Exploring The Wearability And Design Of A Fully-Integrated Sleep Tracker

Master's Thesis
by

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Zusammenfassung

Mit einer ständig wachsenden geriatrischen Bevölkerung und modernen Lebensumständen stellt die zunehmende Verbreitung von Schlafstörungen eine ernste Bedrohung für unsere Gesellschaft dar. Spezialisierte Schlaflabore können derzeit das gesamte Spektrum der Schlafkrankheiten nicht umfassend für eine breite Masse diagnostizieren und behandeln. Steife Drähte und Schläuche sowie die inhärent unnatürliche Schlafumgebung im Labor schaffen einen schlechten Ruf und Vorurteile bei den Patienten. Lange Wartezeiten von bis zu drei Monaten verringern die Akzeptanz und Teilnahme weiter. Darüber hinaus bildet der aktuelle klinische Prozess eine teilweise unzufriedenstellende Datenbasis für eine genaue Diagnose oder Verhaltensanalyse, da die meisten Patienten nicht länger als zwei Nächte in einem Schlaflabor verbringen.

Daher haben wir die Tragbarkeit und das Design eines voll integrierten Schlaf-Trackers untersucht, um eine detaillierte, komfortable Analyse für eine Vielzahl von Schlafproblemen zu Hause zu ermöglichen. Wir haben uns ein Gerät vorgestellt, das bestehende handelsübliche Sensoren mit neuartigen Sensormodalitäten und einer mobilen Anwendung kombiniert. Dieser einzigartige Ansatz würde eine langfristigere Datenbasis für die Diagnose schaffen und Studien auf Basis einzelner Personen ermöglichen, um etwa alltägliche schlafbeeinflussende Verhaltensmuster zu identifizieren. Bestehende Lösungen decken nicht die gesamte Bandbreite der Schlafparameter ab, sind wissenschaftlich ungenau und kompliziert in der Anwendung.

Wir führten eine Literaturrecherche durch, um Anforderungen aus dem bestehenden Satz von sieben Kategorien von Schlafstörungen zu ermitteln, zu denen unter anderem Schlaflosigkeit und schlafbezogene Atmungsstörungen gehören. In einem zweiten Schritt untersuchten wir den diagnostischen Prozess von Schlaflabors. Somnologen verwenden eine Kombination von Fragebögen mit nachgewiesener Validität, Spezifität und Sensitivität zusammen mit der Goldstandard-Polysomnographie. Sie messen Gehirnaktivität, Atmung, Bewegung, Geräusche und den Herz-Kreislauf-Zyklus. Alle Daten werden mit einer hohen Abtastrate aufgezeichnet und Schlafexperten leiten weit über zwanzig Parameter ab, die die Schlafqualität der Patienten beschreiben. Im Gespräch mit fünf Experten erhielten wir vertiefende Einblicke in die Probleme von Schlaflaboren, wie z.B. lange Aktualisierungszyklen für neue Geräte oder strenge Vorschriften für den Diagnoseprozess.

Um die Benutzer besser zu verstehen, haben wir uns mit Statistiken über den Umgang der Patienten mit ihrem Schlaf und ihre Präferenzen für schlafbegleitende Technologien beschäftigt. Komfort, Zuverlässigkeit, Benutzerfreundlichkeit und Anbringungsort des Geräts gehören zu den Schlüsselattributen für tragbare Schlaftechnologie. Zusätzlich haben wir Interviews mit sieben Anwendern aus verschiedenen Altersgruppen durchgeführt. Die gewonnenen Erkenntnisse zeigen, dass sie wenig über die Parameter, die den Schlaf charakterisieren, wissen. Um alle Merkmale der verschiedenen Benutzer zusammenzufassen, haben wir fünf Personae erstellt, die als Vertreter für die verschiedenen von uns identifizierten Subpopulationen dienen. Wir

haben auch verschiedene Möglichkeiten zur Befestigung mit über 100 Teilnehmern getestet und uns für eine Umsetzung als Stirnband entschieden.

Durch die Zusammenfassung aller Erkenntnisse, die wir aus unseren vorherigen Untersuchungen gewonnen hatten, haben wir ein Beispielsystem entwickelt. Insgesamt haben wir vier verschiedene Sensoren integriert, die die Klassifizierung von Schlafstadien, die Messung des Herzzyklus, die Überwachung der Atmung und auch die Quantifizierung der Bewegung im Schlaf ermöglichen. Wir haben außerdem eine App entwickelt, die sich mit dem Gerät verbindet und Analyseergebnisse anzeigt. Darüber hinaus können Benutzer Fragebögen beantworten, ihr Profil einsehen und auch das tägliche Verhalten verfolgen, um den Einfluss auf ihre Schlafqualität zu erfassen. Wir vervollständigen unsere Softwarekomponenten mit einem Backend für die Authentifizierung der Nutzer und Speicherung der Ergebnisse sowie der Firmware auf dem Gerät zur Komprimierung, Speicherung und Verschlüsselung von Messdaten.

Um unser Sensor-Stirnband zu evaluieren, haben wir zwei Studien durchgeführt. Für die erste Studie hatten wir zwölf Benutzer, die zwei verschiedene Versionen von Mock-up-Geräten für jeweils eine Nacht trugen. Die zweite Studie lieferte Erkenntnisse, indem acht Benutzer die App während einer Think-aloud-Studie nutzten, in der sie kontinuierlich zum Ausdruck brachten, was sie taten. Unsere Ergebnisse zeigen, dass unser Prototyp angenehm zu tragen und die App einfach zu bedienen und zu erlernen sind. Zu den von uns identifizierten Problemen gehörten die lose Befestigung des Stirnbandes beim Bewegen im Schlaf und das Fehlen von Hinweisen, die die Bedeutung von Elementen der Benutzeroberfläche in der App unterstützen oder das Verständnis der Schlafergebnisse weiter vereinfachen. Außerdem haben wir ein System zur Messung der Atmung am Kopf mit Hilfe einer inertialen Messeinheit umgesetzt und getestet. Wir haben für einen Teil der Studienteilnehmer gute Ergebnisse, aber es verbleiben offene Fragen für große Genauigkeitsunterschiede bei der Bestimmung der Atemfrequenz zwischen einzelnen Subjekten.

Zusammenfassend lässt sich sagen, dass es uns gelungen ist, die meisten Sensoren, die in Schlaflabors verwendet werden, in ein einziges Gerät zu integrieren und zu zeigen, dass unsere App eine einfache Möglichkeit für die Benutzer bietet, sich unserer Lösung zu nähern. Wir haben gelernt, dass die Messung und Identifizierung von Schlafstörungen ein herausfordernder Prozess ist und Fähigkeiten aus vielen verschiedenen Disziplinen erfordert. Durch die Fertigstellung unserer Lösung und die Ergänzung des bisherigen Diagnoseverfahrens werden wir Schlafexperten weitere Einblicke in den Schlaf des Patienten geben und sie so bei der Suche nach der richtigen Therapie unterstützen. In Zukunft werden wir herausfinden müssen, ob unser Sensorsystem hält, was es an hoher Genauigkeit und exzellenter Benutzerfreundlichkeit verspricht. Darüber hinaus sind wir sehr daran interessiert, weiter zu untersuchen, welche Erkenntnisse wir aus der langfristigen Schlafüberwachung und dem Aufzeichnen des alltäglichen Verhaltens gewinnen könnten, um neue Lösungen für Patienten zu finden, die mit ihrem Schlaf Probleme haben.

Abstract

With an ever-growing geriatric population and modern lifestyles, the increasing prevalence of sleep disorders poses a significant threat to our society. However, specialized sleeping labs currently fail to diagnose and treat the full spectrum of sleep diseases broadly. Stiff wires and tubes, as well as the inherently unnatural sleep environment in labs, create a bad reputation and prejudice among patients. Long waiting times of up to three months further decrease acceptance and participation. Additionally, the current clinical process partially fails to form a satisfying database for an accurate diagnosis or behavioral analysis because most patients spend not more than two nights at a sleeping lab.

Therefore, we explored the wearability and design of a fully-integrated sleep tracker to enable an in-depth, comfortable, at-home analysis for a multitude of sleep problems. We envisioned a device that combines existing off-the-shelf sensors with novel sensor modalities and a mobile application. This unique approach would create a more long-term data basis for diagnosis and enable individual studies to identify daily sleep-influencing behavioral patterns. Existing solutions do not cover the entire bandwidth of sleep parameters, lack scientific accuracy, and are complicated to use.

We carried out a literature review to come up with requirements from the existing set of seven sleep disorder categories, which include insomnia, sleep-related respiration disorders, and others. In a second step, we looked into the diagnostic process of sleeping labs. Somnologists apply a combination of questionnaires with proven validity, specificity, and sensitivity together with gold-standard polysomnography. They measure brain activity, respiration, movement, sound, and the cardiovascular cycle. All the data samples at high rates and sleep experts derive well over twenty parameters describing the quality of sleep of patients. By talking to five experts, we got more in-depth insights into the problems of sleep labs such as longsome update cycles for new devices or strict regulations for the diagnostic process.

To better understand the users, we looked into statistics related to how patients deal with their sleep and also their preferences for sleep tech. Comfort, reliability, usability, and location of the device are among the key attributes for wearable sleep technology. Additionally, we carried out interviews with seven users from different age groups. The insights we got show that they know little about the parameters that characterize sleep. To summarize all the characteristics of the different users, we created five personas which serve as representatives for the different sub-populations we identified. We also tested different attachment options with over 100 participants and decided for a wearable headband as implementation.

By aggregating all the insights we got from our previous investigations, we proposed an example system. In total, we have integrated four different sensors which can enable the classification of sleep stages, the measurement of the cardiac cycle, the monitoring of respiration, and also the quantification of movement during sleep. We developed an app which connects to the device and shows analysis results. Additionally, users can answer questionnaires, view their profile, and also track daily

behavior to grasp the influence on their sleep quality. We complete the set of software components with a backend for authentication and storing results as well as the firmware on the device to compress, store, and encrypt measurement data.

In order to evaluate the wearable, we performed two studies. For the first one, we had twelve users wear two different versions of mock-up devices for one night each. The second study generated insights by having eight users use the app while doing a think-aloud study where they continually expressed what they were doing. Our results reveal additional aspects to improve comfort, and the app is easy to use and learn. Issues we identified included loose attachment of the headband when moving during sleep and lack of cues that support the meaning of user interface elements in the app or simplify understanding sleep results. Also, we implemented and tested a system for measuring respiration on the head using an inertial measurement unit. We have good results for some of the study participants, but open questions remain for significant accuracy differences between individual subjects.

In conclusion, we succeeded in integrating the majority of the sensors used in sleeping labs into a single device and showcased that our app provides an easy way for the users to approach our solution. We learned that measuring and identifying sleep disorders is a challenging process and requires skills from many different disciplines. By finalizing our solution and building on top of the diagnostic process, sleep experts will be able to get further insights into the patient's sleep and therefore help with finding the right therapy. Going forward, we must find out if our sensor system holds up to its promises on high accuracy and excellent usability. Additionally, we are much interested in investigating further which insights we could get from long-term sleep monitoring, and tracking behavior to come up with new solutions for patient's struggling with their sleep.

Contents

1. Introduction

Before we go into the details required for understanding this report, we like to introduce readers to the thoughts that sparked us to work on the topics covered by this thesis. We first present our problem statement and then go on to summarizing our idea and the research questions which we answer. Finally, we introduce readers to the methodologies we used and how our work is structured.

1.1 Problem

State-of-the-art in sleeping labs is so-called polysomnography, where somnologists hook patients to several cables and tubes [96]. Some alternatives exist for tracking sleep at home; however, they are lack scientific accuracy or only measure a single parameter [78]. Additionally, patients are scaring away from sleeping labs because they have a bad reputation due to an unnatural environment and increased discomfort during sleep. This situation is likely to also affect sleep quality during the time in the sleeping lab. Long waiting times of up to three months further decrease a quick and comfortable diagnostic process for patients with sleep disorders [29]. Finally, even after receiving a diagnosis, patients usually only spend one or two nights at the sleeping lab which makes it hard to perform long-term monitoring in a natural environment such as at home for, e.g., tracking therapeutic progress.

1.2 Idea

Our idea is to integrate the majority of all sensors that are currently applied to patients in sleeping labs into a single integrated device. This unification also includes coming up with new sensor modalities to measure parameters more comfortably. We envision to enable users measuring their sleep at home without requiring any manual intervention by a doctor or other professional. This new platform would also create the opportunity to collect more data over more extended periods which is likely to improve the diagnosis and could also help to monitor therapy progress. Ultimately, we also believe that the broad and in-depth database which we can collect for every user could enable new use cases such as correlating daily behavior with quality of sleep to identify sleep improving and disturbing factors.

1.3 Research Questions

The thesis explores the wearability and design of a fully-integrated sleep tracker. Our main focus is on comfort and at-home, independent usage of the device. The underlying goal is to make sleep measurement, analysis, and improvement more accessible for patients. The following paragraphs introduce the research questions which we answer with this thesis.

First, we look into the fundamentals of sleep, answer what characterizes human sleep, and explain the purpose. Next we consider questions regarding what constructs human sleep. Additionally, we stress the different functionalities of sleep by aggregating different findings in order to motivate why we should aim for a good sleep. To get an understanding of what disturbs human sleep, we have to look into different sleep disorders, including symptoms, epidemiology, therapies, and also understand how they affect human sleep. This overview helps to create the requirements for a sleep tracking device. Besides that, we would also like to answer which diseases can have behavioral root causes. On top of that, we are also investigating which previous work of our research group applies to our solution.

Next up, the thesis answers how the current diagnostic process in sleep labs looks like and how this creates implications for our proposed solution. We look into established standards for diagnosing sleep-related disorders such as anamnesis and polysomnography. As we are developing a sleep tracking device, we also investigate how and at which accuracy to track different sleep parameters. Besides looking at the standard sensor inputs used in sleep labs, we also look at the question of which alternatives exists from literature to measure the parameters in sleeping labs. Finally, we would also like to reveal any restrictions and constraints from a professional perspective on sleep technology.

When developing new software or devices, it is always mandatory to create empathy with the user. We, therefore, look into the groups of users who might be using our system. We ask ourselves how to characterize typical representatives of the different user groups. Additionally, we would like to learn more about the contexts of the user's behavior and how they influence the design of our system. We also aim to answer how to integrate electronic components by adhering to wearability guidelines into a single device that is comfortable and appealing to our users. We have to answer these wearability questions directly with the user.

By implementing hardware and software prototypes, we aim to learn how we can aggregate the insights of the previous sections into a single wearable device. We also answer questions related to how different components in such a system communicate and interact with each other and what technologies are used to realize them. We also look into the prototyping process for such a device. Answering questions about tools, technologies, and materials that we apply in order to build a device and app complete a set of questions related to execution.

Finally, we are interested in learning how users perceive the overall concept which we have developed and want to get insights into what they value about our device and app. We want to learn how they perceive the usability of the app and the comfort of the device that we propose. Additionally, we would like to evaluate, at which accuracy we can track physiological parameters. We also stress work that remains for the future.

1.4 Methodology

To learn more about sleep and sleep disorders, we apply a literature review and online research, where we collected all the information we identified to be relevant to our work.

For getting a better understanding of the diagnostic process, we apply expert interviews and also perform another literature as well as online research.

In order to come up with a final design, we did an online research and executed interviews with the different user groups. We also held design workshops and conducted online surveys to learn more about the preferences of users.

For the implementation of an example system, we showcase architectural diagrams and flow charts as well as hardware, and software prototypes.

In the final evaluation, we apply in-situ user studies and think aloud sessions to generate insights into the user's thought processes. Addditionally, we do a controlled experiment.

1.5 Structure

In chapter 2, we kick things off by looking into how sleep and its regulating processes work. We also give an in-depth introduction into the seven categories of sleep disorders defined by the *American Academy of Sleep Medicine (AASM)* [5] and showcase which previous research of our group applies to this thesis.

The following chapter 3 goes on to introducing the current diagnostic process. We look at different questionnaires for anamnesis and their application. We also look into the gold-standard polysomnography measurements used in sleep labs. By highlighting different alternatives from related work, we also present which other approaches have been used to compute the wide variety of sleep parameters. The chapter concludes with an analysis of restrictions and constraints which we summarized from our conversations with sleep experts.

In chapter 4, we present various design considerations that we made including information about sleep tech in general based on our online research and insights we gained from our interviews with members of different user groups. We present a persona that serves as a representative for a subpopulation of our potential users. We also describe how he would interact with the system based on the user journey.

Chapter 5 aggregates all the previous findings by integrating them into a single solution. We present two functional hardware prototypes and a mock-up device focusing on wearability. Additionally, we introduce our software stack which includes an app with 26 pages, our backend, and the firmware of the device.

Finally, in chapter 6 we evaluate the hardware mock-ups and app which we have developed by applying in-situ wearability studies followed by interviews and think-aloud studies for three different scenarios. We also evaluate an alternative sensor approach which we thought might provide an opportunity to track additional bio-parameters with more comfort.

To wrap up this thesis in chapter 7 we summarize our work and conclude thoughts which we draw from our results. We also give hints to future work.

2. Sleep Fundamentals

The purpose of this chapter is to describe the fundamentals required for understanding the subjects covered in this thesis. We introduce and showcase several factors that characterize human sleep. Then we also specify the functionality that sleeping has for humans. This introduction follows an in-depth overview of different sleep diseases, including symptoms, epidemiology, and possible therapeutic approaches. Finally, we also introduce previous work that has been published by the *TECO* research group [100] where this thesis was carried out. Recommendations that stem from the results of this literature review are indicated as grey boxes and contribute to the final solution design of a fully integrated sleep tracker. The majority of the summarized information presented in this chapter comes from a specialized professional book on sleep medicine [96] as well as the formal definitions for sleep diseases defined by the *American Academy of Sleep Medicine (AASM)* [5].

2.1 Sleep

We start by introducing several characterizing aspects of sleep, such as sleep phases, the duration of sleep, and other physiological changes that the human body undergoes during sleep. Even in 2019, the purpose of sleep is highly unresolved [96]. Nevertheless, the following sections introduce the functionalities that sleep specialists consider to be contributing to why we sleep.

2.1.1 Phenomenology

Five different sleep phases are at the core of human sleep characteristics [96]. They result in various changes throughout different physiological parameters that can be quantified using sensors. Additionally, the duration of sleep plays a crucial role in characterizing sleep. Sleep diseases are mostly affected by or related to either one of those two main characteristics by causing irregularities in sleep phases or disturbing the duration of sleep (too short or too long). The following two sections will go into the details of those characteristics.

2.1.1.1 Sleep Stages

According to the *American Academy for Sleep Medicine (AASM)* [5] starting at the age of two to six months four different sleep stages and the wake phase can be differentiated. In general, when analyzing sleep data in sleep labs, it is separated into thirty seconds windows [84]. Professionals supported by software then go through each of those windows. To classify the different phases, a clinical measurement procedure called polysomnography (PSG) [96] records, brain activity, eye movement, and muscle activity. Also, it is common to track other parameters, but we do not go into any further details because of their irrelevance to classify sleep stages. The classification decision depends on the specific characteristics of the measured signals. We have listed a simplified version of the formal classification criteria for the different stages in Table 2.1 below.

Stage	**Patient State**	**Brain Activity**	**Eye Movement**	**Muscle Activity**	**Ratio of Total Sleep Time**
W	patient is awake	dominating alpha and beta waves	blinking and fast eye movement	high tones, movement artifacts	< 5 %
N1	transition from awake to sleeping	theta activity (vertex spikes)	slow, partially rolling eye movement	lower muscle tones (< W)	55 - 60 %
N2	stable sleep	theta waves, K-complexes and sleep spindles	no eye movement	lower muscle tones (< N1)	
N3	deep sleep	delta waves < 2 Hz	no eye movement	lower muscle tones (< N2)	15 - 25 %
REM	dream-intensive stage	theta and slow alpha waves, sawtooth waves	conjugated, fast eye movement, REM	lowest muscle tones (< N3), phased activity	20 - 25 %

Table 2.1: Simplified table based on the characteristics of sleep stages by the AASM scoring manual [15] and [96].

