PSG [5]. This dependability of actigraphy together with its ease of use over time has allowed researchers to use actigraphy to assess circadian rhythms and identify patterns of disruption, for instance to detect circadian rhythm disturbances in the diagnosis of delayed sleep phase syndrome [22].

While actigraphy is less invasive than some of the procedures associated with biomarker measurement and is more practical than PSG, it still requires a participant to wear a specialized device all day and night for the duration of the study period, which typically lasts at least 7 days but preferably spans 14 days or longer to ensure capture of the individual's non-entrained pattern [77]. This condition may be less problematic for laboratory or field studies of a short duration, but using actigraphy to track circadian rhythms over an extended period of time and across a large population is still difficult due to device-burden and wear-compliance.

Self-Report Instruments

The use of biophysiological assessments such as those mentioned above are mostly limited to small laboratory studies given their invasive nature. For more broad scale investigations, manual self-report via survey or diary instruments can be a more suitable approach for capturing sleep and wake patterns—and the underlying circadian rhythms.

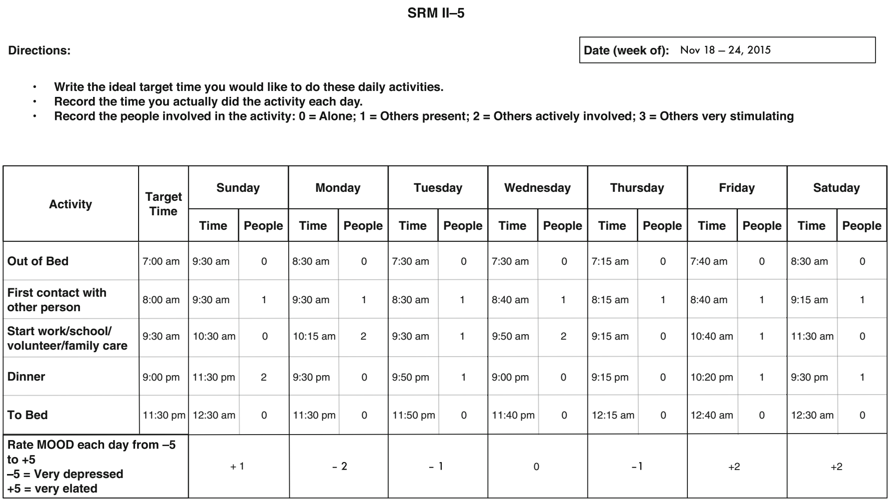
One of the most prominent survey-based instruments for assessing behavioral manifestations of circadian rhythms is the Munich ChronoType Questionnaire (MCTQ) [89]. To measure individual chronotype, the MCTQ includes questions related to sleep-wake behaviors (e.g., timing, preferences) as well as daily activities (e.g., light exposure, lifestyle details) for both work and free days. The use of the MCTQ to assess chronotype has been clinically validated in controlled settings against biomarkers, actigraphy data, and sleep logs [87].

To provide a quantified, comparable representation of chronotype, the MCTQ estimates chronotype based on a corrected measure of the halfway point between sleep onset and waking on free days [104]. Previous studies have found this mid-sleep point to be the best phase anchor for biochemical indicators, including melatonin onset [98].

A number of studies have also utilized sleep logs, sometimes in combination with actigraphy, to determine sleep onset, offset, awakenings, and duration; and they are often applied as part of diagnosing and treating sleep disorders and circadian rhythm abnormalities [109]. Comparison with actigraphy-based estimation of sleep behaviors generally shows reasonable agreement [55]. However, the validity of sleep logs has not been fully established against circadian biomarkers, plus a diary-based instrument faces limitations associated with self-report in general, including non-adherence, inconsistent completion, and potentially unreliable subjective and retrospective recall.