Chapter 3 provides more details on how brain activity is measured. In a sense, skin-contacting electrodes capture electrical signals to measure alpha, beta, theta, and gamma brain waves [96]. The main difference from a signal point of view for the different waves lies within the frequency and amplitude of the measured signals. Vertex spikes, K-complexes, sleep spindles, and sawtooth waves are additional distinct, non-sinusoidal patterns which can be identified in the electric signals and are therefore also used for classification. The sleep stages are then usually depicted as

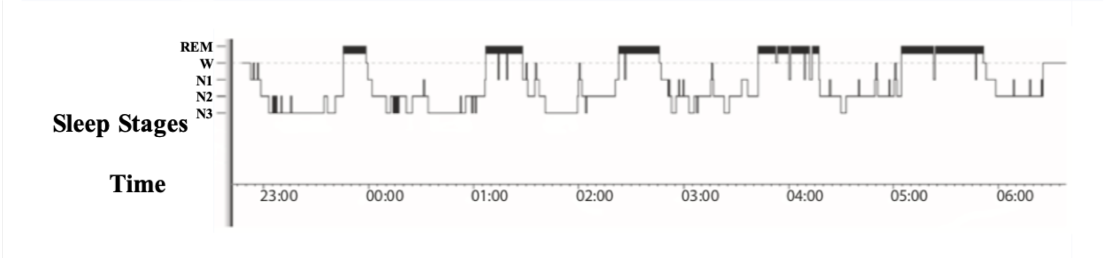


Figure 2.1: The hypnogram shows the sleep profile of a healthy adult male with five sleep cycles. It is visible that each cycle lasts about 90 minutes [96].

a so-called hypnogram, whereas Figure 2.1 shows an example of such a diagram. A healthy sleeper goes through all stages several times - depending on the duration of sleep and the patient four to seven times per night. Each cycle has a duration of about 90 to 110 minutes. As the cycles progress, the proportion of deep sleep decreases, whereas REM (rapid eye movement) sleep increases. Besides the classifying factors listed in Table 2.1, other physiological factors also change during the transition from one sleep stage to another. Most notably, the heartbeat frequency lowers 10% to 20% during the transition from wake to non-REM sleep stages and has a higher variability during the transition from non-REM to REM sleep. Additionally, the body temperature has its maximum right before going to bed and decreases overnight having its minimum in the early morning hours.

Conclusion 2.1

A fully-integrated sleep tracker requires a set of sensors that enable a reliable classification of ideally all four sleep stages (N1, N2, N3, REM) and the wake stage. A common way to represent these stages is a Hypnogram which we should use for, e.g., displaying sleep stage data in an accompanying app.

A side note, which is worth mentioning here is that in 2019, critique about the strict classification of sleep stages exists as it does not allow the analysis of, e.g., transitory sleep stages. Additionally, there are no strong reasons for the 30-second time frame windows. Therefore, research has been conducted to create probabilistic models that classify sleep stages in probabilities across the set of all sleep stages for each point in time during sleep [93].

2.1.1.2 Sleep Regulation

The body temperature is the primary indicating variable for the so-called circadian rhythm [96, 17, 40]. It is a little less than 25 hours long and only due to external factors such as light and social influence (e.g., work) synchronized to 24 hours. Additionally, melatonin and cortisol levels change throughout day and night. Healthy humans suppress melatonin production when light is present, which creates a coupling between hormone production during day and night. The body reaches its melatonin maximum during the night.

For sleep regulation, three core mechanisms exist. The homeostatic process which is caused by the previous sleep and wake-up time and therefore creates pressure to sleep. Secondly, the circadian rythm which is essentially the daily oscillating degree of wakefulness. The third process is the so-called ultradian rythm which supports the switch from REM to non-REM sleep within the sleeping period.

Conclusion 2.2

We should avoid interfering with the biological sleep-regulating processes. Instead, we should think about ways to support them with our system and encourage the user to follow its biological rhythm.

Borbély Two-Process Model

The sleep-wake cycles as we know them today are based on the two-process model by Borbély [17] who proposed it in 1982. It consists of the homeostatic processes (S) which asymptotically rises to a maximum during wake times. During sleep, it falls back down. The circadian process (C), however, is the degree of wakefulness, which has its lowest value during the evening.

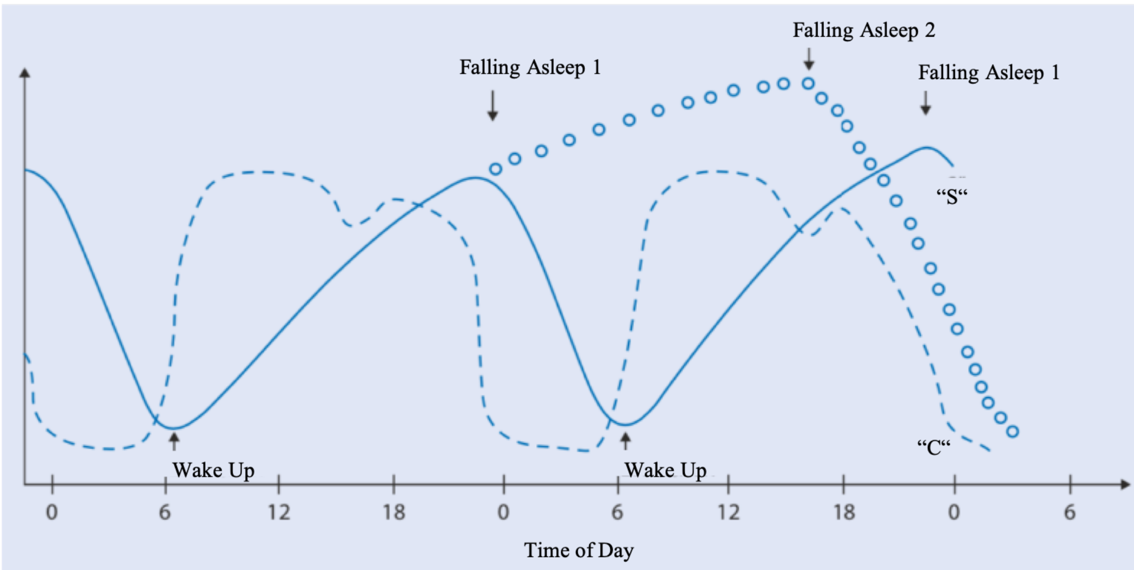


Figure 2.2: C shows the circadian degree of wakefulness and S the accumulating endogenous pressure for sleep in the wakeful phase. Falling asleep occurs if C is low, and S is high (Falling Asleep 1). The dotted line shows the curve if patients skip a night of sleep, which leads to the person falling asleep around the afternoon during the next day (Falling Asleep 2) [96].

Model of reciprocal interaction

The model of the ultradian rhythm of the non-REM-REM-sleep-cycles was developed as early as 1975 by Hobson and McCarley [40]. Their model of reciprocal interaction is still valid today and was adapted by neuroscientists throughout recent years. It describes the interaction of different neurotransmitters from wake to non-REM and REM sleep, whereas the different phases have elevated activities of different neurotransmitters.

2.1.2 Purpose of Sleep

Even today, the purpose of sleep is highly unresolved. However, sleep physicians and researchers identified several functions. As some of these factors are crucial to our health, it underlines the importance of sleep for a healthy and balanced lifestyle. With modern lifestyles, the time that we as human beings spend asleep decreases and therefore, the lack of sleep creates a severe threat to our modern society [46].

Purpose	Description
Recovery	Recovering seems to be the most apparent purpose of sleep as everyone inevitably has made the experience of lacking sleep. Increase of glycogen stores during sleep which provides energy in the form of glucose support this theory [96]. Additionally, studies observed longer sleeping times after sleep deprivation [14]. However, the amount of sleep is unchanged even after physical efforts which counteracts this theory [96].
Saving Energy	Lower body temperature is typical during sleep [96]. The energy consumption of the body is around 10% lower than during wake times. This effect is also observable by the activity of neurons responsible for the thermals of the body and sleep regulation.
Immune System	There is evidence that sleep deprivation has adverse effects on the immune response [20]. As sleep-deprived patients are more susceptible to infections and have a worse response to vaccination, we can assume that coupling exists between sleep and immunity [96]. In controlled experiments with rats, sleep deprivation resulted in a breakdown of the immune system and even death [77].
Memory Consolidation	Research does leave little doubt that memory reprocessing happens during sleep [94]. Especially for tasks related to the procedural memory (”knowing how”) sees a significant improvement after ’sleeping on them’ suggesting that memories are formed and shaped during sleep. For declarative memory (”knowing that”) fewer evidence on consolidation during sleep exists. Ultimately, the rules which determine what the brain consolidates during sleep are still unresolved, and also why these processes occur during certain sleep stages.

Table 2.2: This overview presents the different purposes of sleep and explains them.

2.1.3 Dreaming

Dreams are mental activities during sleep [96]. The things we can remember about these activities are called sleep reports, also described as dreams in colloquial speech. Dreaming comprises a holistic set of sensory impressions with feelings and thoughts. Dreams can not be quantified from outside the patient but rather through questions and answers. It is possible to improve dream recall capabilities by regularly writing them down after waking up. Remembering dreams is not always possible, and patients can only report about them when awake and if they can remember. Not everyone can remember their dreams, and women are generally better at remembering them or at least report to have more memories about them. Sleep problems are many times related to higher dream recall. The functionality of dreaming is still unresolved, but scientists speculate that they help to resolve problems with thoughts and shape new impressions.

Conclusion 2.3

By providing a dream diary, users can improve their dream remembering capabilities. As increased dreaming can relate to sleep disorders tracking sleep could also help with identifying sleep problems.

2.2 Sleep Diseases

By 2019, sleep physicians have identified and characterized around 80 sleep diseases [23]. Meanwhile, estimations suggest that around 30% of the population are suffering from disturbed or non-relaxing sleep [96]. The following sections will introduce seven sleep disease groups which have been defined by the *AASM* in the *International Classification of Sleep Disorders (ICSD)* [5, 84]. The classification is also accepted and used by the community of sleep physicians in Germany that organizes itself as the *German Association for Sleep Research and Medicine (Deutsche Gesellschaft für Schlafforschung und Schlafmedizin - DGSM)* [24].

2.2.1 Insomnia

Insomnia is one of the most prevalent diseases known in medicine [96]. Patients have trouble falling or staying asleep even though no external causes are present. The low energy level during the day results in a higher focus on the sleep problem itself, making it even worse. Treatments involve pharmaceuticals or cognitive-behavioral therapy (CBT).

2.2.1.1 Symptoms

According to *ICSD* patients have trouble falling or staying asleep or waking up too early or a combination of all three [84]. Typically patients report fatigue and a feeling of sickness. Additionally, they have trouble to focus, concentrate, or remember. These problems usually also harm their social, family, professional or academic life and performance. For chronic insomnia, the described disturbances have to be persistent for at least three months and three times per week. Patients who sleep short are not considered to have insomnia if they do not have any sleep-woke complications. For the formal diagnosis of insomnia, the *ICSD* defines an extensive list of symptoms that can be used to classify patients. For diagnosis, sleep experts apply a combination of questionnaires and polysomnography.

2.2.1.2 Epidemiology

In a study with 2000 adults from Quebec (Canada) 30% reported insomnia symptoms [61]. Around 10% of the population meets the criteria of the insomnia syndrome, whereas women are more likely to be affected than men [23]. Probability for insomnia rises during mid-age, menopause or after a regulated lifestyle is interrupted due to reaching the end of professional life. The economic burden of insomnia is huge - costs of medical treatment and, e.g., lost productivity or accidents result in annual loss between $92.5 and $107.5 billion in the U.S. alone [95].

2.2.1.3 Therapy

The therapy of insomnia is a highly complex task, as root causes can vary drastically between patients [96]. The disorder can have psychological, organic, behavioral, or substance-induced root causes. Many times insomnia has multiple factors which, therefore, requires a multimodal treatment approach. First of all, so-called cognitive behavioral therapy is considered to be the most critical point of attack when treating insomnia, even before medication. Psychoeducation then primarily helps to improve sleep hygiene. Incorrect bedtimes, stressors such as work documents near the bed, alcohol consumption, or the use of new media characterize lousy sleep hygiene. To achieve good sleep hygiene, regulating the bedtime to a necessary extent, and optimizing the regularity of sleep is essential. A pleasant bedroom atmosphere and avoiding substances such as coffee or alcohol as well as physical strain also improve sleep hygiene. Pharmaceutical substances can be used to improve insomnia in the short term, but they do not generally lead to a long-term solution to the problem. Above all, a large number of drugs in use for treating insomnia makes patients dependent. They are hard to discontinue in a short time, which speaks against their use. Psychotherapy and behavioral therapies, on the other hand, are an effective means of achieving long-term success in eliminating insomnia. They aim to reduce mental effort while falling asleep and thus improve sleep behavior. Also, establishing bed rituals or other techniques help to suppress dysfunctional thoughts before sleeping.

Conclusion 2.4

The system could support behavioral changes and provide tracking of insomnia treatment progress. It could also support with correlating, e.g., sleep diary entries to objective sleep quality measures tracked with a wearable to understand what affects sleep negatively.

2.2.2 Sleep Related Respiration Disorders

Most of the sleep-related respiration disorders are linked to snoring, daytime sleepiness, and being overweight. Even though mostly man are affected by these disorders, thin woman and even children can be affected by these diseases. The respiration disorders can lead to focus problems but can also result in insomnia effects and reduction of productivity or performance [114]. The breathing issues can also worsen comorbid diseases such as depressions. A significant issue while diagnosing the disease is that many times, the problems are thought to be related to age or exhaustion by patients and not to respiratory issues during sleep [23].

2.2.2.1 Symptoms

The symptoms vary strongly depending on the type of respiration disorder. The following paragraphs introduce the different problems each and illustrate the most critical factors that enable doctors to identify them. Snoring, interruption of breathing or shortness of breath after waking up are typical risk indicators for sleep-related respiration disorders.

Obstructive Sleep Apnea Syndrome (OSAS)

According to [84], in order to diagnose sleep apnea, a series of conditions have to be met. A blockage of the airways causes obstructive sleep apnea. Even though patients do not breathe notably, an abdominal and thoracic movement can be measured, indicating that the neural impulse is present but an obstruction makes breathing impossible. The obstruction can be caused by access weight while sleeping on the back as the muscles relax during sleep which results in a collapse. This relaxation can also occur due to alcohol consumption. Enlarged tonsils or a large overbite can also cause obstructive sleep apnea. Formally, per hour, 15 signature events have to be measured. These events are obstructive sleep apnea (full interruption of breathing for at least ten seconds), obstructive hypopnea (reduced breathing for at least 10 seconds) and respiratory effort-related arousals (at least 10 seconds of reduced breathing without a drop of blood oxygen but with a wakeup reaction due to the increased respiratory effect).

Conclusion 2.5

To classify OSAS, we need to be able to track airflow and optionally respiratory effort on abdomen and thorax. OSAS depends on sleep positions for some. The system could identify correlations between sleep positions and apnea events. Additionally, individual behaviors such as alcohol could be correlated with the number of sleep apnea events to understand the severity of influence on an individual level.

Central Sleep Apnea

The main difference between central apnea and OSAS is that a malfunction of the brain causes it and not an obstruction. Central sleep apnea results in sleepiness, trouble with falling and staying asleep, regular awakenings and unrelaxing sleep — additionally, shortness of breath, snoring, and apnea events are characteristic during the night. For a diagnosis of central sleep apnea, observing at least five central apneas or central hypopneas per hour during sleep is mandatory. Out of the total number of all apnea and hypopnea events, 50% must be of the central type.

Conclusion 2.6

For a differential diagnosis between OSAS and central sleep apnea, we have to understand if the patient's abdomen or thorax does move during the apnea event.

A specialized type of central sleep apnea includes so-called Cheyne strokes respiration. For this particular condition, the regulating unit in the brain has problems with adapting to the changing carbon dioxide levels in the bloodstream. This malfunction results in cyclic over- and underreaction of the respiratory frequency and apnea events.

Hyperventilation

An increased breathing rate characterizes hyperventilation during sleep. This effect can lead to the body exposing more carbon dioxide than it can produce ultimately causing hypocapnia that causes, e.g., a tingling feeling in the limbs, cramps, or seizures. The root cause can be many different factors, and the disease can be idiopathic, however also organic failures, medication, or obesity can be the reason for sleep-related hypoventilation. Chronic obstructive pulmonary disease (COPD) is also one of the main factors for hyperventilation during sleep.

Conclusion 2.7

Questionnaires about physiology, medication, comorbid diseases, and other diagnosed illnesses of patients can help to find root-causes and enable the differential diagnosis of sleep-related problems.

2.2.2.2 Epidemiology

Sleep apnea is estimated to affect three to seven percent of men and two to five percent of woman [73]. However, some studies even suggest that 25% of the population are affected by sleep apnea [96]. Currently, around 10% of all patients are estimated to be of the central sleep apnea type. However, this number might be incorrect as many of the sleep lab patients are affected by snoring which serves as a first indicator for going to a sleep lab which is not the case for central sleep apnea. Obstructive sleep apnea is many times related to age and gender. Also, ethnic and genetic factors play a role in obstructive sleep apnea. Especially obese men are affected, and Afro-American patients are more affected than Caucasian or Asian ethnicities, independent of the imbalance in obesity rates [96].

2.2.2.3 Therapy

Sleep apnea is a complex disease which can have multiple root causes. In general, therapy includes conservative, operative as well as apparatus-based treatments [96]. They can also be combined and are usually helpful for patients. Many times the sleep disorder does not occur on its own, which creates frustration for patients during treatment. Especially if it takes more time to treat than expected, increased problems occur with staying asleep throughout the night due to frustration and insomniac effects. The goal of every apnea therapy is always to reduce the number of respiratory events and reduce cardiovascular risks.

Especially for sleep apnea weight reduction is indicated; however, no fast therapeutic effect levels out. Moreover, patients should try to avoid alcohol and medication. Good sleep hygiene is mandatory for avoiding sleep apnea. Studies regarding the consumption of alcohol are inconsistent and the medication of sleep apnea is not possible.

Most times, treatment includes the application of CPAP, APAP, or BIPAP masks. CPAP (continuous positive airway pressure) puts overpressure onto the patient's airways by using a face-covering mask. APAP (automatic positive airway pressure) adapts to the patients breathing to achieve an optimal therapeutic effect and improve comfort. BIPAP (bilevel positive airway pressure) has two different pressures - one for breathing in and one for breathing out, improving comfort even more. Other apparatures are trying to increase the tonus of airway muscles by electrical stimulation; however, they are falling behind expectations in the latest clinical studies.

Interestingly, training of the pharynx muscle by playing digeridoo shows evidence for successfully treating sleep apnea. Around 50% of all sleep apnea patients have an increased number of apnea events when sleeping on the back, therefore avoiding this position can have a therapeutic effect, which can be supported by wearing a specialized vest. Additionally, functional lower jaw-splint can change the displacement of the jaw to increase the airways' diameter basically through a mechanical approach. However, this requires certain anatomical preconditions of the patient.

Physicians only recommend surgeries for severe cases of respiratory disorders. Surgeries include a correction of the nose to improve nasal airflow, stabilization or removal of the soft palate which is many times responsible for snoring and an extension of the pharynx or positional correction of the lower jaw to improve airflow.

Conclusion 2.8

An objective sleep tracker for at-home usage enables continuous tracking of therapy progress. This insight could reduce the frustration created by the subjectively hard to notice therapy progress. Additionally, conducting individual small scale studies help to precisely analyze the effect of alcohol or medication. Additionally, we could support patients with avoiding sleeping on the back, e.g., through vibrotactile cues.

2.2.3 Hypersomnia

Patients with hypersomnia suffer from excessive daytime sleepiness [96]. Few people are struggling with this problem however patients who have it are severely burdened.