Mental Health Care

As mentioned earlier, circadian disruption has been associated with a wide range of mental health issues including bipolar disorder and schizophrenia. A number of studies have therefore focused on assessing circadian stability in the context of mental health. These studies often focus on using sleep information as an indicator of underlying circadian disruptions. For example, in their review paper, Cohrs et al. [21] note that a large number of studies have investigated the impact of sleep on



SRM II–5

Directions:

Date (week of): Nov 18 – 24, 2015

- **Write the ideal target time you would like to do these daily activities.**
- **Record the time you actually did the activity each day.**
- **Record the people involved in the activity: 0 = Alone; 1 = Others present; 2 = Others actively involved; 3 = Others very stimulating**

Activity	Target Time	Sunday		Monday		Tuesday		Wednesday		Thursday		Friday		Satuday	
		Time	People	Time	People	Time	People	Time	People	Time	People	Time	People	Time	People
Out of Bed	7:00 am	9:30 am	0	8:30 am	0	7:30 am	0	7:30 am	0	7:15 am	0	7:40 am	0	8:30 am	0
First contact with other person	8:00 am	9:30 am	1	9:30 am	1	8:30 am	1	8:40 am	1	8:15 am	1	8:40 am	1	9:15 am	1
Start work/school/ volunteer/family care	9:30 am	10:30 am	0	10:15 am	2	9:30 am	1	9:50 am	2	9:15 am	0	10:40 am	1	11:30 am	0
Dinner	9:00 pm	11:30 pm	2	9:30 pm	0	9:50 pm	1	9:00 pm	0	9:15 pm	0	10:20 pm	1	9:30 pm	1
To Bed	11:30 pm	12:30 am	0	11:30 pm	0	11:50 pm	0	11:40 pm	0	12:15 am	0	12:40 am	0	12:30 am	0
Rate MOOD each day from –5 to +5 –5 = Very depressed +5 = very elated		+ 1		- 2		- 1		0		-1		+2		+2	

Fig. 2 Sample paper-based Social Rhythm Metric form that is used to assess circadian disruptions in bipolar disorder

clinical variables in schizophrenia. To assess patterns of sleep, both subjective (e.g., sleep diaries) and objective (e.g., electroencephalogram—EEG) measurements have been used. Other studies have used actigraphy based instrumentations to assess rest-activity rhythms and circadian disruptions [58, 106].

Further, circadian disruptions can trigger relapse onset for patients with bipolar disorder. Similar to the case of schizophrenia, subjective and objective sleep assessments as well as actigraphy based measurement have been used to assess circadian disruptions in patients with bipolar disorder [46, 47, 64]. The irregular biological rhythms of individuals vulnerable to bipolar disorder have lead to the development of the Social Zeitgeber hypothesis, which suggests that the effect of certain life events on an individual's social routines may lead to the onset of bipolar episodes [27]. Specifically, these routines can affect endogenous circadian rhythms and lead to mood symptoms and, for susceptible individuals, full mood episodes.

The Social Rhythm Metric (SRM), shown in Fig. 2, is a paper-and-pencil based self-report daily diary measure of social routines designed to quantify the rhythms of daily life. It has been tested and applied as a therapeutic self-monitoring tool in psychosocial interventions [35]. The SRM has proven effective for assessing stability and rhythmicity of social routines [34]; however, it faces the known disadvantages of paper-based manual self-report, including non-adherence and the difficulty of longitudinal self-tracking.

Mobile Sensing

Altogether, we thus see that a number of techniques exist for assessing circadian rhythms and disruptions. However, while research has successfully used these methods over the years to untangle the biological basis of circadian rhythms, most studies are done either in the artificial settings of a laboratory or through subjective self-report. Understandably, the methods used in laboratory studies (e.g., participants sleeping with electrodes fastened to their heads or being asked to provide blood samples at regular intervals) are not scalable for administration to a large population. On the other hand, subjective reports and surveys, while more broadly deployable, are not well-suited for continuous monitoring over longitudinal periods and often fail to capture subtle details and instantaneous changes regarding the relationship between the circadian system, individual sleep patterns, and environmental effects. As a result, chronobiologists have pointed out the need for broad, *in-situ* data-collection methods that can record real-time data for a large population spanning various time zones and geographical locations [84]. Thus, such an ability to detect and infer behavioral traits of circadian biomarkers in a manner that is low-cost, reliable, and scalable is necessary to answer fundamental questions about sleep and circadian rhythms in real-world settings.

The widespread use and deep reach of smartphones in modern life, along with the rich embedded sensing capabilities of these devices, motivate the use of smartphones to track behavioral cues related to circadian disruptions in an affordable, reliable, and unobtrusive way. Similarly identifying this opportunity, a multitude of recent work has focused on the automatic measurement of sleep using smartphone sensors. For instance, the systems iSleep [39] and wakeNsmile [51] use a phone's microphone to detect sounds and body movement in order to predict sleep phases, while ApneaApp [75] emits frequency-modulated sound signals from a phone to detect sleep events through a sonar-like system. Best Effort Sleep (BES) [18] uses a phone's light and motion sensors along with information about application usage to infer a user's sleep duration, and Toss 'N' Turn [66] collects similar data to classify sleep state and quality.

However, such work typically does not take circadian rhythms into consideration nor include important endogenous and exogenous factors (e.g., chronotype, light exposure, social schedules) as part of sleep assessment. Research lacking these chronobiological underpinnings is thus missing the full picture. Moving towards a vision of circadian computing that is guided by a deep understanding of the biology behind sleep and daily behaviors, our research investigates the use of smartphone data and other types of digital footprints both as a window to gain insights into the interplay between external factors and internal rhythms and as a means for passively detecting circadian patterns and disruptions.

In a 97 day study with 9 participants, we demonstrated that smartphone patterns varied according to chronotype and were reliable in reflecting idiosyncratic sleep behaviors and circadian misalignments [2]. Specifically, we used smartphone screen-on/off patterns to detect sleep onset and duration as well as symptoms of

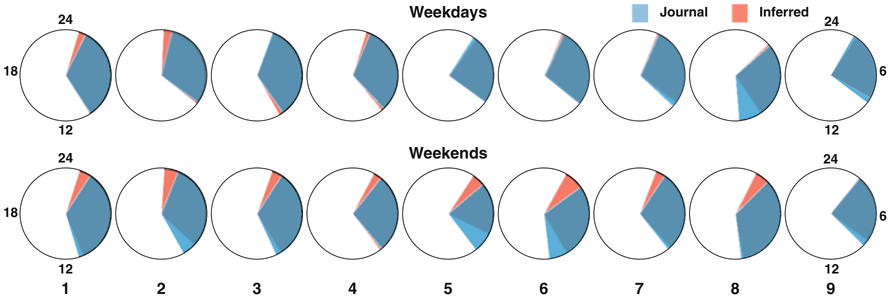


Fig. 3 Average sleep onset and duration across participants from phone and journal data from Abdullah et al. [2]. Sleep events coincide with phone non-usage, which can be used to passively track circadian disruptions (e.g., social jet lag)

sleep deprivation, including the sleep debt that accumulates after undersleeping on workdays and oversleeping to compensate on free days, as shown in Fig. 3. We also used this inferred sleep onset and duration to quantify social jet lag across chronotypes according to the discrepancy between mid-sleep on free days and workdays. Moreover, we found that smartphone usage patterns could identify sleep inertia—a transitional period from sleep to a fully awake state that can be symptomatic of circadian misalignments. Expanding our circadian computing framework to incorporate social sensor data from phone calls, text-messages, and social media enabled us to improve the accuracy of detecting sleep events and interruptions as well as measuring social jet lag [72]. Further analysis, including of text-based Facebook content, allowed us to also assess the impact of insufficient sleep on subsequent neurobehavioral functioning with respect to attention, cognition, and mood—specifically, finding lack of quality sleep to be associated with increased cyberloafing activity, reduced demonstration of complex thinking, and more negative mood.