2.2.3.1 Symptoms

Compared to daytime tiredness daytime sleepiness describes the tendency to fall asleep during the day while performing monotone tasks, e.g., reading. Depending on the severity, this can create potentially dangerous situations for patients.

Narcolepsy

Patients with narcolepsy have a tendency to fall asleep much more quickly during the day with cataplexies (loss of muscle tone without losing consciousness), also accompanied by sleep paralysis. They also report increased dream reports and nightmares. For a diagnosis, physicians use questionnaires about daytime sleepiness which have to differentiate between listlessness and actual daytime sleepiness validly. Laboratory tests and polysomnography (PSG) support the diagnosis. Besides the night analysis, also a daytime multiple sleep latency test (MSLT) is conducted, where a patient undergoes several short nap sessions during the day. For differential diagnosis, it is especially important to identify a premature REM sleep.

Conclusion 2.9

We have to ensure questionnaires, e.g., presented in an app, are valid according to medical requirements and suited for differential diagnosis. Besides nighttime sleep tracking, daytime sleepiness analysis plays a crucial role in diagnosing sleep disorders such as narcolepsy.

Ideopathic Hypersomnia

Also characterized by elevated daytime sleepiness, but night sleep is mostly healthy. Higher tendencies to fall asleep during the day. Also has to be tested using MSLT. Compared to narcolepsy, measuring does not indicate increased REM activity. Sleep during the day is not relaxing and followed by drowsiness.

2.2.3.2 Epidemiology

The prevalence of narcolepsy is relatively low, with only around 0.03% [96]. Children of patients with narcolepsy have a higher risk of 1 in 100 to also have narcolepsy. Idiopathic hypersomnia also accumulates within families. However, no reliable numbers on prevalence are available. The progression of both diseases is chronic and starts at the age of 15 to 25 years.

2.2.3.3 Therapy

For narcolepsy, several medication options exist to treat the symptoms of daytime sleepiness, cataplexy, and night's sleep. Many times comorbid diseases such as respiratory disorders occur, which have to be treated separately. Idiopathic hypersomnia has very few treatments that are clinically validated. However, making sure that sufficient night's sleep is available is essential. Some small-scale evidence exists for success with medication.

2.2.4 Circadian Sleep Wake Disturbance

Deviations of the natural circadian rhythm and reactions to light/dark changes are characterizing for the formerly introduced disorders [96]. Either the intrinsic pacemaker is disturbed, or external factors cause time shifts of sleep. The foundation for diagnosis, in general, are sleep diaries which are usually collected over two weeks.

Conclusion 2.10

For objectifying sleep quality, we can apply automated sleep tracking and also digitize manual sleep diaries.

2.2.4.1 Symptoms

Several different types of sleep-wake disorders exist. The main difference for the different types is mostly within the timing of the disturbance in the sleep-wake cycle.

Sleep Phase Disorder

It is characterized by a delay of more than two hours of sleep phases compared to the duration of healthy sleepers. Sleep itself is normal, whereas quality and duration are sufficient according to individual needs.

Delayed Sleep Phase Disorder

It is characterized by problems to fall asleep, whereas some patients are struggling up until the early morning hours. Patients report extreme drowsiness in the morning, feel weak throughout the day; however, have a performance peak towards the evening. Ignoring the inner clock can result in psychosomatic problems

Premature Sleep Phase Disorder

Sleep phases are displaced forward with high pressure to sleep. Patients report fatigue in the early evening. Many times morning types that wake up early between two and five in the morning and start to feel tired between six and nine in the evening. Many times, patients try to fight the symptoms with coffee or other supplements. In general patients have fewer problems with their daily lives, especially in professional environments; however, might have trouble when meeting friends in the evening.

Other Sleep Rhythm Disorders

More complex sleep-wake disorders exist, for example, irregular patterns in daytime sleep and disturbance while falling and staying asleep. For example, a clinical picture exists where the sleep rhythm shifts one or two hours behind every day.

2.2.4.2 Epidemiology

Delayed sleep disturbances affect around 0.5% of the population. Family anamnesis is positive in around 40% of all cases, which suggests a genetic connection. Many times sleep-wake disturbances also occur for people who lack social time givers for standing up, such as when not having a day-to-day job. Working shifts or jetlag also can result in sleep-wake cycle problems.

2.2.4.3 Therapy

When treating circadian sleep-wake disturbances, regular bedtimes are very important. Additionally, exposure to light with light therapy can help to prevent melatonin contraception. It is also possible to use medication which, e.g., supports falling asleep. A chronotherapy is a therapy for reprogramming the circadian rhythm. A targeted delay of sleep time aims to achieve the desired timing and helps to adjust regulation. Behavioral measures include avoiding loud music or playing soft, relaxing music before going to bed. Employers should respect the individual sleep-wake behaviors of their shift workers to support their natural sleep-wake cycles.

Conclusion 2.11

An app can remind the user to go to bed for supporting regular bedtimes. Additionally, it can provide audio functionality to support playing relaxing, soft music or to support users with performing a targeted chronotherapy.

2.2.5 Parasomnias

Parasomnias are sleep disorders that occur besides sleep [96]. The term comes from the Latin words para (besides) and somnus (sleep). The clinical picture includes, for example, nightmares or sleepwalking.

2.2.5.1 Symptoms

The disorders and related symptoms are complex. In the following, we introduce two specific groups.

Wake-up Disorders

Includes, for example, sleep terror, which results in patients repeatedly startling from deep sleep (non-REM), often accompanied by a scream and sitting up in bed. Besides, the eyes can be wide open. For diagnosis, a thorough anamnesis and a visit in the sleeping lab to exclude root causes linked to epilepsy are mandatory. Also, sleepwalking falls into the same clinical picture and often occurs following sleep terror. Contrary to general perception, sleepwalking is usually not associated with walking around. If so, well-known behavior from everyday life is played out. Both in sleep terror and sleepwalking, patients usually can not remember what happened and what they have done. Therefore, third-party anamnesis is inevitable. Negative nightmares can also cause a wake-up reaction, but for pathologic diagnosis, a high burden associated with the nightmares is crucial.

REM-Sleep Parasomnias

This disease leads to dreams being acted out through body movements and can even result in some patients leaving the bed. The inhibition of muscle tone is lost, resulting in the movement. The diagnosis is made by anamnesis and by differentiating the presence of movements and occurrence of dreaming. A visit to the sleep laboratory is indispensable for a differential diagnosis.

2.2.5.2 Epidemiology

The diseases described here mainly affect children and the problems usually fade with increasing age. Wake up disorders are partially genetically caused, but can also be triggered by stressors and traumas. Medication can also be a root cause. REM sleep parasomnias mainly affect patients with neurodegenerative problems, such as Parkinson's disease, whereas about one third is affected. Overall, the diseases are sporadic and well below 1%.

2.2.5.3 Therapy

For the presented disorders, it is of particular importance to educate the patient, on how to create a safe environment for sleep. Also, it is crucial to provide the patient's social environment with information that helps to react calmly and correctly in sleep-wake situations. For treatment, it is also useful to maintain good sleep hygiene and to carry out relaxation exercises or other therapeutic measures. Systematic desensitization for the treatment of nightmares helps to improve sleep. The goal here is to strengthen the so-called dream-me. By coming up with new ends for nightmares, patients overcome threats in their dreams, and they learn to cope with them.

Conclusion 2.12

For some disorders, it is essential to include the partner or loved ones of the patients into the diagnostic and therapeutic process to perform third-party anamnesis and emergency support.

2.2.6 Sleep-related Locomotory Disorders

Sleep-related locomotory disorders are many times related to insomnia; however, patients do not notice them [96]. They lead to frequently waking up and thereby destroying the restfulness of sleep. In general, the causes of the disorder are usually within neurological problems.

2.2.6.1 Symptoms

Different types of locomotory disorders exist, whereas the main difference is within the part of the body that moves or the type of movement.

Restless Leg Syndrome

With restless leg syndrome (RLS), patients experience a restless feeling in their legs and also a feeling of discomfort. Sometimes this also occurs in the thighs and arms — also, a feeling of pain accompanies the disorder. The diagnosis is performed using questionnaires and sleep diaries to capture the severity. Polysomnography is necessary for the differential diagnosis of RLS and also tracking during the day with actigraphy.

Periodic Movement Disorders of the Limbs in Sleep

Also called periodic leg movement disorder (PLMD) which results in a repetitive, stereotypic movement of the limbs during sleep which can cause insomnia and non-relaxing sleep with increased daytime sleepiness. Additionally, patients are burdened by increased motoric arousals which result in fragmentation of the sleeping pattern.

Nocturnal Muscle Cramps

Leg cramps with unexplained causes occur (idiopathic). Healthy people mainly experience the problem after physical exertion. Estimations suggest that about 10% to 16% suffer from the disease, whereby connections between magnesium and neuromuscular effects are suspected. For diagnosis, sleep labs use PSG. For differential diagnosis, we can observe an awakening combined with muscular tension.

Bruxism

Describes the grinding of teeth during sleep, which can also occur during waking hours and ultimately lead to wear and tear of the teeth. The diagnosis is made utilizing sleep anamnesis and together with a dentist. Besides, polysomnography measures increased activity of the chin muscles.

Rhythmic Movement Disorder

Patients repeatedly experience rhythmic muscle movement of large muscle groups, especially when falling asleep but also during sleep. The diagnosis is made when there are severe clinical consequences.

2.2.6.2 Epidemiology

Due to the neurological connections of the diseases, they often occur when changes to the brain happen, such as for children, neurologically ill persons, and older people. A genetic connection and hormonal disorders have been identified as additional root causes. Depending on the severity of the disease, RLS is assumed to affect about 1% to 15% of the population. Bruxism usually begins in childhood and then decreases with age. Women are affected more frequently overall. Rhythmic movements disorder is common for infants, and occurrences at higher ages are usually heavily related to psychological or neuropsychological disorders.

2.2.6.3 Therapy

For RLS, different options for medication exist to treat the symptoms. Additionally, doctors have to treat comorbid diseases. For patients who are a lot in pain, physicians might also prescribe painkillers. By correcting the jaw position, a misalignment can be removed to get rid of bruxism. In severe cases, medication for muscle relaxation can also be recommended.

Conclusion 2.13

For some sleep disorders such as RLS it is necessary to track the patient during the day by applying actigraphy.

2.2.7 Other Disorders

Generally, not all symptoms are attributable to a particular sleeping disorder, or the occurrence is not significant enough to have clinical relevance. Low prevalence of diseases make it also challenging to define a clear clinical picture.

Long- and short-term sleepers Patients sleep either for a too short or too long time. Patients who sleep more than ten hours are referred to as late risers and less than five hours as short sleepers. Both groups have no severe difficulties if they follow their natural sleep rhythm. However, the disorder can lead to problems if they try to shorten the time or try to adapt to the social norms of sleep duration. Anamnesis and sleep diaries support a diagnosis. Therapy primarily provides psychotherapeutic support.

Speaking and moaning while sleeping Patients talk and moan during sleep. Depending on how excessive the disorder is, it can lead to problems for fellow sleepers. Severe cases of moaning can also lead to effects comparable to apnea. For differential diagnosis, sleep labs use recordings with a microphone. If psychological root causes are suspected, psychotherapy can help to resolve the problem.

Environmental Sleep Disorders The problems for patients arise when they are negatively influenced in their sleep by noise, warmth, coldness, or their bed neighbors. Currently, no studies on the prevalence exist. However, those affected usually know the disruptive factor and find ways to treat themselves. Sleep physicians use anamnesis and sleep protocols for diagnosis, and a detailed consultation is usually sufficient for successful therapy.

2.2.8 Summary

The following Table 2.3 summarizes the techniques for diagnosing and treating the formerly introduced sleep disorders. The next chapter 3 will introduce polysomnography and sleep anamnesis in detail.

Disorder	Diagnosis	Therapy
Insomnia	anamnesis, PSG (mainly sleep stages)	psychotherapy, behavioral therapy, pharmaceuticals
Sleep Related Respiration Disorder	PSG (respiration, respiratory effort, blood oxygen, sleep stages, body position), anamnesis	CPAP, APAP, BIPAP, dental splint, electro simulation, playing digeridoo, sleep hygiene, sleep position training, surgery
Hypersomnia	anamnesis, sleep diaries, PSG (sleep stages), multiple sleep latency test	pharmaceuticals
Circadian Sleep Wake Disturbance	PSG (sleep stages), sleep diaries, anamnesis	sleep hygiene, light therapy, pharmaceuticals, chronotherapy, audio therapy
Parasomnia	PSG (sleep stages)	clarification, save environment, sleep hygiene, relaxation, psychotherapy
Sleep-related Locomotory Disorders	PSG (EMG, sleep stages), anamnesis, third-party anamnesis	pharmaceuticals (painkillers), jaw correction, mouthguard
Others	individual diagnosis by the doctor which can include all of the above	simple consultation sessions to highly complex treatment attempts on individual level

Table 2.3: The table summarizes the different disorders and the diagnostic processes as well as therapy approaches.

Conclusion 2.14

Diagnosing and treating sleep disorders is a complex process. Diagnosing involves anamnesis and objectified measurements using gold-standard polysomnography (PSG). Treatments are complex and based on medication, apparatuses, and even surgery. The design of the sleep tracker will focus on the technical feasibility of integrating questionnaires and sensors into a single device and application.

2.3 Previous Work

This master thesis has the goal to conceptualize a fully-integrated sleep tracking solution. In previous work, we have evaluated a novel respiration system called VOCNEA (volatile organic compounds + apnea) and conducted a systematic comparison of current sleep coaching and tracking products on the market. We would like to briefly discuss both reports as they also provide additional insights relevant to our final design.

2.3.1 Sleep Apnea and Hypopnea Detection Using a Novel Tiny Gas Sensor

State-of-the-art respiration tracking during sleep requires nostrils that are attached in the user's nose. In [80] a novel sensor is introduced that measures volatile organic compounds (VOC) in order to track breathing during sleep. The VOC gases naturally occur in human breathing whereas the concentration in the area around mouth and nose rises during exhalation and drops during inhalation. The solution uses a small *Bosch BME680* [18] environmental sensor to measure the compounds, which makes it possible to integrate the device into a tiny form-factor placed onto the nose of the user. In Figure 2.3, the device prototype is illustrated and also a fully integrated version of the system which fits onto the nose as a kind of small sensor patch. In order to detect interruption or reduction of breathing, a spectral analysis is performed to get the peak frequency of the signal. The algorithm determines whether the frequency is under a set threshold. This process allows for a reliable diagnosis of sleep apnea, where breathing is interrupted for 10 seconds or more during sleep. It can also detect hypopnea. The system uses off-the-shelf components making the approach very cost-efficient and a lot more comfortable than nostrils that go inside the nose.

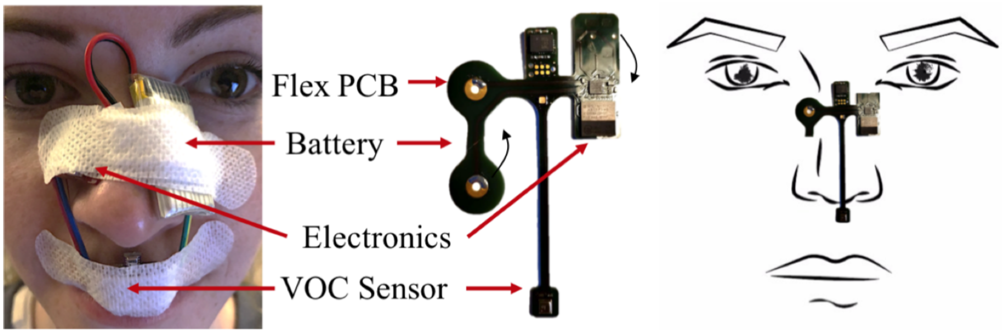


Figure 2.3: The picture on the left shows a simple prototype device that can measure volatile organic compounds under the nose. The pictures in the middle and on the right show a fully-integrated, flexible printed circuit board which is implemented as a patch which wraps around the user's nose.

As the author of this master thesis contributed to the development of the sensor and filed a patent in Germany, we will prefer this sensor for our example system. The formerly mentioned advantages give enough reasons to decide for this sensor setup even without considering the bias towards this idea.

Conclusion 2.15

Use respiration sensing based on volatile organic compounds for a fully integrated sleep tracker because it does not require any nostrils which go inside the nose and is a low-cost solution with a small footprint.

Initially, the paper did not state any attachment mechanisms besides using patches for attaching the sensor within the airways of the patient's breath. We, therefore, decided to investigate different attachment mechanisms that are reusable and do not require any disposable parts. For the evaluation readers should refer to chapter 4.

2.3.2 Comparison of Sleep Coaching And Tracking Products

To understand the broad range of existing products on the sleep wearables technology market in a previous seminar, we investigated the different sensors and implementations of devices. In total, we have analyzed 24 sleep trackers, from medical to low-cost consumer products. The evaluation included the different device implementation types, e.g., as a headband, watch, ring, or to be placed on the user's bed shelf. We also investigated the various sensors, whereas most devices come equipped with an inertial measurement unit and a pulse oximeter. This combination is capable of providing the foundation for tracking sleep parameters such as movement to compute sleep phases and pulse, which changes throughout sleep stages. However, accuracy is minimal. Additionally, these sensors come as standard components and at a low price tag. Different devices have different amounts of outputs which they provide to the user. The most advanced tracker is the *Dreem 2* band which during the time of the seminar provided 12 different outputs that inform about sleep [101].

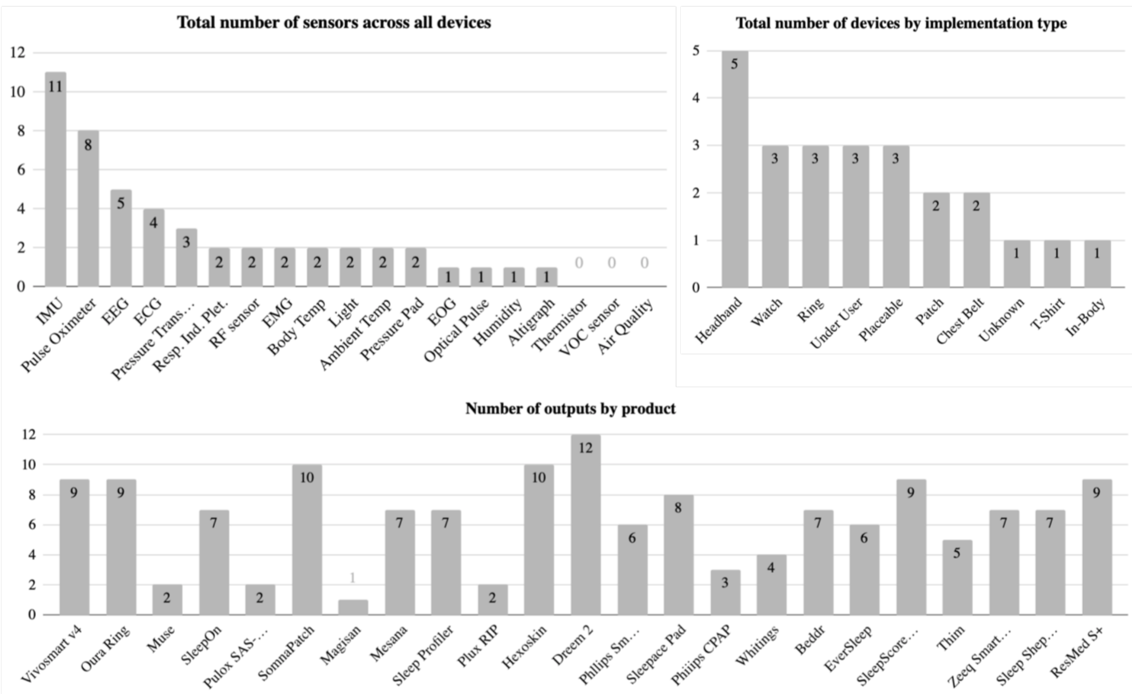


Figure 2.4: The chart in the top left shows the type of sensors and their occurrence across devices. The chart in the top right shows the different implementation styles for wearable sleep trackers. The chart in the bottom shows different devices and their number of outputs about sleep.

The results of the seminar indicated that currently, a fully integrated solution (besides complex state-of-the-art polysomnography) for tracking the entire set of sleep parameters is lacking — especially a sufficient device for tracking respiratory rates. We, therefore, suggested filling this gap by developing and conceptualizing a fully-integrated sleep tracking device that compromises all sleep parameter into one. This device could create the foundation for a broad set of use cases. We could perform root cause mining for behavioral sleep problems by correlating daily behaviors with objectively measured data. Overall we also identified that a significant disadvantage is within the lack of scientific accuracy of existing trackers which creates a substantial mistrust between doctors and consumer devices. Looking at the medical market, we either have sophisticated polysomnography devices or simple devices which only measure one parameter. Therefore, the diagnostic market also creates a great opportunity because it lacks a sufficient solution for a comfortable, low-access barriers diagnostic device, e.g., for at-home usage.

Conclusion 2.16

A commercial opportunity exists for tracking the entire set of parameters similar to the ones tracked in sleeping labs. However, this requires the integration and simplification in a unified device.

3. Measuring and Assessing Sleep Quality

Measuring and assessing sleep quality is usually performed in specialized sleep labs for diagnosing and treating the entire bandwidth of the previously introduced sleep disorders. The following sections will introduce the diagnostic process. This overview includes an introduction to anamnesis, polysomnography, and actigraphy. Without these different tools and techniques, the differential diagnosis would be impossible. Besides that, this chapter includes a section that introduces several alternatives for the measurement approaches used for state-of-the-art polysomnography (PSG) which, e.g., are contactless and therefore more comfortable to use. Finally, we also conducted five interviews with sleep experts to identify possible challenges when developing a fully-integrated sleep tracking device to perform a PESTLE analysis (political, economical, social, technological, legal, environmental). As this thesis also considers a possible commercial utilization of the final result, we also looked at the market situation. We took the information we got from our interviews as input and performed a SWOT (strengths, weaknesses, opportunities, threats) analysis.

3.1 Diagnosis

The diagnosis of sleep problems is a complex process which requires a multitude of insights into the patient's life through anamnesis and objective measurements with medical certified devices [96]. Sleep diseases are often related to many different fields, such as pneumology, cardiology, neurology, and psychology. Therefore, it can be a longsome process to diagnose sleep problems reliably. Also considering the set of different clinical pictures introduced in the previous chapter, therapy requires close cooperation between the doctor and patient. We first cover the fundamentals of established questionnaires, also providing an overview of questionnaires applied by German sleep labs. Then we give a detailed introduction into the process of sleep labs, including measuring a patients sleep using gold-standard polysomnography (PSG).

3.1.1 Anamnesis and Questionnaires

Besides physiological parameters that can be measured by diagnostic devices, questionnaires play a crucial role during the identification of sleep problems. Several standardized questionnaires exist which have proven validity and speed up the process of interviews as they can be filled in while waiting for the doctor or even at home. Additionally, for tracking therapeutic progress, sleep experts also use questionnaires, which require proven sensitivity and specificity. They objectify the anamnesis and cover self-assessment of sleep quality and quantity. The perception of daily life and observations by the bed partner also feed into the diagnostic result. Therefore, they do not only take the personal view during and after sleep into account but also look into things observed by others.

In detail, they measure bedtimes and their regularity and also behavior and emotions before going to bed and after standing up [96]. Additionally, the subjective identification of sleep duration, individual extent or duration of wake-up-phases, personal response during the wake-up-phases, unusual phenomenons such as snoring, interruption of breathing or sleepwalking and sleep-wake-structures is possible. Assessing personal life circumstances such as new diseases which have been diagnosed at the start of sleep problems or duration since the sleep problems have existed can further support a diagnosis. Questions about constant or phased occurrence of the issues, emotional or cognitive tension before and after waking up, sleep expectancy fears or focus on sleep problems and other sleep hygienic factors also take psychological effects into account. The movement of limbs during sleep, and nightmares or start-up from one's rest complete the set of insights covered by sleep questionnaires [96].

Besides these night time factors, daily behavior plays a crucial role in the diagnosis of some disorders such as insomnia. Questionnaires cover the emotional state such as depression, sleep expectancy anxieties, monotony intolerance, sleepiness, and tiredness during the day, and performance such as attention or concentration issues.

The table on the following page shows some of the most critical questionnaires for diagnosing a variety of sleep-related diseases. Most importantly, experts designed and proved the validity, which is mandatory when providing a reliable diagnosis for patients. We differentiate between the type of questionnaire, some general information, the process involved in the inquiry, what they capture, and their application. This overview is intended to help readers with understanding the wide variety of parameters that can be measured even without using any sensor measurements. Some of the questionnaires have very high accuracy and many times agree very well with the results from polysomnography.

Conclusion 3.1

Varying types of questionnaires exist. Some are for standard usage with every patient coming to the sleeping lab; others are for specific diseases such as sleep apnea or restless leg syndrome. By developing a funnel, users could be lead through a set of questionnaires depending on their replies in a previous, more generalized questionnaire.

Questionnaire	General Information and Process	Inputs and Outputs	Application
Sleep Diary [89]	by the DGSM, recommended standardized questionnaire, filled in before bed / after standing up, for two weeks, available for free	subjective sleep quality, sleep hygiene, nightly events, substance usage, sleep-disturbing behaviors	standard
Pittsburgh Sleep Quality Index (PSQI) [21]	developed by University of Pittsburgh, recommended standard questionnaire, self-anamnesis, third-party anamnesis by fellow sleeper, duration of one month	sleep quality, sleep latency, sleep efficiency, sleeping pill usage, daytime sleepiness, frequency of sleep disorders, reliably separates good from bad sleepers	standard
Landecker Inventory for Sleep Disorders [106]	based on ICSD, standardized objectified scoring, high consensus with PSG, takes 5 to 15 minutes	provides a probability score for respiratory disorders, insomnia, narcolepsy, RLS, and circadian sleep-wake disorders; also isolates relation to medication or drugs	standard
Personality traits of sleep-deprived [42]	based on descriptive reasoning, consists of 64 + 23 items on a five point scale	cognitive irregularities, musing tendencies, focus on sleep disorder	insomnia, CBT therapy evaluation
Sleep-related Cognition [81]	high sensitivity for changes, 30 items rated on a four point scale	sleep-related cognitive sleep fear, catastrophisation, serenity, positive self-instruction, sleep drugs	insomnia, therapy evaluation
Insomnia Severity Index [12]	seven items on a five point scale, provides linear rating score, very simple	type and severity of insomnia, effects on social life and daily performance	insomnia
STOP BANG [86]	validated on general population, provides linear rating score for apnea risk	snoring, tiredness, apnea events, blood pressure, body-mass-index, age, neck-circumference, gender	sleep apnea
International RLS Study Group Rating [35]	ten items on a zero to four points scale, international studies fulfil quality criteria	severity of RLS on five different levels	RLS

Table 3.1: The table lists questionnaires intended for diagnosing and for tracking therapeutic progress of a variety of sleep disorders.

3.1.2 Polysomnography (PSG)

State-of-the-art in sleep labs is polysomnography (PSG). It is at the core of understanding the underlying root causes for identifying sleep problems. Studies show that PSG results are the correct diagnosis in around 50% of all cases [96]. The *American Academy of Sleep Medicine* defines the standards for conducting PSG and provides the *International Classification of Sleep Disorders (ICSD)*. Besides establishing how the different sensors are supposed to be attached to the patient, they also define scoring guidelines for the various sleep-related events and disorders. Additionally, the *German Association for Sleep Research and Medicine* defines the necessary equipment required in sleep labs and even the number and types of employees [24].

3.1.2.1 Preparation and Administration of PSG

Before a patient undergoes polysomnography, performing a so-called biological calibration is mandatory. This process helps to distinguish different events that occur during sleep from disturbing artifacts and ensures the correct amplification and polarity of all sensors. Also, this allows an assignment of the physiological responses to calibrated derivation patterns. Calibration includes, for example, opening and closing the eyes, blinking, snoring, forced in- and exhalation, and stretching the legs. During calibration, the patient lies down as usual in bed, and personal then instructs via an intercom system. These steps ensure that the various calibration points are provided with the appropriate marks so that they can be assigned to events later. The preparation process involves additional insights by collecting information about medications, ongoing therapies, and the emotional state of the patient. Supervising personnel documents technical issues and, if possible, fixes them on the spot while the patient is sleeping (e.g., correction of electrodes).

3.1.2.2 Conducting the PSG

The attachment of all the sensors is complicated and requires monitoring throughout the night. Figure 3.1 shows the different attachment points and sensors used in PSG according to the guidelines provided by *AASM* [5].

Electroencephalography (EEG) Three channels are used to measure the various characteristic electrical signals of the brain. Sleep laboratories follow the international 10-20-system using the F4-A1, C4-A1, and O2-A1 channels [49]. Besides that, the guidelines recommend the usage of a backup channel. The frontal channel allows the measurement of K-complexes and delta waves. With the help of the central channel, it is also possible to detect vertex spikes. The occipital channel (back of the head) is used to measure the fall asleep process and wake-up reaction.

Electrooculography (EOG) EOG is used to detect the movement of the eyes as it occurs, for example, during REM sleep. One electrode is respectively placed at one centimeter distance from above and below, and left and right of the eyes. This setup makes it possible to detect both horizontal and vertical eye movements.

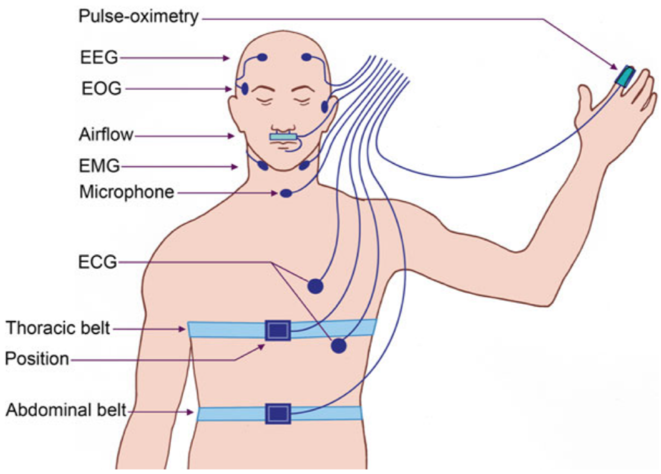


Figure 3.1: The picture above shows the different attachment points of all the different sensors used during polysomnography [71].

Electromyography (EMG) By placing electrodes on the legs, the contraction of the muscles can be detected. Besides that, an additional electrode can be applied to the patient's chin to quantify the movement of the mandible.

Elektrocardiogram (ECG) An ECG with one channel is used to detect cardiac events. The main goal of the measurement is to assign cardiac rhythm changes and to combine this with various abnormal activities such as sleep apnea.

Respiration Respiration is measured oronasally with pressure transducers. This sensor input allows a quantified statement about the breathing activity in terms of volume. Additionally, to derive breathing effort at the thorax and abdomen, it is possible to measure the expansion of the surface around the body. The sensor belt for doing so is called respiratory inductance plethysmography. If oral airflow should be measured thermistors are used.

Position Sensor For measuring positional changes (left, right, supine, prone), a 9-axis inertial measurement unit is used and attached to the patient's chest. For tracking sleepwalking or other movements, sleep labs use videography.

Pulse-oximetry A pulse-oximeter is attached to the patient's finger to measure blood oxygen saturation during sleep. State-of-the-art monitoring devices use photoplethysmography that combines red and infrared light with Fourier movement artifact suppression technology (FAST). By measuring the reflection of blood, it is possible to compute the color of blood and, therefore, the oxygen saturation [43].

Microphone Besides the formerly mentioned parameters, a microphone records snoring sounds and also sleep talking or moaning.

3.1.2.3 Technological Specifications of PSG

The previous sections introduced the different sensors used while performing PSG. However, we are interested in developing a fully-integrated sleep tracking device from scratch that can perform at medical-grade accuracy. Therefore, we looked further into the technical specifications. The Table 3.2 shows the recommended sampling rates and filters applied to the signals measured in sleep labs. Generally speaking, sampling rates are very high, which results in a large amount of data generated over a short period for every patient.

Sensor	**Technology**	**Sampling Rate [Hz]**	**Filter [Hz]**
EEG	electrodes	500	0.3 - 35
EOG	electrodes	500	0.3 - 35
EMG	electrodes	500	10 - 100
EMG (leg)	electrodes	10 - 100	-
ECG	electrodes	500	0.3 - 70
Respiratory flow	pressure transducer, thermistor	100	0.1 - 15
Respiratory effort	induct. plethysmography	100	0.1 - 15
Blood oxygen saturation	pulse-oximeter	25	-
Snoring	microphone	500	-
Body Position	position sensors	1	-
Video	video camera	5	-

Table 3.2: Different sensors with their recommend sampling rates and recommend filter frequencies [58].

Conclusion 3.2

A sleep tracking device will record sensors at a high sampling rate which will result in the creation of vast amounts of data in a short time. To transfer the data over, e.g., Bluetooth, we need to apply compression algorithms.

In general, sleep labs are required to use medically certified devices. Today, the interpretation of the sensor data is not fully automated. Trained personnel manually goes through the pre-labeled sleep data at a window size of thirty seconds. For final confirmation, a somnologist or a doctor checks the validity of the results — the criteria for evaluation bases on the characteristics defined by the *AASM* [5].

3.1.2.4 Parameters Derived from PSG

The number of parameters which sleep labs determine from PSG is enormous. We have summarized overall categories and the sleep parameters which we have identified to be the most relevant for a fully integrated at home sleep tracking solution. The main decision criteria were, if we decided, that specific parameters could be understood in a reasonable time by non-professional users.

Topic	Parameters
Sleep Staging [71, 90]	*Light off / on:* when was the light turned off / on *Sleep onset latency:* time between lights out and first sleep *Sleep period time:* time from sleep onset to final awakening *Time in bed:* time from lights turned off to final wake up *Total sleep time:* the actual amount of sleep time *Wake time after sleep onset:* time during the night spent awake *Sleep efficieny:* ratio of total sleep time to time in bed *REM sleep-onset latency:* time from first sleep to first REM episode *Stage times:* total time spent in every sleep stage
Arousals [90]	*No. arousals:* the total number of arousals *Arousal-index:* total number of arousals × 60 / total sleep time
Respiration [90]	*No. obstructive apneas:* the total number of obstructive apneas *No. central apneas:* the total number of central apneas *No. hypopneas:* the total number of hypopneas *AHI:* apnea hyponea index (all previous × 60 / total sleep time) *Blood oxygen desaturation:* times when more than 3% *No. respiratory effort related arousals:* number of those events *Other events:* cheyne strokes respiration or hyperventilation
Cardiac Cycle [90]	*Average heart rate:* observed during sleep *Highest heart rate:* observed during sleep
Movement [90]	*Periodic limb movements:* number of occurences during sleep *PLM index:* periodic limb movements × 60 / total sleep time

Table 3.3: For the different categories we have listed the most important parameters that are relevant for understanding the user's sleep.

Besides the more high-level features in Table 3.3 there are many more parameters defined in [84]. This set includes abnormalities in EEG, ECG, and behavior as well as findings relating to sleep disorders. Most interestingly, even though many apps show patients a hypnogram of their sleep, deriving a hypnogram is only considered optional by the *AASM* [5]. One of the largest factors which we left out of this table is several arrhythmias related to the cardiac cycle. These parameters are very complex and specific to in-depth medical knowledge. We think providing this information to patients should be left for medical experts and requires an ECG signal which is why we do not list them here.

3.1.3 Actigraphy

Actigraphy is a method to determine how a person moves throughout the day objectively. An actigraph is attached to the wrist or leg. The activity patterns then allow concluding the sleep-wake rhythm as well as the leg movement during sleep periods. The sensor data also makes it possible to diagnose RLS. Problems with actigraphy arise when the device is taken off as it cannot distinguish between the person resting. Movement induced from the outside, e.g., while driving on a bumpy road, can also cause problems.

Figure 3.2: Philips Actiwatch 2 [72].

3.2 Alternatives to State-of-the-art PSG

The previous paragraphs introduced the state-of-the-art methodologies used for tracking the various parameters relevant for a patient's sleep. However, alternative ways for tracking sleep has received much attention within the research community. To help readers get an understanding of recently proposed approaches, we summarize them in Table 3.4. We do not provide details on the accuracy and readers should refer to the cited publications to learn more about how the different systems work in detail. The purpose of the table is to present the various alternatives. They can be used for tracking some of the previously introduced parameters to inspire their usage within an integrated sleep tracking device. To create this list of related work items, we skimmed through the first forty publications in the *ACM* digital library [1] based on the parameter listed in the left column in Table 3.4. Additionally, we collected papers that we discovered along the way while working on this thesis and by attending the conference *Ubicomp'19* in London [2]. We did not find related work on respiratory effort or periodic limb movement besides the formerly described gold-standard approaches.

Parameter	Methodology
Sleep Staging	*Infrared sensor:* above eye to detect changes in eye movement [56] *In-Ear Earplug:* with electrodes embedded into the ear cannel [64] *Ballsitocardiography:* pressure sensor sheet with neural network [75]
Respiration	*Vision:* by measuring morphing effect of pattern projection [7] *Depth:* by detecting spatial displacement of the chest [55, 65] *Thermal imaging:* of medium which user breathes onto [83] *Pressure:* mat which detects changes in pressure [54, 105, 47] *Microphone:* by detecting sound artifacts [44] *Acceleration data:* measured on chest, wrist or head [97, 87, 38, 36] *RF / Radar:* by measuring changes of reflection [39, 115, 65, 76] *Volatile organic compound:* changes in gas concentration [80]
Heart Rate	*Radar:* by measuring changes in reflection [76] *Camera:* by detecting changes in face color or motion [53, 11] *Seismocardiography:* measure eruptions created by pulse wave [36] *Piezoelectric:* measure expansion created by pulse wave [30]
Blood Oxygen	*Photoplethysmography:* performed on toe, ear lobe or forehead [43]
Sleep Position	*Depth:* to classify the shape of the depth map above the bed [34] *Accelerometer:* by using a smartwatch on the wrist [97]

Table 3.4: Alterantive methodologies and modalities to measure sleep parameters.

Conclusion 3.3

Many of the alternatives to state-of-the-art PSG either try to use a subset of the parameters to estimate another or move away from the user by leveraging e.g., vision, RF-signal or depth information.

3.3 Restrictions and Constraints

The previous sections have introduced information about tracking and assessing sleep quality. This chapter is supposed to illustrate, which factors influence a solution that goes out on the market. Different political and legal restrictions exist when trying to ship a wearable with a medical purpose. This chapter seeks to give an idea of which factors we should consider and how this might change the development process or even the final solution.

3.3.1 PESTLE Analysis

To perform a so-called PESTLE analysis (political, economical, social, technological, legal, and environmental), we conducted unstructured and semi-structured interviews with five experts. Specifically, this included a leader of a sleep lab who is also a board member at the *DGSM* [24] and another leader of a German sleep lab. We talked to a researcher who conducted research in the field of Narcolepsy and is also a *DGSM* member. A fourth interview was with a researcher who has undertaken sleep-related research, including behavioral root cause mining for patients who sleep bad and novel bio-sensing technologies. Finally, we talked to a professor for medical technologies who supported the development of a multitude of innovative sensing technologies. We have summarized the results of these interviews in Table 3.5 and added information which we could find online to support these arguments. We focused on the German market.