Going beyond sleep modeling, we have also explored relationships between daily cognitive performance, mobile use, and latent biological traits [3, 73]. In particular, we focused on the continuous assessment of alertness based on in-situ data captured using smartphones. Conducting a 40 day study with 20 participants, we collected alertness data in the wild using the clinically validated Psychomotor Vigilance Test (PVT) and found variations in alertness patterns between early and late types, as illustrated in Fig. 4. In addition, we observed that not only chronotype but Daylight Savings Time, hours slept, and stimulant intake can influence alertness as well. We also found that mobile application usage can reflect alertness patterns, chronotype, and sleep-related behaviors, particularly when it comes to the use of productivity and entertainment oriented applications [73]. Leveraging these findings, we developed statistical models to passively and automatically infer alertness from smartphone usage patterns. Our model achieves a root mean square error (RMSE) of 80.64 ms when estimating response time from the PVT test, which is significantly lower than the 500 ms threshold used as a standard indicator of impaired cognitive ability [3].

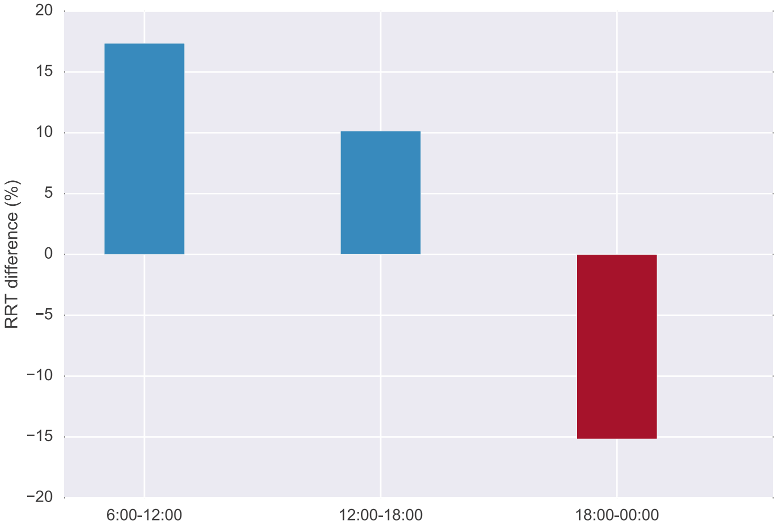


Fig. 4 Relative response time (RRT)—an indicator of alertness based on the Psychomotor Vigilance Test—of early chronotypes compared to late chronotypes across the day. *Blue and red* indicate higher RRT for early and late types, respectively. In the morning, early chronotypes display much higher alertness than late types, while the opposite is observed later in the day

Our ongoing work continues to explore the use of various forms of personal data traces in order to better understand, unobtrusively model, and reliably predict individual biological characteristics and patterns related to circadian rhythms.

Automatically Assessing Stability in Bipolar Disorder

One branch of our circadian computing research has focused on assessing disruption of the circadian system in the context of mental health—specifically, for the case of bipolar disorder (BD), which is associated with poor functional and clinical outcomes. BD has also been linked with high suicide rates [7] and is recognized as one of the eight leading causes of years lost due to disability [59]. As of 2009, the direct and indirect costs associated with BD are estimated at $151 billion in the United States alone [26].

As mentioned before, BD is characterized by circadian disruptions, and a number of clinical interventions have therefore focused on maintaining circadian stability to reduce the risk of relapse onset. For example, Interpersonal Social Rhythm Therapy (IPSRT) is a psychosocial behavioral therapy specifically developed to help patients with bipolar disorder maintain a stable daily and social rhythm in order to prevent relapse [33]. IPSRT uses the SRM self-report instrument described earlier and shown in Fig. 2 to establish and keep track of daily routines, mood, and energy.

However, this paper-and-pencil based clinical tool poses a number of challenges for longitudinal self-tracking. In particular, momentary and retrospective recall can be unreliable, especially during certain stages of the illness. Non-adherence is also a common problem. As a result, crucial and subtle behavioral cues relevant to bipolar disorder can often get lost in the process of manual tracking.

The emergence of mobile technologies and aforementioned novel sensing techniques has introduced opportunities for more automated and passive behavioral monitoring that could help to address these challenges associated with manual tracking. In the case of bipolar disorder, a smartphone application could facilitate the completion of the SRM on a device that is likely to be more accessible and more frequently in a patient's possession compared to his or her SRM log; and such a technology could further passively sense behaviors, affective changes, and a range of other bipolar disorder relevant indicators without requiring a patient's explicit input. The recognition of this potential held by technology-driven forms of digital tracking and intervention led to the development of MoodRhythm [60, 61, 103], a mobile application designed to track and stabilize daily routines, predict mood episodes, and provide personalized feedback to users.

In a recent study with MoodRhythm, we used smartphone based sensor data to automatically predict SRM scores. Specifically, we gave the MoodRhythm app to seven participants with a confirmed diagnosis of BD for 4 weeks and collected behavioral (e.g., detected speech, activity, SMS and call logs) and contextual data (e.g., location). Based on this data, we found that automated sensing can be used to infer key clinical markers of stability as assessed by SRM scores. Using location, distance traveled, conversation frequency, and non-stationary duration as features, our classifiers were able to predict stable (SRM score $>=$ 3.5) and unstable (SRM score $<$ 3.5) states with high accuracy (precision: 0.85 and recall: 0.86) [1].

Given the importance of maintaining circadian stability as part of effective BD management, these findings can have a considerable impact on clinical care. First, our developed method can help overcome issues associated with existing clinical tools by significantly lowering the user burden of manual tracking. In addition, our reliable automated sensing can enable capture of much more granular and diverse data, which can facilitate the development of early-warning systems for relapse detection. Such systems can also support novel technology-mediated strategies for providing interventions—enabling preemptive care at the right moment and the right place.

Beyond bipolar disorder, the SRM has also been used as part of treatment for a number of other clinical conditions including stroke [13], Parkinson's disease [12], myoclonic epilepsy [91], anxiety disorders [93], and unipolar depression [23]. A mobile sensor based method for automatic and passive assessment could thus be potentially applicable to a wide variety of clinical cases.

Applications of Circadian Computing

As described, circadian rhythms control numerous biochemical changes that occur in our bodies over 24 h and consequently have a direct impact on our behavior, cognition, and emotions. Circadian Computing and the development of technologies that can both sense and react to our individual circadian variations can significantly expand the existing role of ubiquitous technology in the domains of sleep, performance, health, therapy, and well-being. In particular, the ease of applying our robust passive sensing approach in an inexpensive, scalable, and unobtrusive manner across large and geographically diverse populations throws open a range of opportunities for a class of circadian-aware technology capable of measuring, monitoring, and maintaining circadian rhythms.

The ability of these technologies to be dynamically aware of variations in our circadian rhythms can not only facilitate broad scale experimental research that has the potential to untangle relationships between biological rhythms and behavioral cues, but it can lead to user-facing "circadian-aware" tools that better accommodate and support our sleep, daily performance, and overall well-being. Here we discuss particularly promising application areas.

Cognitive and Physical Performance

Given that our patterns of cognitive and physical performance follow circadian rhythms, the ability to continuously assess our biological rhythms can lead to technology that adapts dynamically to the idiosyncratic needs of its users based on their current or predicted levels of performance.

Scheduling and Activity Management

Since cognitive performance varies across the day, circadian-aware tools can help improve scheduling of events and tasks based on the cognitive demands of those activities and the circadian profiles of involved individuals. For example, by taking chronotype and personal alertness models into account, a circadian-aware calendar could provide recommendations for when to schedule cognitively-intensive versus rote tasks, and notifications might alert users when an event is being scheduled at a non-optimal time.

Systems for collective scheduling could benefit from going beyond mutual availability to also consider biological rhythms at a particular time of day and whether participants are likely to be at peak alertness. Similarly, tools to support organizing group-based activities such as project teams or study sessions could suggest members who share similar chronotypes and might synchronize more easily.