Political	**Economical**	**Social**
increasing support by German government for digital health and tech supported treatment	sleeptech market predicted at \$1.4 billion in 2017 with CAGR of 7.6% (consumer market) [45]	overreaction of patients who track themselves with imprecise devices annoys sleep labs
support by politics e.g. through research funds	established players with large market shares	shift from a reactive to proactive health
lobbyists influence politics to protect from radical new medtech products	sleep labs do not have a lot of money; device update cycles of 5 to 7 years	increasing sleep problems due to modern lifestyles (e.g., obesity, stress) [85]
sleep guideline by *AASM*, *DGSM* and *ICSD-3*	lack of a holistic at-home sleep tracking solution	US and Chinese market faster for new hardware
Technological	**Legal**	**Environmental**
development of new, reliable sensors modalities	medical certification requirements (e.g., *FDA*)	shortness and exploitation of noble metals
stable, tested hardware requires much time, otherwise high liability risk	privacy concerns about medical records; required to store data in Germany	concerns about pollution of small scale disposable plastic parts
high sampling rates challenging, synchronizing devices is hard (clock)	hardware certification (e.g., *FCC*, *CE*, *TÜV*, *Bluetooth SIG*)	sustainable materials and production increasingly important
correct attachment critical to measure reliably	intended use defines the medical requirements	"Made in Germany" as an attribute of quality

Table 3.5: The table shows various factors which we identified with our interviews.

Conclusion 3.4

The medical and hardware market are both complex and challenging fields which require stamina and patience.

3.3.2 SWOT Analysis

The PESTLE analysis in the previous section illustrates varying factors and has the goal to analyze the external environment of the development process of a fully integrated sleep tracker. We now also performed a SWOT analysis (strengths, weaknesses, opportunities, and threats). The purpose of a SWOT analysis is to understand the state of a project. As this thesis should also consider the possibility to create a business opportunity based on our findings, we aggregated the insights we gained from the interviews described in the previous subsection. The factors listed in the Table 3.6 are comments which we got during the interviews and aspects that we self-assessed based on our reflections.

Strengths (Internal)	**Weaknesses** (Internal)
- pending patent from previous work - only solution uniting all parameters - aiming for reliability and accuracy - in touch with strong sleep 'players' - good sense for look and feel - broad technical skillset - research driven approach	- no internal medical know how - dependency on hardware suppliers - lack of professional design resources - depend on few employees to execute - high technical / medical complexity - risk of being uncomfortable - underfunding for timely progress
Opportunities (External)	**Threats** (External)
- lack of a fully-integrated sleep tracker - sleep labs interested in alternatives - use of resources (e.g., questionnaires) - no market leader established yet - consumer waking up on sleeptech [32]	- medical product process is complex - 20+ competitors in the same field - investments happen outside Germany - high and complex regulations - forced feature removal due to law - danger of loopholes in patent - lack of trust into a medical startups

Table 3.6: Analysis of internal strengths and weaknesses as well as external opportunities and threats based on our interviews and self-asessment.

Conclusion 3.5

Internal strengths include technological depth combined with external opportunities created by the lack of a fully-integrated sleep tracking solution. We identified external threats as the sophisticated and aggressive medical market and the internal weaknesses, which include the lack of in-depth medical know-how.

4. Design Considerations

In the previous chapters, we have given a detailed introduction to various sleep disorders and looked at the measurement of sleep parameters from a technical point of view. As the next step, it is necessary to understand what kind of users will use our system. Therefore, we summarized information from statistics collected online and conducted qualitative interviews with different user groups. The insights we gained allowed us to create several personas, and we present one of them as an example. In the next step, we propose a concrete set of functionalities for a sleep tracker. We check open design aspects directly with the user and draw further conclusions based on related work.

4.1 Users

An essential part while designing a new system is to get an understanding of the end-user. For this, it is necessary to gain insight into how the user will possibly behave by leveraging different methods. Therefore, we gathered information online to understand better which people are using sleep tech today and how people generally deal with their sleep. We aggregate the results of our investigations in the following sections. In a second step, we also conducted interviews with seven people. This process leads us to develop empathy to ultimately conceptualize so-called personas that are exemplary for specific user groups.

4.1.1 Online Research

The results of this sub-section have been collected from various reports and resources online. We have fused them into a single text and added references to every source of information accordingly. In the following, we introduce the two sources which contained a lot of information we used and we also present the methodology and the respective goals of the studies. We do not explain the smaller statistics' methodologies, and readers should refer to the cited reference to learn more about methodology and sample sizes.

4.1.1.1 Methodology and Sources of Information

We were interested in several aspects surrounding sleep technology. We searched the internet for information on the usage of sleep technology and the typical user profile for sleep tech users. We also checked how users are dealing with their sleep problems and which share of the population is struggling with sleep problems in the first place. Additionally, we were also interested in the willingness to share medical data to improve the personal healthcare situation. We also looked into the purchase decision making process of sleep tech and the product attributes, which push sleep tech users to decide for a product.

In [9] 1,029 U.S. adults participated in an online survey in 2015. The authors weighed the results to known demographics of the population, such as gender and age, and it, therefore, can be generalized across the entire U.S. population. The goal of the study was to develop a demographic and sleep pattern profile of consumers, measure awareness, and purchase intent and to develop a profile of sleep technology owners. Additionally, the authors aimed to understand the current perception of sleep technology products.

The German insurance company *Techniker Krankenkasse* has collected the data presented in [82]. To learn more about sleep behavior in Germany, they conducted a study together with their customers. The study participants were a representative cross-section of the population. The leading German opinion research institute *forsa* [31] executed the study and, therefore, we should presume that this claim is valid.

4.1.1.2 Summary

According to [9], 22% of all U.S. adults use sleep technology. 57% of all sleep tech users are male, and around 50% of all sleep tech users are between 25 and 44 years old. 40% of all sleep tech users have a college degree or higher, and 50% are married or living with a partner and in a household of three or more. 69% of all sleep tech users consider themselves as early adopters for new technology. 55% of all sleep tech users have a yearly income of $50,000 and higher. 82% of all sleep tech user exercise more than once a week. Looking at the results of a survey in 2015 [99], the average tech spending per year was around $9,000 in the age group between 25 and 44 years.

In general, sleep quality and prevalence of sleep disorders are reported more by women, whereas 26% reported to sleep poorly, and only around 20% of men reported this [82]. Additionally, only approximately 50% of the population report to get enough sleep [9]. Overall, sleep tech users tend to sleep better than none sleep tech users [9]. When it comes to tackling sleep problems, 25% of the population in Germany use sleep drugs daily [82]. More than 50% ventilate their room and aim for keeping regular sleep timing. Other solutions for sleep problems include reading, going for a walk, doing sports, and performing sleep rituals such as drinking tea, or a glass of wine. When asked about reasons for sleep problems, 40% reported having issues with the room climate followed by around 30% who say stress with family and employment is the root cause for inadequate sleep. 25% report the source of bad sleep to be in medication or due to other medical conditions. In [9] 7% of all study participants reported being users of smart home technologies to support a better sleep environment. Around 5% reported using sleep-related capabilities of smartwatches such as *FitBit* [28] or apps on the smartphone. Only 3% said that they use sleep technology devices such as *Beddit* [13].

Conclusion 4.1

Many sleep problems are related to psychological root causes. Different strategies exist to cope with issues associated with falling or staying asleep.

As our solution would be recording medical data of patients, we looked into the willingness of users to share it. In a representative study [92], 2,092 participants from Switzerland were asked whether they would make their medical records more transparent if it would help to improve their access to better healthcare. There are no significant differences across all ages, and around 60% tend to be willing to share their medical data. Only approximately 10% are firmly rejecting to share their data for improving their health.

When it comes to making a purchase decision for sleep tech 35% of all users look at online reviews followed by recommendations of healthcare professionals (27%) and recommendations by friends or family (26%) [9]. In terms of trustworthiness to inform oneself for the purchase decision, the healthcare professional is considered to be the most trustworthy source of information. The preferred place for purchasing, however, is in a store (23%) or online (22%). Of all users who are currently not using sleep tech, approximately 60% report to be at least somewhat interested in using it.

Conclusion 4.2

Users are willing to share their data if it helps to improve their health. Online stores and health care professionals are critical when buying sleep technologies.

Finally, we would like to highlight the attributes which are most relevant for users of a sleep tracking solution. The top three factors are comfort (74 %), reliability (74 %), and price (73 %) [9]. They are followed by usability (68 %), durability (68 %), and location of the device when sleeping (59 %). Interestingly, only around 50% of all users reported caring about the accuracy of the device or the capability to derive actionable results for sleep improvement.

Conclusion 4.3

Comfort, reliability, usability, and location of the device are among the key attributes for users which emphasizes the importance of thorough and thoughtful wearable design.

4.1.2 Interviews

In total, we conducted seven semi-structured interviews with participants of different backgrounds. Questions included sleep habits, consciousness about sleep, and health in general. Moreover, we were interested in learning more about how and if users track their sleep. We were also excited about learning what users would be interested in their sleep and wanted to investigate what they think affects their sleep. Finally, we also asked them about things they try to do to improve their sleep. A single person took bullet points and conducted the interviews at the same time. To broaden the scope of the interview results, we also asked participants about sleep-related topics which they observe for friends and family (e.g., sleep habits) which helped us to gain additional insights for our personas. We did three interviews over the phone and four interviews in person. Two interviews were with students aged 24 (f) and 26 (m). The other interviews were with two female and three male users, around 50 years old (mean age: 52.4 years).

4.1.2.1 Summary

The study participants all reported stress to be an influential factor for lousy sleep. One interviewee expressed that his mother has a calm lifestyle; however, because of a lack of proper sleep, she feels stressed and therefore she sleeps even worse, which result in a vicious cycle of stress-induced sleep quality loss. Additionally, participants reported hot weather being a root cause for struggling with sleep and also mentioned problems related to psychological factors. Poor sleep does not cause much trouble for two participants in the early morning; however, it hits after a couple of hours which is usually counteracted using coffee. One participant also stated that with increasing age, different things tend to require more energy than in the past which also influences tiredness. Two participants reported sleeping worse during pollen fly times which triggers allergic reactions. However, the medication makes tired, which somehow solves the problem. One participant expressed that resting for too long creates increased discomfort and irregular sleeping habits hurt to sleep well, whereas this causes him to be frustrated. Moreover, he reported light sleep which causes him to wake up. Ultimately this results in lower capabilities to perform while studying. One of the participants said to not sleep at all for one time every month.

Users who mentioned poor sleep reported a feeling of pain in the morning similar to partying a little too much and the urge to challenge the alarm clock by snoozing till they have to get up or otherwise they will be too late.

Conclusion 4.4

Sleep-influencing factors are highly individual, however, most users know what causes their sleep problems.

Then, we talked about aspects that users would like to learn about their sleep. They reported interest to know more about wake-up times and their circadian rhythm in general. Additionally, all users, except for one, would like to understand what influences their sleep and are interested in finding root causes for their differences in sleep quality. However, the majority reported they already know the origins of low sleep quality. They either can not change them due to external reasons or because they are accepting a lack of sleep, e.g., in favor of a career. Three users reported that they have no idea what can and should be tracked during sleep and they would need support in understanding relevant parameters. One user mentioned that he would be interested in learning how much he sweats during sleep. Also quantifying snoring behavior was mentioned by four participants. One participant mentioned the air quality as an essential aspect for good sleep. Two participants expressed that they would like a device which confirms what they already suspect to be causing their sleep problems. Additionally, one participant mentioned that it would be nice if the sleep tracker would provide functionality beyond sleep, e.g., also tracking data during the day.

Conclusion 4.5

In general, most of the users we talked to know little about the parameters which a device could track during sleep.

When we asked users how they counteract sleep problems, three mentioned that applying techniques from the autogenous training helps them to calm down and relax their thoughts. The methods include, e.g., smiling to get rid of negative ideas or meditation. Additionally, to avoid being tired during the day, they reported going for a walk or sitting in the sun to energize. One participant particularly mentioned that he is very strongly against the usage of sleep drugs to improve sleep quality. Another participant suggested that a little bit of alcohol can help with sleeping better when stressed; however, too much disturbs sleep. One user mentioned that he could not sleep without earplugs because he is susceptible to any noise since he started using them during an exchange year where his roommate was snoring badly. Another participant reported blockage of the nose, which she tries to treat by blowing it. Applying nasal spray was not an option because it can lead to addiction.

One study participant mentioned that he could observe peaks in the heart rate signal of his current wearable, which made him wonder. Going to a sleeping lab revealed that he was struggling with sleep apnea. Another participant mentioned she is wearing an Apple Watch during the day; however does not wear it during the night. What she reported is that she especially likes that the watch objectifies her daily routines and health behavior. If she forgets to take off the smartwatch, she mentioned disturbance by notifications which wake her up when she has already fallen asleep. Another participant said that his sleep quality is not bad enough that he is interested in tracking it. One participant mentioned that such a device should receive updates so that it feels like it is continuously improving.

Conclusion 4.6

In general, users find it interesting to learn more about their health status; however, for some a certain level of discomfort is required to create interest in the topic.

During the interviews, someone expressed that the device should be different when using it as a personal consumer device compared to a professional medical tool. For consumers, the device should be more oriented to measuring all the time and optimizing sleep. For a medical context, the interviewee recommended to take longer time and focus on accuracy rather than a perfect user experience when using the device. Additionally, the participant reported concerns about not being able to sleep when wearing a tracking device, especially for multiple nights. One participant expressed that he feels that wearables for tracking sleep would be outside of his budget range, and he is unsure about the usefulness of such devices. He also expressed potential trust issues in a non-medical sleep tracker, especially if an unknown company has developed it. Participants liked the option to analyze themselves at home instead of having to go to a sleeping lab.

To learn more about healthy habits, we asked the participants how they react when they have an issue. Even though some of our interview partners mentioned to have sleep problems, they did not visit a sleep lab before except for one. However, some expressed that they have thought about it. One of the study participants mentioned that it took her husband several years until he saw a doctor who finally diagnosed him with sleep apnea.

We also took a look at data privacy. The users we talked to expressed not to be concerned much about sharing their data as long as it is not shared with the employee or given to someone without their consent. One subject revealed that her attitude might be different if she would know that she has a sleep disorder. A participant with a data science background stressed that he would be very interested in getting access to the data himself to experiment with it on his own. One participant also mentioned that she would be excited to share the data with her doctor or family. Willingness to track anything manually about daily behavior seems to be related to the quality of sleep as participants appeared to have a higher acceptance to, e.g., manually enter their daily routine if they report being bad sleepers. Entering information about daily behavior by voice seemed to be preferred by users; however, participants did doubt that such a system would work reliably. Another option would be to use shortcuts.

Conclusion 4.7

Users are willing to share their personal health data as long as they keep the control of where this data ends up.

In terms of device implementation, the device should not smell, and also the battery should not explode on the forehead due to bad quality. Additionally, the device should be as flat as possible. It should not put any constant force on parts of the body and preferably be flat on the skin. Having something in the face during sleep was criticized by three participants, and the female participants reported that they would be concerned about any marks left by the wearable. Preferably, the device would turn of any WiFi or Bluetooth connections during the night. Also, a mask was said to be a no go. Participants expressed concerns when wearing a device for multiple nights which could cause the device to smell due to sweating. During sleep, the device should not expose any light which could disturb sleep or make any noises which wake the user up. One participant mentioned they would rather spend more money on a nice-looking device than having something which is not visually appealing. Two participants mentioned that they would be annoyed by the device if it requires charging every day. One participant suggested that for a sleep tracking device, it would be fine to place it on the nightstand for charging every morning because one will not use it at that time.

Three participants mentioned the besides using the device for themselves they would also like to hand the device to their partner and friends. One participant who visited a sleeping lab reported that he thinks that there is a high necessity for something which can be comfortably used at home because then he would have checked his sleep earlier. Furthermore, he believes that this might help to convince some of his friends who are not willing to go to a sleeping lab even though he recommended them to do so. Two also suggested that instead of buying any equipment, they could imagine renting a device. Five participants mentioned that they would expect or hope for the insurance to support the purchase of such a device.

Conclusion 4.8

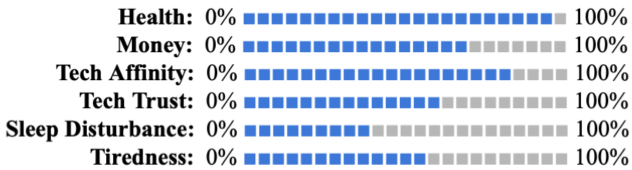
Ensuring safety and turning off radio signals could create an additional trust for the users. We must reduce discomfort to the absolute minimum.

To conclude the results from our interviews, we would like to stress that our insights align with those from online statistics that we looked at in the previous section. The next step will be to aggregate all the collected information as personas.

4.1.3 Personas

Based on the information we found online and the data we previously collected with our interviews, we went on to define a total of five personas. According to [22] this technique is well suited to successfully accommodate the different users because they help to design for specific needs instead of for a generic set of all possible functionalities. The needs of the representatives might interfere with each other, and therefore, we have to prioritize users and design the system for them accordingly.

Arno Achtsam



Age: 42
Location: Berlin

Job Title: CEO @ Design Agency

Manages strategy, meets with customers, travels regularly.

Interested in abstract ideas. Likes good design. Enjoys inspiring conversations. Biking as hobby, wishes to do it more often.

1 child, married

Personality
- loves good design, is an early adopter of technology
- healthy lifestyle (regular sports) however light/too short sleep (stress)
- full schedule and always ready to perform (sometimes workaholic)
- has used his smartwatch to track his sleep, excited to optimize his sleep
- tried some things to improve his sleep, had minor success
- would use the device to track everything, enters a lot of data

Objectives
- wants to understand his body and improve his health/sleep efficiency
- wants to perform better (willing to adapt sleep for it)

Needs
- optimize health and be mindful
- maximize time efficiency and stay in control

Motivations
- being on the bleeding edge of tech
- improving his health without investing a lot of time
- be the best version of himself, always sleep perfect
- worry less

"Success is the result of hard work and a little bit of luck."

Figure 4.1: The table above shows 'Arno' who is a representative of a typical sleep tech user. He was developed based on the information from online statistics and the insights we gained from talking to users.

The Figure 4.1 shows one of these personas. Additionally, we have included the other personas in the appendix of the thesis. The different needs of the various personas boil down to individual requirements created for our sleep tracking system.

Arno is a typical representative for someone who would use a sleep tracking device. He is a successful middle-aged man with interest in technology and sees himself as an early adopter. Arno is married and has one child. It is important to him that a sleep tracker looks good, and he sees it as a way to further analyze and improve his healthy lifestyle. Due to his job, Arno sometimes has much pressure to work, which leads to a loss of sleep quality. However, he accepts the lack of sleep because he wants to follow his career. In the past, Arno already used the sleep tracking functionality of his smartwatch and also used a sleep app. Therefore, he has some knowledge about sleep. However, Arno is not satisfied with the results as he feels that the device he owns does not measure accurately. Recently he started snoring more and heard from others about sleep apnea. Therefore, Arno is a little bit worried about his health and looks for ways to stay in control. Going to a sleeping lab is currently not an option because it does not fit his tight schedule; however, he is willing to invest in his health on his own.

Conclusion 4.9

The primary target user has basic knowledge about sleep and has a good understanding of technology.

4.1.3.1 User Journey

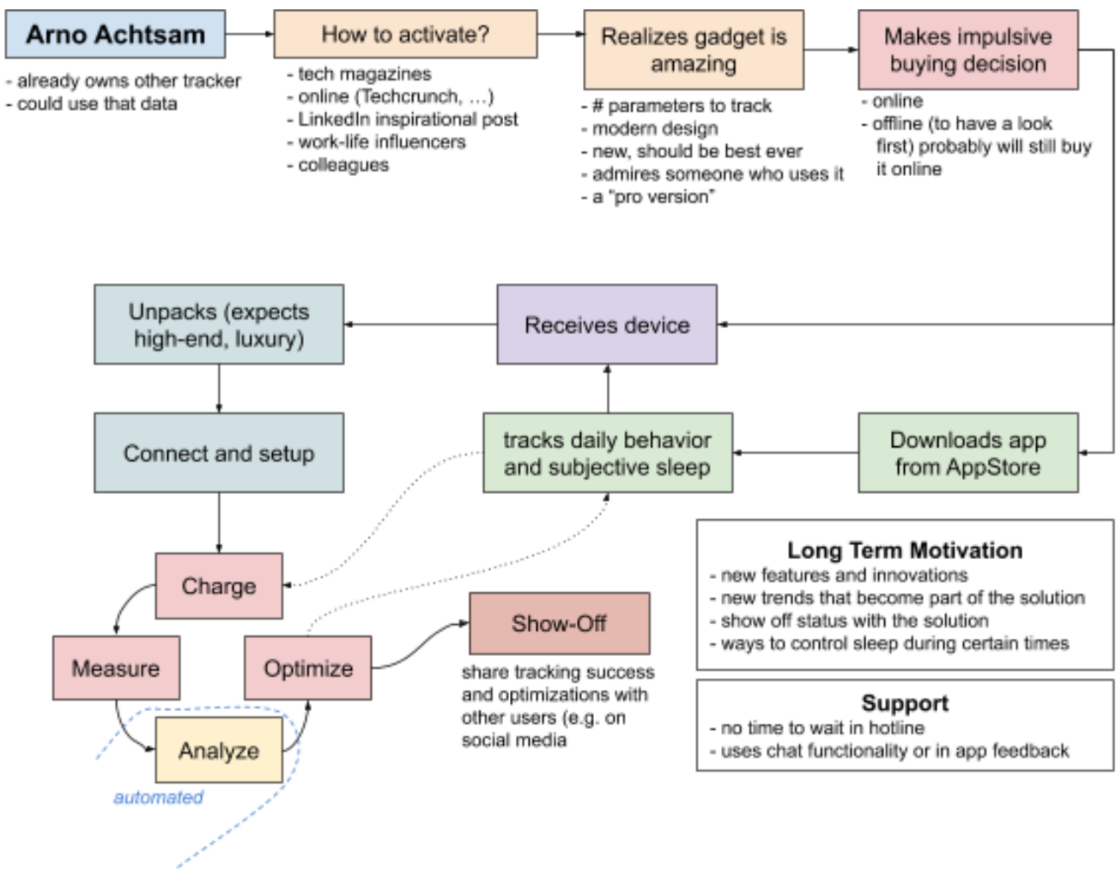


Figure 4.2: The graph above shows the user journey of the previously introduced persona 'Arno Achtsam'.

As we were also thinking about how and when a user would be interested into learning more about our device, e.g., before buying it or in which scenarios he or she might use it and what drives them, we created a user journey. This journey help to understand how a user would be navigating throughout the experience of a fully integrated sleep tracker and create additional requirements. We also considered where the persona would buy such a device and under which circumstances.

The graph in Figure 4.2 shows the user journey of the formerly introduced persona. It includes information where to activate the user for a purchasing decision, which factors come into play for making that decision and how they interact with the device after receiving it. Arno would see the sleep tracker either online or in a tech magazine. As he gets very excited about new technologies quickly he is likely to make an impulsive buying decision however good design is important to spark his interest or also a pro version, e.g., that can track a large amount of his health parameters. He is the kind of guy who is willing to constantly measure his sleep for a longer period of time to understand what influences his sleep.

Conclusion 4.10

Users who would be most excited about our solution are interested in getting as many insights into their sleep parameters as possible and are willing to invest time into measuring their sleep.

4.2 Evaluations Towards Final Solution

In the previous sections, we have presented several aspects that have an impact on our final solution. They have helped us to understand what it takes to design a device that can meet usability and functionality requirements. We summarize the necessary functionalities once again. Based on the sensors used for measuring all parameters during sleep, our solution must be attached to the user's head. As there are different ways of designing our device, we have tested the different options together with our users. We were particularly interested in the visual perception of our solution. Furthermore, we had to find out how to attach a respiration sensor to the nose, similar to the one presented in chapter 2.

4.2.1 Functionalities

For this first iteration of a fully-integrated sleep tracking device, we aim to focus on the most critical parameters that we can measure during sleep. All disorders require the possibility to track the sleep phases using EEG and EOG. Additionally, we have to monitor pulse and blood oxygen levels as well as respiration. Besides that, recording the sleep position can generate additional insights on obstructive sleep apnea and comes in handy to detect disorders related to movement such as RLS. Ideally, all these sensors can integrate into a device that wraps around the user's head as all the formerly mentioned parameters can be measured there. For therapy, we think about providing insights into the influences of behavior and sleep by correlating the two aspects. In favor of comfort and having a fully integrated solution, we do not take attaching electrodes to the chin or legs into account because it would make it hard to incorporate these aspects into a single wearable device. Some of these functionalities might be augmented based on other sensors; however, this requires a lot of data and more research outside the scope of this thesis. Finally, we do not look into how to integrate a thoracic or abdominal belt for respiratory effort because this would break the single solution approach.

Additionally, we believe that the device which we design will be accompanied by an app that provides valuable feedback about the tracked data and standardized questionnaires to improve the analysis results of the app further. Information displayed in that app will match established parameters that we introduced earlier.

4.2.2 Wearability

In this sub-section, we evaluate different design options for our wearable device. This consideration includes best practices from related work, the overall head-strap implementation and a mechanism which straps the respiration sensor on the user.

4.2.2.1 Best Practices from Literature

Before going into two studies which we conducted to understand which design users would likely prefer for a wearable sleep tracker we looked into related research to understand how we should design a device that attaches onto the user's head.

According to Zeagler [116], a device which straps around the user's head should not be thicker than around 2.5 centimeters to make the user feel like it is a natural part of the body. In terms of weight, the area around the face is susceptible, and the maximum which we can accept for our wearable should be below 230 grams. The motion impedance describes the obtrusion created by a wearable attached in a specific position that is disturbed by motion. The head location avoids any obtrusion by the wearable, making it a comfortable spot to wear independent from movement. Additionally, the forehead, in general, is an excellent position for detecting motion of the limbs, suggesting that with the appropriate algorithms, we might be able to identify RLS. Not directly related to wearability is that the user's head is the perfect position for reception, e.g., over Bluetooth as it avoids interference with the body mass.

4.2.2.2 Overall Implementation

Figure 4.3: The design options include a strap with plastic front, a strap made from fabric [109], a cap [91] and an eye mask [113].

A headband is the most suitable solution to measure a broad set of sleep parameters. Before executing a particular attachment mechanism, we opened the design space to collected different approaches on how we could implement such a system. We ran a workshop with three participants, where we brainstormed different solutions. We distilled four final designs from 12 ideas. In Figure 4.3 we showcase a device made from plastic for a distinct shape, one made from fabric entirely, a cap which users wear over the head and an eye mask.

Participants and Design

The primary purpose of our study was to understand which design option is most appealing to our users from a visual perspective. We, therefore, asked them to rank the options. Besides picking from these options, we also collect information about the user's sleep quality (1 to 6, German school grade). Additionally, we asked them if they would like to improve their sleep and be willing to use their favored design rated on a five-point Likert scale. We also conducted general demographic information (age and gender) and gave the option to leave any comments which they might have. We did a sample of convenience at the local canteen close to our research lab. We recruited participants at the waiting line by approaching them directly and asking if they have time. They were handed a clipboard with a paper questionnaire. The canteen is at the heart of a technology hub where people who go there are predominantly working in the tech industry. We want to note that this might have an effect on our results compared to a broader, more diverse population.

Results

In total, we recruited 73 participants (20 female, 50 male) with a mean age of 35 years. We show our results in Figure 4.4 which indicate that the users prefer a headband which straps around the head made from fabric. Either a cap or eyemask follows it. The least favorable solution is the strap with a plastic case on the front. Based on the comments we got in the free-text form, a cap seems to be too warm, and the plastic device looks uncomfortable. The eye mask would be too obtrusive. Out of all participants, around 40% would be interested in improving their sleep. 50% of all subjects would be willing to wear their favored implementation for several nights if it helps to improve sleep.

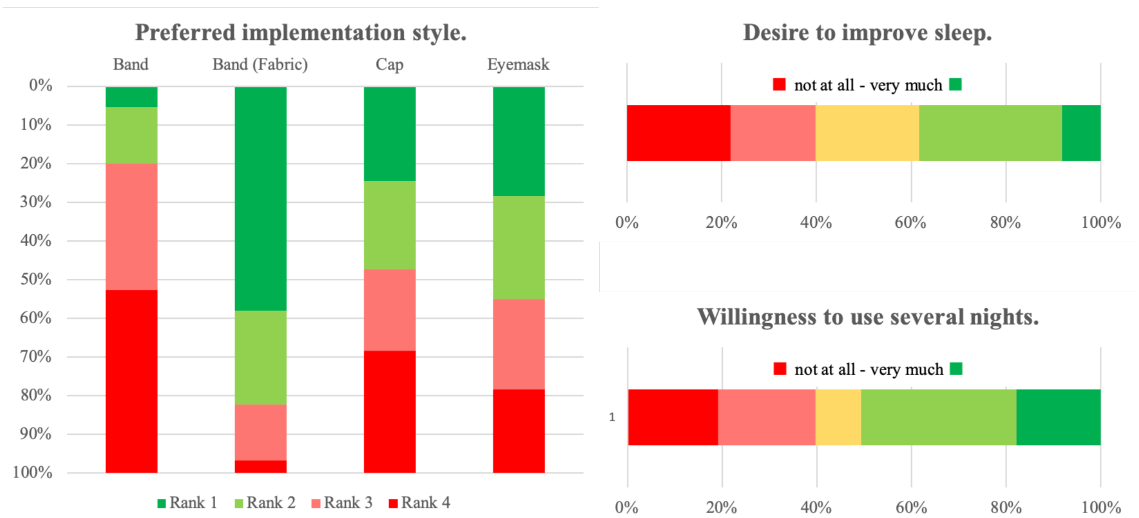


Figure 4.4: Left shows the distribution of rankings. Right the attitude of users.

Figure 4.5: The graphs above compare different properties of the users to their willingness to use their favourite kind of design for multiple nights.

In Figure 4.5 we also illustrate the willingness to use such a sleep tracking device compared to different properties of the users (sleep quality, age, gender, desire to improve sleep). According to our findings, the quality of sleep is not a reliable indicator of the willingness to use a head-worn sleep tracking device. Much stronger, the desire to improve sleep and therefore, the urge to change something about inadequate sleep seems to indicate acceptance for a sleep tracking device. Depending on age and gender, we can not report any significant differences for willingness to use a sleep tracking solution. Overall, ten participants graded their sleep at one, 33 at two, 14 at three, and nine at four. Additionally, seven rated their sleep at five, and none of the participants rated their sleep at six. Therefore, the average sleep quality was 2.6 for our study participants.

4.2.2.3 Nose Piece

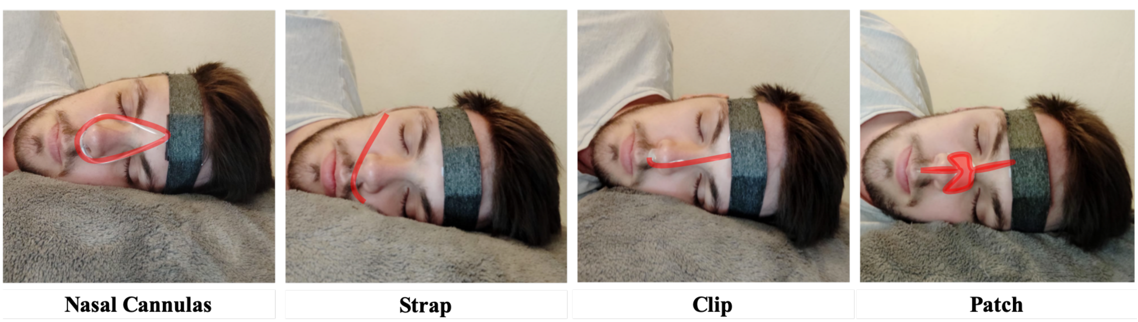


Figure 4.6: Different attachment options for a respiration sensor colorized in red.

Now that we decided on a shape of the head strap, we were also interested in evaluating a nose piece for the respiration sensor. Ideally, it attaches in the area between mouth and nose. We did a small workshop where four people sat together and brainstormed ideas for about one hour. We collected eight ideas and had ourselves inspired by various medical attachments. We finally decided on the four options shown in Figure 4.6. The first option is nasal cannulas that go inside the nose and redirect airflow to the head. Our second design is a strap which wraps under the nose and behind the ears. With our third version, we propose a clip which attaches on the septum. Finally, our last option is a cable stuck with a patch onto the nose.

Participants and Design

We conducted an online survey where we asked the participants to rank the four different design options according to their preferences. Similar to the previous questionnaire, we also asked them if they could imagine wearing the strap for multiple nights and if they would like to change something about their current sleep situation rated on a five-point Likert scale. Additionally, we asked them if they would like to know how many apnea events they have every night and also what their sleep quality is (1 to 6, German school grade). Finally, we also collected demographic information (age and gender) and additional comments which they might have.

Results

In total, we recruited 38 participants. The mean age was 31 years, and of all subjects, ten were female and 28 male. In Figure 4.7 we present the results of our online survey. According to our findings, participants prefer the strap and clip option. Of course, this test does not give insights in what users would prefer when sleeping with the device for a night or more. Therefore, we also explored the two most preferred design options strap and clip in the evaluation chapter 6 of this thesis.

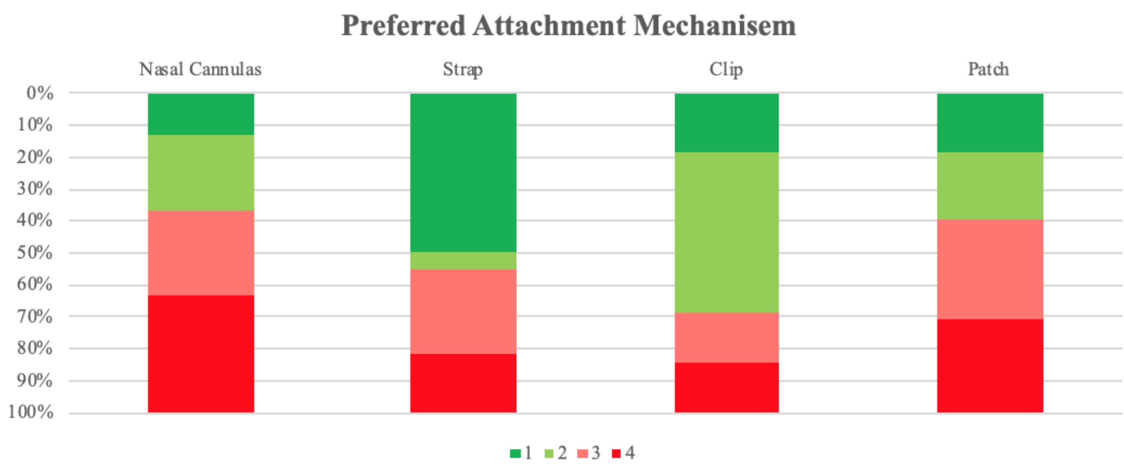


Figure 4.7: Preferred attachment mechanisms based on a visual evaluation by our study participants.

Out of all participants, 31 subjects reported that they could imagine likely or very likely to sleep for several nights with their preferred attachment mechanism. 24 subjects are at least interested in learning if they suffer from interruption of breathing during sleep. The sleep quality averaged as 2.7 across all participants.

4.2.2.4 Discussion and Limitations

The previous paragraphs evaluated different design aspects from a visual standpoint. Results that we present can be used to understand how users perceive the different options visually and what they prefer based on what they see. We identify the fabric strap to be most pleasing for the user and will have to investigate further if they prefer a clip or strap for the respiration sensor. Ultimately, to assess wearability, we will have to give the user something which they can wear to get insights into comfort or durability. Therefore, we further evaluated our system on the user in chapter 6.

5. Aura

Aggregating the previously collected information we went on to implementing a system that aims to integrate everything into an exemplary device and application. We developed the device through several iterations. The app was developed in parallel and can connect to the device using Bluetooth low energy. From our app, the data transfers to a backend application intended for processing the data and finally sending the data results back to the user's device where the app displays analysis results. We split the development of the hardware into functional and design mock-ups which made it easier to iterate. Additionally, we stress that the evaluation of design options of the previous chapter and the implementation of the functional device ran in parallel. Therefore, some of the findings do not already apply to those functional devices.

5.1 Hardware

We developed three different prototypes, two functional prototypes which help to learn more about how the sensors and electronic components interact with each other. A student with a background in electrical engineering supported with integrating and building these boards. The design mock-up was developed to come up with a basic idea of how a device could look when we optimize it for comfort. We will first introduce the learnings generated from the two functional prototypes and will then go on to presenting how we developed and manufactured the design mock-up prototype.

5.1.1 Functional Prototype 1

The first functional prototype focuses on getting the sensor for tracking movement and respiration into a single package and then iterating from there. The Figure 5.1 shows the printed circuit board and the different soldered components as an explosion rendering. The colors correspond to the colored paragraph titles. Additionally, we added a picture showing a user who is wearing the device while sleeping. The detailed schematics of the device can be found in the appendix of the thesis.

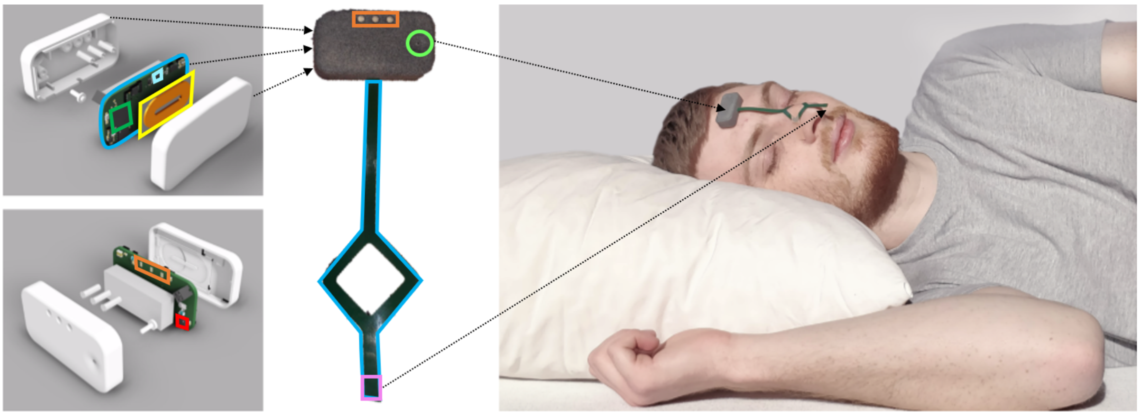


Figure 5.1: The two pictures on the left show an explosion rendering of the device. The picture in the middle shows the actual device and the picture on the right shows a user wearing it.

5.1.1.1 Implementation

This prototype consists of two different printed circuit boards. The first functional prototype comes equipped with two sensors - an inertial measurement unit data for movement and an environmental sensor for respiration and climate.

Printed Circuit Board (PCB)

The device uses a rigid six-layer printed circuit board. Additionally, a single layer flexible board connects onto the rigid PCB to have an adjustable nose piece for the respiration sensor which attaches onto the nose.

Inertial Measurement Unit (IMU) - *TDK InvenSense ICM-20948* [98]

By capturing acceleration and gyroscope as well as magnetometer data, this sensor can be used to track movement during sleep and identify the head orientation. This setup allows the detection of movement-related disorders, e.g., periodic limb movement or micromovements caused by bruxism. The configuration also enables identifying if, for example, someone has sleep position induced apnea. Therefore, we could suggest that users change their sleep positions and investigate how the number of apnea events varies.

Environmental Sensor - *Bosch BME680* [18]

The *Bosch BME680*'s capability to measure volatile organic compounds applies to this functional iteration. It allows the measurement of breathing and detection of respiration as described earlier in chapter 2. Additionally, the thermometer can be used to detect small changes in temperature while breathing in and out. Overall, the environmental sensing capabilities features can also help to understand the room climate. Humidity, temperature and air quality might support the analysis of more factors influencing the quality of sleep.

Qi Charging - *Wireless Power Consortium Standard* [108]

The device uses a wireless Qi-Charging coil. Therefore, no cable is required to charge the device. Instead, users can place it on an off-the-shelf wireless charging pad.