Learning and Education

Regarding education contexts specifically, many other relevant aspects of cognitive performance beyond alertness—including attention, learning, memorization, and problem solving—also reflect circadian rhythms [9]. For example, research shows the process of sequence learning is modulated by circadian rhythms [11], and recent studies have also reported a relationship between circadian phase and academic performance [25, 49]. At the same time, disruptions in our internal rhythms can adversely affect our memory and learning capabilities [105] and overall lead to negative educational outcomes.

Taking biological rhythms of learning into consideration would be particularly helpful for high school and college students, who are mostly late types given their ages. However, the early start times of most schooling systems run contrary to their attentional rhythms, potentially resulting in inefficient memory recall and learning deficits.

A circadian computing based assessment of academic performance rhythms could thus both help facilitate large scale chronobiology studies on the biological suitableness of current high school start times; support educators at both the institutional or classroom level in making decisions related to the timing of particular classes, activities, or exams; and help individual university students make more informed decisions when choosing classes to maximize their own learning.

In addition, and especially applicable considering recent trends towards more technology-mediated educational approaches in both the physical classroom and online (e.g., Massive Open Online Courses, or MOOCs), personalized circadian-aware learning services could tailor delivery of learning tasks, for instance by factoring in individual chronotype along with chronobiology domain knowledge like the fact that memory recall is more efficient in the morning while delayed recall works better in the evening [30].

Accident Prevention

Our cognitive ability to maintain vigilance and alertness has been shown to vary considerably across the day [14]. This circadian trend towards impaired performance as time goes on can be a serious issue when safety is concerned. Indeed, 20% of road accidents have been attributed to fatigue and sleepiness [44], with circadian disruption identified as a significant risk factor [80]. Overall, vehicular accident patterns display a circadian cycle with major peaks around 2 AM, 6 AM, and 4 PM [44]. Similar patterns have also been noted for industrial accidents [31].

Thus, there is a place for technology capable of assessing and predicting individual circadian variations in performance, including vigilance and alertness, to play a significant positive role in preventing such accidents. While a mobile-sensing methodology dependent on user-interactions may not be applicable, circadian-aware designs that incorporate alternative passive sensor streams (e.g., acceleration sensors or steering patterns) to continuously monitor cognitive performance could help to significantly reduce the risk factors related to vehicle accidents.

Therapy and Well-Being

Circadian computing can also play a major role in clinical therapy and interventions, from enhancing the administration of diagnostic testing and medication delivery to supporting self-care and clinical-management in the context of mental health.

Diagnostic Tests and Medication

Diagnostic test results can be affected by underlying biological rhythms and therefore need to take a patient's circadian phase into consideration. For example, clinical tests for allergies show a time-of-day effect [94], and tests based on blood pressure monitoring (e.g., hypotension, normotension, and hypertension) similarly show a circadian pattern [43]. The time of testing is also known to impact the results of glucose tolerating [110], hematology, coagulation, and hormone [41] tests. Symptom intensity for a number of medical conditions can also show rhythmic patterns. Asthma conditions [100], gout [40], gallbladder [83], and peptic ulcer attacks [68] are all known to worsen during the night; while acute myocardial infarction, sudden cardiac death [20], stroke [28], and congestive heart failure [108] peak during the morning.

Moreover, the effect of medications can have markedly different outcome, depending on the taker's circadian phase. Medications that are safe and effective for a given window of circadian phase might be ineffective or even unsafe when applied during a different biological time [54]. The field of *chronotherapeutics* focuses on delivering medications at biologically opportune times by taking circadian phase, rhythms of disease pathophysiology, and particular characteristics of a given medication into consideration [95].

By monitoring and predicting patients' circadian phase and disruptions, circadian computing can play an integral role in chronotherapeutics. Circadian-aware technologies could not only improve the efficacy of medications by providing recommendations about delivery times, but they could also enhance the accuracy of diagnostic tests to assess that efficacy and the associated condition. For example, depending on the rhythm of the medical condition being tested, such a system can suggest the best times for attempting to make a diagnosis (e.g., by testing for asthma conditions during the night).