Charging Controller / Gauge - *TI bq25120a* [19]

For charging the device we have equipped it with a chip that ensures that the battery is charged correctly. It can also be used to read the state (e.g., charging) and battery load percentage.

Button / Light Emitting Diodes (LED) - Standard Components

To allow user inputs, the device comes equipped with a button in the front and three RGB-LEDs (multi-color) which can be used to show the device state.

Main Computing Unit (MCU) - *nRF52840* [67]

The prototype uses the *nRF52840*, which is a high-end Bluetooth low energy system-on-chip. It comes equipped with a *32-bit ARM Cortex-M4* CPU with the floating-point unit running at 64 MHz. Additionally, it has the "*ARM TrustZone CryptoCell* cryptographic unit included on-chip which brings an extensive range of cryptographic options that execute highly efficiently independent of the CPU" [68]. We can use it for encrypting data directly on the device, ensuring that medical records are securely stored and processed at all times.

5.1.1.2 Manufacturing

Würth Electronics in Germany manufactured the PCBs [110]. We ordered all parts on *Mouser* [62] and *Digikey* [25]. To assemble the prototype, we used a microscope, added soldering paste supported by a soldering mask, and placed the components onto it. Then we used a vapor phase oven to heat and solder everything at once. This process is particularly suitable for BGA (Ball Grid Array) components which we used for the testing device as it can equally distribute heat and works better than, e.g., an infrared soldering oven. The case was printed using an *Ultimaker 3*, and designed using *Autodesk Inventor* [102, 10]. The flexible PCB solders to the rigid board on four points. The case clips on the board from both sides and we fixated it with hot glue.

5.1.1.3 Interaction

The device used double-sided medical tape to attach onto the user (Figure 5.1). The upper side of the patch is intended for skin contact whereas the backside has glue that sticks strongly to plastic. One piece of the patch sticks on the backside of the nosepiece. A second one places onto the backside of the headpiece. Finally, the entire device sticks on the user's head whereas most of the weight is placed on the forehead, and the flex board applies on the nose. The respiration sensor loosely hangs in front of the nose. To charge the device, the user can put it on a wireless Qi charging pad. The device continuously advertises Bluetooth low energy (BLE) if no user device is connected. The device's button embedded on the front side can be used for resetting the device after it was connected to, e.g., the a phone. Additionally, the three LEDs facing the front-side, display the device state.

5.1.1.4 Learnings

We did perform informal testing with the device and figured, that the double-sided tape gluing mechanism is unsuitable because it takes much time to apply the two patches, is environmentally unfriendly when using multiple times and is hard to place the device intuitively so that it is in the correct position. Additionally, when removing the tape, the flexible printed circuit board which goes down to the user's nose quickly breaks when removing the adhesive because trying to rip it off results in much force being applied to the circuit by bending. This problem results in breaking the wires within the board and even tears the flexible PCB off from the soldering positions from the main board on the forehead.

As mentioned earlier, this iteration included a wireless charging coil for Qi charging. However, we had problems getting the charging to work which we, therefore, decided to leave out in the future in favor of a stable, functionally working device. We also figured that wireless charging today still requires the device to be placed onto a charging mat which we thought does not provide significant benefits over using a cable for charging.

The button on the front side was too small to be pressed easily and required the usage of a pen to push it, we, therefore, anticipated to make it bigger and also move it to the upper side of the device to avoid any button presses caused by laying down on the device facing forward.

We also had to realize that the capacity which we planned on using was not enough (70 mAh). We, therefore, intended to switch to a larger battery as the *BME680* is very energy hungry.

5.1.2 Functional Prototype 2

The prototype shown in Figure 5.2 is more sophisticated and adds the missing functionalities to achieve a fully integrated sleep tracking device for potential at-home usage. It combines EEG and EOG capabilities for sleep staging features as well as photoplethysmography (PPG) features for oximetry and pulse computations. Additionally, it comes equipped with a battery capacity of 250 mAh, making it easily last for an entire night. Colors correspond to the previous subsection.

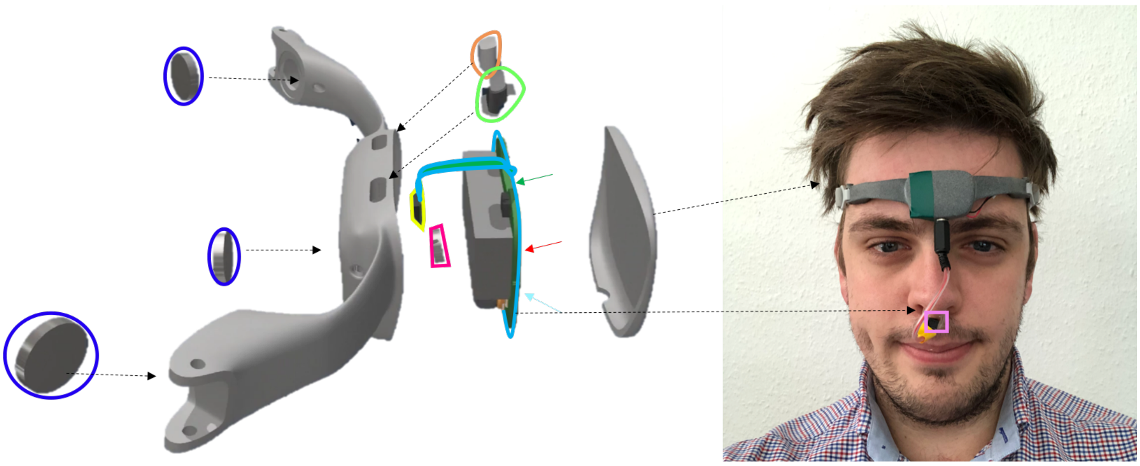


Figure 5.2: Second prototype disassembled (left) and worn by a user (right).

5.1.2.1 Implementation

Instead of using a flexible board for the respiration sensor connected to the nose, this version uses cables to connect to the *BME680* making it more stable. Additionally, this prototype does no longer require the user to stick anything to the face.

Printed Circuit Board (PCB)

In total, the second iteration prototype requires three printed circuit boards. The mainboard has the same computing unit as the previous version. Additionally, it connects to one flexible PCB using a "Board to Board" connector. This flexible board accommodates the LEDs of the PPG sensor. Furthermore, we designed a small shuttle board for the *BME680* respiration sensor which connects to the board using a jack plug and cable. The electrodes for EEG and EOG measurements are connected using special shielded cables which ensure no electromagnetic interference disturbs the signals. The design of the second generation prototype also uses a PCB antenna which makes the device thinner; however, it does require more horizontal real estate.

Photoplethysmography - *Maxim Integrated MAX86150* [57]

The chip which we used can deliver both photoplethysmography (PPG) and electrocardiograms (ECG) in a single integrated package. According to the manufacturer, the sensor setup is at an FDA-certifiable level of accuracy and recommend for compact form-factors and power-saving designs. We do not use the ECG functionality and rely on the PPG capabilities to compute pulse and blood oxygen saturation.

Electroencephalography/-oculography (EEG / EOG) - *TGAT2S* [63]

The *Neurosky* chip *TGAT2S* is a specialized chip intended for measuring brain activity. It has one EEG channel, one reference, and one ground electrode. It is designed for extremely low-level signal detection and comes equipped with advanced filters for high noise immunity. It can capture RAW EEG signal at 512 Hz. Additionally, we can turn off hardware filtering to capture EOG signals. The dry electrodes are recommended to have a size of 15 mm and made from high-grade steel. We had them laser-cut and polished for our device. We can use the data we get from this sensor to classify sleep stages. Mainly, the forehead is ideal for measuring delta waves and REM eye movement.

Vibration actuator - Standard Component

As we wanted to integrate an actuator that can alert the user even when asleep (not possible reliably with an LED), we decided to incorporate a vibration actuator. It can vibrate subtly and therefore wake up the user in the morning or alert the user, e.g., during sleep apnea events.

Other Sensors

Similar to the previous iteration, this version of the device comes equipped with an inertial measurement unit and the Bosch *BME680* sensor for measuring volatile organic compounds to track respiration. We also us the same battery controller / gauge as for other version. The button and a single LED have been moved to the top of the device. It chargs over the jack plug.

5.1.2.2 Manufacturing

Again, we had the printed circuit boards manufactured by *Würth Electronics* [110]. For the EEG chip, we had to get in touch with *Neurosky* directly as the currently only sell them after a thorough review of the customer [63]. Similar to the previous iteration, the PCBs were equipped using the microscope and then reflowed using the vapor phase oven. As it was a double-sided PCB, it had to go through the soldering process once for each side. The PCBs for the LEDs of the PPG and the BME680 were soldered independently. We connected the cables of the respiration sensor onto the mainboard by hand. The cases were printed using selective laser sintering which is a more reliable printing method with very high resolution and dimensional accuracy [51]. The electrodes for the EEG were spot-welded.

5.1.2.3 Sleep Tracking Capabilities

The following Table 5.1 shows all sensors and the related sleep tracking parameters which we identified can be derived using the sensors. Some of these parameters can not be directly read from the sensor outputs (e.g., sleep stages) and will require the collection of large datasets with a broad set of participants to train machine learning classifiers. However, based on the insights we gained from our previous literature reviews and expert interviews, we are confident that they will be sufficient to achieve all the parameters listed in Table 5.1.

Sensor	Possible Sleep Tracking Capabilities
Electroencephaleography (EEG)	Sleep Stages (W, N1, N2, N3, REM)
Electrooculogram (EOG)	Sleep onset, arousals, latency and efficiency
9-axis intertial measurement unit	Sleep position and agitation
BME680 (VOC, Temp, Hum, Press)	Sleep apnea, hyopnea, RERA and AHI
Photoplethysmography	Resp. cycles per minute
	Pulse and pulse rate variability
	Bloody oxygen
	Room climate (air quality)
	Overall sleep score (custom computation)

Table 5.1: Sensors of the device and sleep parameters derivable from sensor outputs.

The device tracks all the parameters according to best practices from sleep science. Readers should refer to chapter 3 to learn more about those recommended sampling rates. Due to limitations of the sensor for respiration, we can only sample at approximately 7 Hz.

5.1.2.4 Interaction

The second generation is more quickly to put on than the previous one. We use a medically approved head strap which grips onto the device with plastic clamps. This mechanism allows users to wrap it around the head and close velcro on both sides according to their comfort. Instead of sticking the nose piece onto the user's nose using double-sided tape, this version uses a nose clip that plugs inside the user's nose similar to the one presented in chapter 4. To connect to the device and interact with it, we added a button on the top side, which can be pressed in order to start the connection process. The new position avoids accidentally clicking the button when sleeping on the belly. As soon as the device is in the connection state, it starts advertising its availability to connect over BLE. Another significant improvement is that the respiration sensor can plug in and out of the device using a standard jack plug. Using the same port for charging the device during the day, and tracking respiration during the night saves space and makes it easier to replace broken sensors.

5.1.2.5 Learnings

Again, we performed informal testing with the device generation presented here. We figured that the inflexible case is not a good fit for the use case of sleep tracking. Even though it does bend a little due to its thin form-factor, it is not suited for wearing it for a longer time. Some force has to be applied to the device so that it bends enough to sit firmly on the forehead. Making the plastic parts thinner is also not an option because then the bending can not be reverted.

The electrodes which we used were applying a constant force which, similar to what we learned in the design chapter is not okay for wearability and comfort. We suggest to use electrodes as gold plated surfaces flex PCBs which products such as the *Xiaomi* eye mask use [113]. Finally, we discovered, that a softer back side of the device would be beneficial because the rigid case results in ambient light passing to the PPG sensor. This effect results in peaks in the sensor signal. A soft device backside would create more grip and make it easier to seal the PPG sensor.

We also observed, that the "Board to Board" connector which we used to connect the flexible PPG sensor LEDs and the main PCB quickly became loose. The bending of the PCB created a force which pushed the two boards away from each other.

We also discovered that for the sensor measuring volatile organic compounds, for some users, we could not see a stable signal for respiration due to humidity in the breath. Therefore, we suggest using semi-permeable membranes which let pass volatile organic compounds but not humidity which seemed to improve measurements based on our first trials.

For the prototyping process, we also have to report a very high scrap rate for the PCBs which we equipped. The majority of devices had problems which were hard or impossible to debug. Unfortunately, the device complexity is very high for this design, and we recommend to rely on third-parties for future wearable devices.

5.1.3 Design Mock-Up Prototype

To compare different designs of a device we decided to manufacture a mock-up prototype. This allowed us to evaluate the user's perception and comfort, independent of the functional devices. In Figure 5.3 we show the result of this process and we will introduce how we built the prototype in the following paragraphs. The head strap combines a comfortable foam cushion on the forehead and a stretchable band with velcro that can be adjusted according to head size. The part which contains all electronics has velcro on the back to easily remove it when washing the strap. We also considered to different nose attachments.

Figure 5.3: The picture on the left shows how we envisoned the device to look like using photoshop. The picture in the right shows two actual prototype implementations, one with clip and one with strap.

5.1.3.1 Preparation

For the foam part, we have milled a mold with a 5-axis CNC machine. A water jet cutter cut the foam into its basic shape. The foam has a height of 8 mm. We heated an off-the-shelf heating plate and applied parting compound to the mold, which makes it easier to remove the finalized part. We shaped the foam by firmly closing the lid of the cast and pressing it down for several seconds. After cooling down, we cleaned the cast using acetone. Shaping the foam makes the edges flat for sewing and adds indentation for the electrodes and also a hole for the PPG LEDs to shine through. We ensured that all materials are well suited for skin contact and do not cause any allergic reactions. Additionally, the foam absorbs sweat and releases it when the user is not wearing it during the day. To match the shape of the fabric on top of the foam, we glued it with double-sided tape and then cut along the line. Then we removed it from the foam. The overall device can wrap around heads with a diameter from 41 to 64 centimeters. This is well beyond the standard hat sizes and therefore our device should work for most users [37]. Readers should refer to Figure 5.4 for an overview of the different parts that we used which we got from a local store. We found the nose clip of version one online, which is usually intended for preventing snoring. We re-purposed nasal cannulas for the connecting tube from the device to the clip. For the version where a strap wraps around the nose we use an elastic band.

5.1.3.2 Assembly

Before assembly, we used needles to get an idea of how the final assembled prototype would look and talked to a fashion designer who has experience with processing different materials. Based on what we learned, we first sewed the velcro on to the front-facing fabric of the device. The flexible strap made from a combination of cotton and rubber goes between the fabric and the foam. Then everything is sewed together into a single piece. Additionally, velcro is stitched on the stretchable band for opening and closing it. For the case mock-up, we designed a small plastic case which we printed using an *Ultimaker 3* [102]. We glue the velcro to the back of the 3D-printed case with two-component adhesive. Only soft materials are touching the user's skin or hair. We positioned the velcro so that the smooth side is facing towards the user avoiding hair being tangled up.

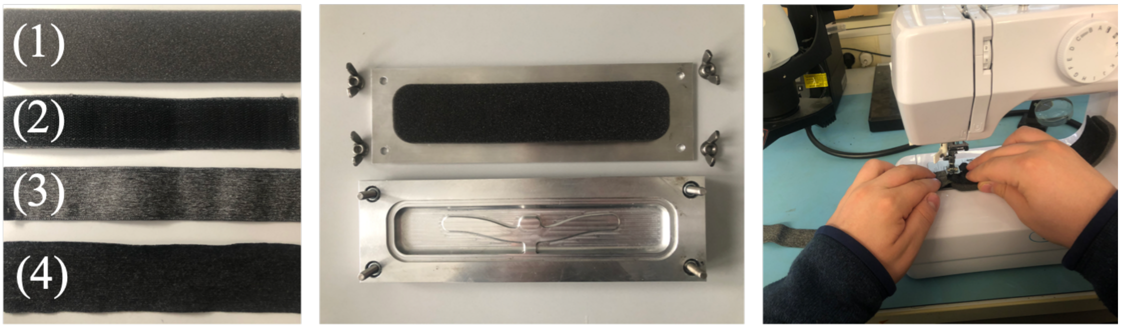


Figure 5.4: The pictures above shows the different steps involved into the prototyping process. The left picture shows foam (1), velcro (2), stretachable strap material (3), and jersey fabric (4) (top to bottom). The picture in the middle shows the mold and a foam part to be shaped. The right picture shows sewing the parts.

5.2 Software

First we will introduce the overarching architecture of the Aura system which integrates from the low level hardware over the app to the backend. As the majority of code was implemented for the app we will introduce it first, then present the backend and finally the firmware of the device.

5.2.1 Overall

Before going into the details of every part of our system, we would first like to introduce the different parts of our overall architecture. The system is quite complex, with various software artifacts. To make development more comfortable, we have defined continuous delivery pipelines for every component (firmware, app, backend), which made it easier to test and integrate. We store the source code centrally in git repositories, which trigger builds on new pushes and even automatically deploy the latest changes without any manual interaction necessary.

5.2.1.1 Architecture and Communication

Figure 5.5 shows the overall architecture of the Aura system. All in all, four overarching components interact with each other. The backend is hosted on the infrastructure at our lab with multiple microservices that combine a set of functionalities. It also contains a messaging queue intended for having an extendable set of services processing data in the future. Our backend has two key interfaces. The first one is based on REST and meant for communicating with the mobile app for providing access to data on a per user basis. Users are issued access tokens once they register or login and then authenticate against the backend API for every request. The second interface uses web sockets for enabling real-time communication for a labeling tool. This tool can be used by administrators or data scientists to get access to the raw sensor data of all users. So the main difference between those two interfaces is the granularity of access. The Aura app communicates with the device using Bluetooth low energy. We have defined a set of services and also use standard characteristics according to the Bluetooth specification. The smartphone itself never sees any of the data recorded with the device as it only serves as a gate to the server, transmitting an encrypted and compressed package. During device provisioning, we store a preshared key on the device and server. This process enables fast symmetric encryption on both ends.

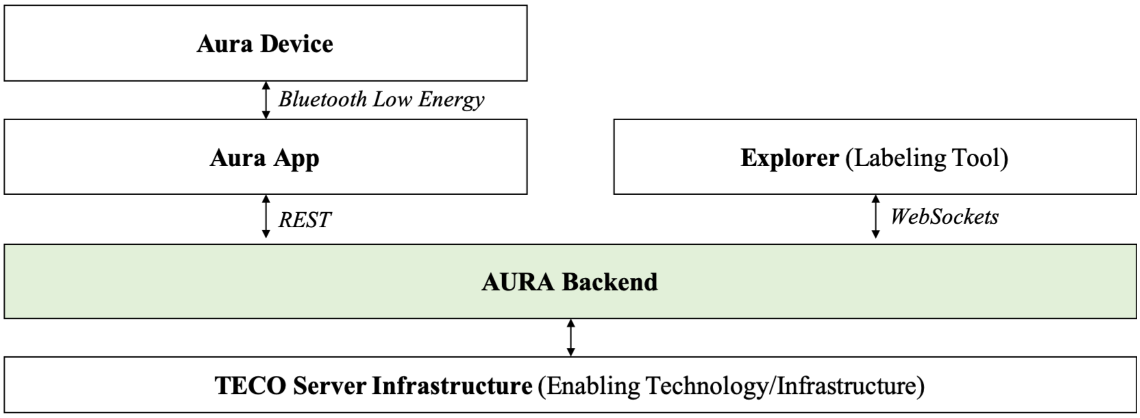


Figure 5.5: The picture shows the overall architecture with our lab's server infrastructure hosting the microservice backend. App and labeling tool build on top of that. The Aura device connects to the app using Bluetooth low energy.

5.2.2 App

The Aura app is for the end-users, and it connects to the device, provides firmware updates and aggregates results through a single coherent interface. Additionally, it includes advice and correlation of behavior to sleep problems. We will first introduce the technology we used to build the app, then present the architecture which follows best practices and finally showcase our implementation. We also show our design process which includes the conceptualization of an entire guideline for user interface elements. Finally, we also present how the user can navigate through the app and get access to every functionality within few steps.