Mental Health

As mentioned earlier, substantial evidence shows that circadian rhythm disruptions are associated with a number of neurodegenerative diseases including bipolar disorder, schizophrenia, and depression. As a result, stabilization of sleep and other aspects of an individual's circadian rhythms is an effective management strategy to reduce the extent and frequency of relapse.

However, current clinical tools for tracking patients' circadian rhythms are typically pen-and-paper based (e.g., the Social Rhythm Metric for bipolar disorder), which come with known limitations described earlier, plus such forms of manual journaling for long-term tracking can be particularly challenging for patients with severe psychiatric disorders. Circadian computing based approaches that use automated and unobtrusive sensing to track a wide range of behavioral and contextual patterns make it possible to detect relapse onset in a manner that is less burdensome for individuals and potentially more accurate, as demonstrated by our recent work that used passively sensed smartphone data to assess clinically-validated markers of stability and rhythmicity for individuals with bipolar disorder [1].

By enabling the identification of disruptions, circadian computing can also facilitate early warning systems for more effective intervention. The result can be the transformation of mental health care from a reactive to a preemptive practice—with a focus on detecting relapse even before it happens and giving individuals or caregivers the sorts of feedback needed to help prevent it.

Fixing a Broken Clock: Sleep and Circadian Interventions

Given the current extent of sleep pathologies, both academic and consumer-facing industrial researchers have a keen interest in measuring, assessing, and improving various aspects of individuals' sleep. However, sleep studies that do not consider circadian patterns and the effect of *zeitgebers* are missing half the picture. Similarly, interventions that only target sleep disturbances may merely be treating the symptoms of misaligned biological clocks rather than helping to address the root causes.

We believe a more holistic approach that takes into account individual chronotype and sleep-wake patterns would be more effective. Circadian-aware systems could firstly support individuals in becoming more aware of their underlying biological rhythms and their resulting idiosyncratic patterns over the day—and in the process, empower them to make more biologically-informed decisions when it comes to sleep. Similarly, digital tools could supply interventions that help people temporally structure meals and exercise in ways that reduce circadian misalignments [92].

Further, given that many of today's popular technologies have been associated with disruptions (e.g., electronic devices for reading, communication, and entertainment) [17], building circadian-awareness of their users directly into these devices (e.g., so that they could automatically dim or adjust a screen's white-blue light at appropriate times of day) could also move people back towards stabilization. As a final example, circadian-aware home and office environments might adapt lighting settings to cue light exposure (a key zeitgeber) at opportune moments to realign "broken clocks".

Conclusion

While modern technology, lighting, working conditions, and social conventions mean that humans no longer lead their daily lives primarily based on the position of the sun, our internal biological clocks still tick to the 24 h cycles of day and night. The resulting circadian rhythms these clocks generate impact almost every neurobehavioral process we experience, including metabolic activity, sleeping, waking, cognitive and physical performance, and mood. Maintaining stable circadian rhythms that are synchronized with our external environments and in phase with these biological functions is therefore key to sustain daily performance, long-term health, and overall well-being; while consistent disruption of our circadian system can have serious negative consequences such as an increased risk for cancer, diabetes, obesity, heart disease, and mental illness.

Given the increasingly widespread incidence of circadian misalignment in modern society and its significantly negative impact on overall well-being, we see a pressing need and opportunity for the development of technologies that can assess and monitor such disruptions in-situ, over long periods of time, and on a global scale. In this chapter, we described *Circadian Computing*, a line of work focused on unobtrusively assessing rhythms, identifying potential disruptions, and helping to bring about biological stability.

Particularly focusing on the advantages afforded by mobile sensing, this area of research develops lightweight computational techniques capable of continuous and passive sensing of daily performance, nightly sleep, and overall circadian stability. Such assessment strategies can not only support the work of chronobiologists seeking to more deeply study humans' innate biological rhythms, but they can also enable the design and deployment of circadian-aware technologies that can provide more adaptive, personalized support in a variety of areas including smart task scheduling, education, clinical therapy, and mental health management—and ideally, improve everyday life on a broad scale.

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