5.2.2.1 Technology

We developed the app using *Xamarin.Forms* [111]. *Xamarin.Forms* is a cross-platform framework intended for developing *iOS* and *Android* applications with minimal overhead and from a single code base. The programming language is C#, and we can define the user interface through the XAML markup language. The XAML code can be updated using data binding to C#, which automatically adapts the user interface after variable changes, indicated by property changed events. The toolbox provided by the framework has a broad set of user interface elements from buttons and labels to free form text boxes. Many extensions are available through *NuGet* [69] which provides libraries also for user interfaces or permission handling. Additionally, custom user interface elements can be defined using so-called custom renderers that we can implement on a per-platform basis. A package called *SkiaSharp* [88] can be used to draw custom charts or other drawings which enables the development of a sophisticated user interface. This collection includes elements such as spider charts or hypnograms. Dependency services are another feature provided by *Xamarin*. They enable dynamic implementations of platform-specific code by defining a unifying interface within the shared code base. These interfaces resolve to platform-specific dependencies during compilation. To compile the app for either of the two platforms *Android* and *iOS*, we have to install *Android Studio* and *XCode* [6, 112]. Additionally, we have to make sure, that we have configured all the required certificates and provisioning profiles from the *Apple Developer Portal* and *Google Play Console* [8, 33].

5.2.2.2 Architecture

We adhere to the best practice by *Xamarin*, which uses the Model-View-ViewModel (MVVM) design pattern. It separates the data model, logic, and the user interface, making it easier to extend functionalities. The Figure 5.6 shows an architectural overview diagram of the application. In total, the app consists of four packages, one for the core functionalities, which includes the model, ViewModel, and services. Another one for the user interface components and one for the platform-specific projects for *Android* and *iOS* respectivly to implement specific dependency code.

In general, we split different parts of the app into services, view models, models, controllers (for backend interactions), and user interface. The four different packages could be tested independently, e.g., through unit tests for the model and core services and automated testing for the user interface elements.

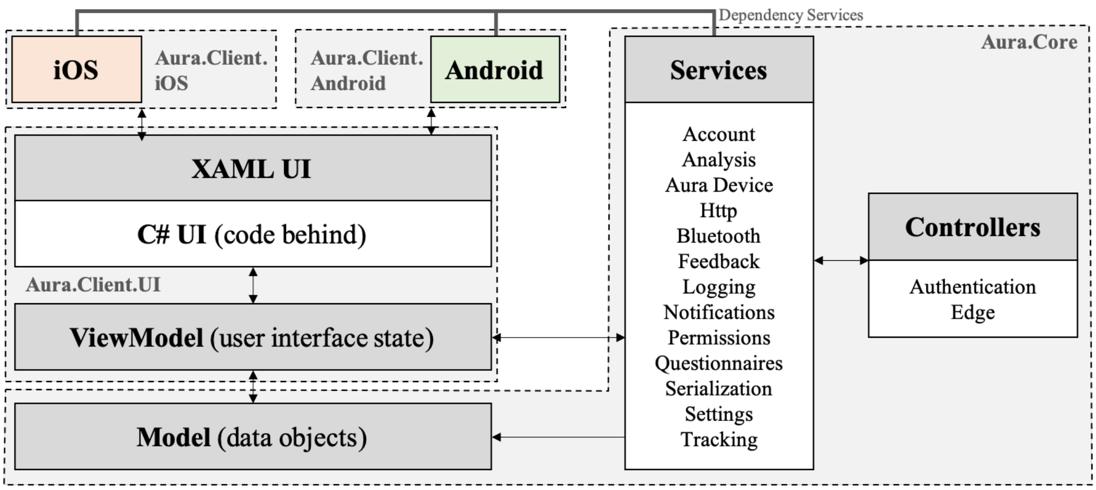


Figure 5.6: The four core packages of Aura and the interaction between the different elements of the app (simplified).

5.2.2.3 User Interface Design

Before implementing the app, we decided to define a set of user interface elements that we can reuse and that have a unique style and look. To do so, we began with designing a mood board for the app that inspires the look and feels. We use a modern gradient design which is very common in recent mobile applications. We went on to defining a broad set of user interface elements to guide implementation.

Mood Board

Before implementing the app, we wanted to create a mood board. We thought about how we think a modern, cutting edge technology wearable would inspire the design of an app. We looked into different colors, shapes, and also conveying a modern feeling. The image shown in Figure 5.7 inspires round and organic shapes and circular elements. At the same time, the app should provide structured information about sleep which is represented by the clear lines of the design. The different colors spark interest, glow, and enable users to understand the quality of their data with the natural matching of color-coding.

Figure 5.7: The mood board illustrates the looks and feel of our app and inspires the design of user interface elements (all images are license free).

Unified Guidelines

Based on the mood board, we created a set of application interface elements and defined a design guideline for our application. This collection includes a set of color gradients, different types of buttons, cards for representing various information, and also different diagrams. In general, we use glowing gradients for drawing the user's attention and represent important aspects of the interface. Buttons with opacity or just outlining indicate less important actions which the user is less likely to choose. We also selected a font intended for user interfaces which comes in different font weights depending on headings or text passages. For the implementation of the elements shown in Figure 5.8 we define a set of global classes. They can be reused all across the app without recoding them for every occurrence. By setting different variables we can change title, values or even colors.

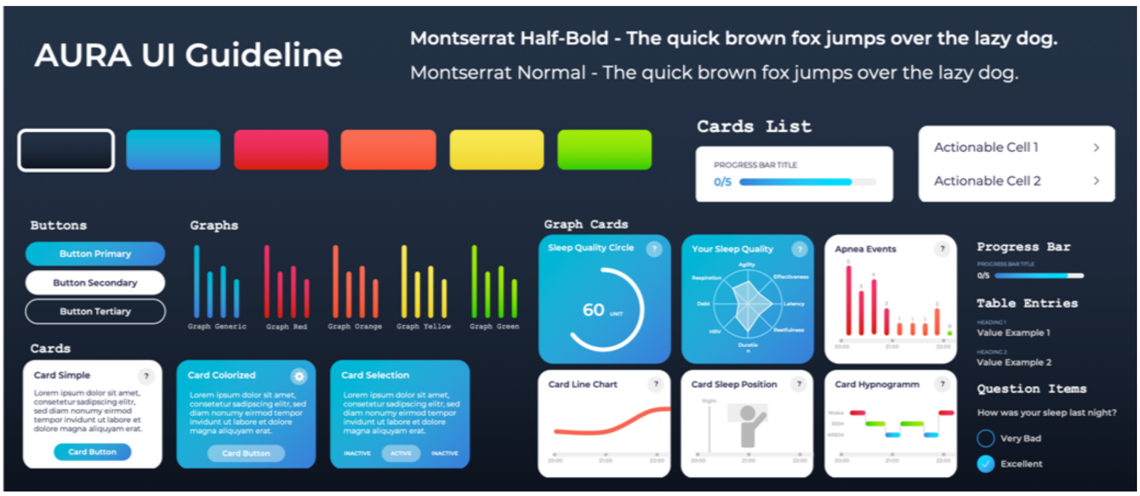


Figure 5.8: Design guideline which we developed for the implementation of our app.

5.2.2.4 Implementation

The following paragraphs will introduce our implementation. We will start by describing how we implemented the underlying services and then present the individual parts of our application. We used *Visual Studio* as integrated development environment (IDE) [104]. We will also show how the pages of the app are interrelated and how the user can navigate through them.

In general, we defined interfaces for all the services we have implemented in our app. All services are made available through a so-called service provider to which we can pass the type of required services, and it will return that service. This pattern ensures that at any time, only a single instance of every service exists. If one service depends on another, we use dependency injection with the constructor to pass the depending service. Applying this principle also improves testing because we can give mock objects as a dependency to model expected and unexpected behavior.

For interacting with the backend, we defined what we call controllers. They share a single static instance of an HTTP client along the whole lifetime of the application. This ensures that we do not use the available sockets too much, and therefore no socket exception will occur. We applied the singleton design pattern. We store all relevant endpoints and routes for the controllers as constant global variables. Additionally, we set global authentication headers for every request once the user has logged in.

Pages

In total, we have implemented 26 pages inside the app, whereas most of them are shown in Figure 5.9. We will present the most relevant pages one by one. Less critical pages have been left out of this report because they provide no significant functionality (e.g., information about the app version). In general, we tried to follow the gradient kind of layout which we introduced earlier.

We reuse components where possible. The majority of all user interface components are custom implementations. Additionally, we apply styling for platform specific rendering differences between *iOS* and *Android* to ensure unified looks and feel. More complex user interface elements which can not be built from standard elements such as buttons or labels are drawn from scratch (e.g., clock selection or graphs). For every page, we define a view model for data binding. We programmed an event-driven user interface, ensuring that users can move freely through the app, even while it is loading. We bind to observable collections for list items (e.g., chat) and apply value converters where necessary (e.g., score to color). For internationalization, we use static value dictionaries which translate generic button and label identifiers to the actual text.

Welcome (1) / Login (2) / Register Page (3) The welcome page provides general information about the app and welcomes the user. The registration page can be opened from the welcome page to enter the information required for creating an account (name, email, password and confirm terms of service / privacy policy). After creating an account, the app leads users to the help pages (4). It gives a general introduction of the overall concept, the app, and the device. If a user already has an account registered, they can also open the login page to enter their credentials.

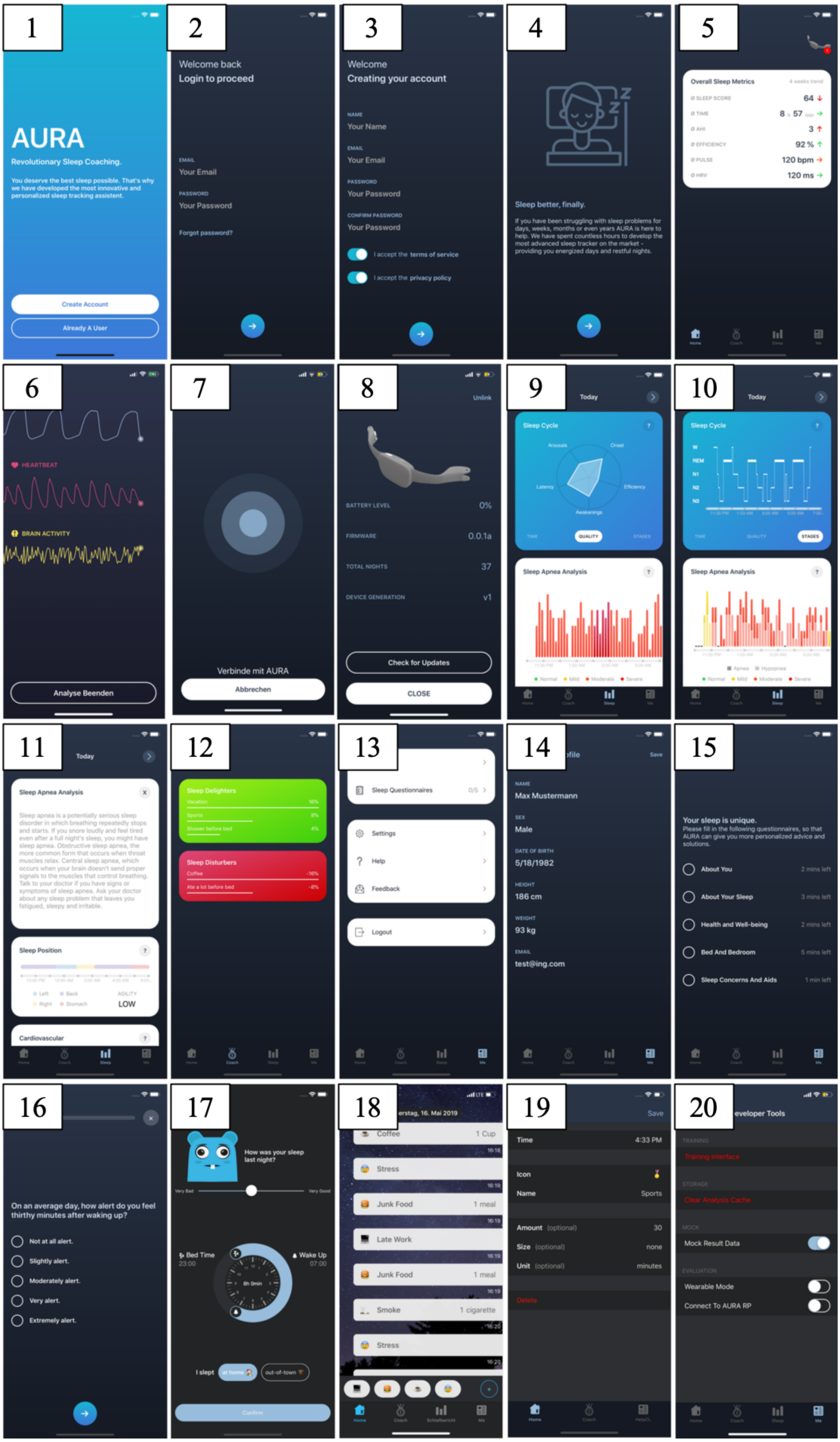


Figure 5.9: Various user interface screenshots implemented in Xamarin (screenshots taken on iOS).

Overview Page (5) The overview page is the general entry point of the app. It shows information about the overall sleep quality trends, indicates different metrics, and lets the user start a new sleep analysis. After pressing the button to start a new analysis, a new page is presented indicating the analysis is running (6). In the top right, a small icon indicates if the device is connected. If it is not connected a red marker is shown otherwise a blue icon indicates that the Bluetooth connection is in place. By clicking on the icon of the device when it is disconnected, the connection process starts (7). By clicking on it when connected, the device management page shows up (8).

Analyis In Progress Page (6) After starting an analysis, this page moves to the foreground. It displays the time for how long the analysis did run. Additionally, it renders sensor data. The top row shows the breathing signal and breathing rate. In the middle, we can see the signal of the pulse sensor, whereas the screenshot indicates the peaks. The third diagram shows the raw EEG signal, which shows the eye movement as well as brain activity. A button to stop the analysis is shown in the bottom. The graphs are a custom implementation and are drawn in real-time as data arrives. With newer data coming in old data moves out to the left.

Connect Device Page (7) This page shows after the user starts the connection process. The circle in the center is a custom animation which pulses as the phone is looking for nearby Aura devices. Upon finding an Aura device, a popup shows up to the user with the unique identifier of the device. If this ID matches with the device that the user wants to connect to, they can confirm to connect. After this, the connection process concludes and the user is ready to perform sleep analysis.

Manage Device Page (8) This page shows the user more about the connected device's state. It displays the battery percentage, if the device is currently charging, how many sleep recordings the device went through and which firmware version it is currently on. Additionally, a button can be clicked to manually check if a software update for the device is available. Currently, this button does not work as updating the device over Bluetooth is not implemented yet.

Sleep Report Page (9, 10, 11) After spending a night with the device and running an analysis, the users can see the results on the sleep report page. The top displays a date switcher which can be used to go back in time day by day. Below that, several cards are displayed showing different sleep quality factors. The first card shows general information about the sleep cycle. The first tab of that card contains information about the bedtime, wake up time, and total sleep duration. In the quality tab, users can see different sleep staging factors, namely arousals, onset, efficiency, awakenings, and latency. The last tab of the first card shows the different sleep stages as a hypnogram. The second card shows information about sleep apnea. A graph breaks down the number of apnea and hypopnea events and also colorizes the number of events according to apnea-hypopnea-index (AHI) during that hour. Additionally, the second tab shows the different metrics for sleep apnea - apnea and hypopnea events, RERA events, the overall apnea-hypopnea-index, and the breath cycles per minute. The third card shows the different sleep positions and how much a user moved during sleep. The last card shows information about the cardiovascular system with a graph over time. In particular, the first tab shows the pulse, the second tab heart rate variability, and the third tab, the blood oxygen levels. Every tab also shows the average and minimum values, respectively. If the user did not record data for a particular night, the app displays a card with an empty clipboard and hides the other cards mentioned before. We want to note that all diagrams and graphs are custom implementations which have been programmed from the ground up.

Coach Page (12) This page is intended to display the positive and negative influencing factors of sleep. To do so, it displays two cards. The card showing negative influencing factors is red; the card showing positive influencing factors on sleep is green. The percentage displayed is the effect it has on overall sleep quality. Later versions of the app could also link single factors to single sleep problems, e.g., drinking alcohol and sleep apnea events.

Me Page (13) This page shows several options for the user to change preferences and also for editing person-related data. It provides an option to go to the profile, or answer questionnaires. The settings option lets the user open the settings where he or she can change, for example, the units (centimeters vs. inches). Additionally, it provides access to the help and feedback controllers which can be used to get an overview of the app or to send feedback to the developers. The app sends feedback to the *HockeyApp* [41] ticket management system, which makes it easier to trace bugs and improve upon user feedback. Finally, the page also provides the option to logout of the app.

Profile Page (14) The profile page lets users edit their meta data. This data includes their name, their sex, their date of birth, their height, their weight, and their email address. Clicking on save stores the information. Leaving the page discards changes; however, discarding has to be confirmed by a popup.

Questionnaires (15) / Question Page (16) The questionnaires page shows a list of questionnaires which the user can answer and which provide medically grounded questions that help to understand the user better. The questionnaires also display an approximate time how much it will take to answer the entire questionnaire. By clicking on a questionnaire, the questions become visible one by one. The progress of the user going through the questionnaire is kept up to date in the top with a progress bar. It can also be closed using the cross in the top right corner.

Help Page (4) The help page has three sub-pages, each explaining information about the Aura system. The first one introduces the overall general concept to the user. The second one introduces what the app does, and finally, the last one shows information about what the device can do. It also provides the option to click on a button which takes the user directly to a shop where they could buy the device in the future.

Track Sleep Subjectively Page (17) To understand how users think they are sleeping compared to how we measure, we added an option to track sleep subjectively. They can track their sleep on a scale from one to five. A little creature displayed on the page also reflects the meaning of the value by changing facial expression as the user slides. Additionally, the page enables tracking sleep duration manually, without using a device by entering it with a custom rendered clock interface. We also collect information about where the user did sleep.

Track Behavior Page (18) As we are interested in understanding how the daily behavior influences how the user is sleeping, we provide a page where the user can track what they have been doing. This input can either be done using predefined templates or through a semi-free-text which has to follow a specific pattern. The information entered by the user is stored daily, and users can go back in time using the switcher in the bottom area. The daily tracked items are displayed as a timeline, very much as a conversational user interface.

Template Management / Item Edit Page (19) Some templates for tracking are already provided by the app. However, users can add their templates according to their preferences. A template always defines an icon, a name, an amount, and a unit. Templates can be created, stored, and deleted. If a template is changed, old entries in the tracking of the daily behavior remain unchanged. If users would like to update them, they would have to go through them one by one using the tracking interface. Additionally, if users would like to update a previous tracking item, they can do so by clicking on it in the tracking chat.

Developer Tools Page (20) The developer tools page is only available in debug builds, not installed through the app store. It provides the option to open a training interface for recording and to label respiration data in real-time, it has the option to clear the local analysis cache and also makes it possible to mock result data for the sleep report. Finally, it is also possible to enable a connection to other BLE devices for studies e.g., to ground-truth respiration or pulse sensors.

Other Pages The feedback page mentioned earlier is provided by the *HockeyApp SDK* [41]. Another page contains information about the version and build identifier as well as references to the privacy policy and terms of service. We also provide a button which takes the user to the system settings page provided by *iOS* or *Android* depending on the user's operating system.

Notifications and Error Handling To send notifications locally and handle errors appropriately depending on the app state (e.g., foreground vs. background), we have implemented a service for dealing with different situations. We can pass messages to this service, and based on the app's state, either a dialog pops up inside the app, or a system notification is triggered to inform the user. Additionally, the overview page shows a red card if Wifi or Bluetooth is not available (e.g., because it is turned off or the device does not support it).

5.2.2.5 User Flow

To aggregate how the different pages of the app interact with each other, Figure 5.10 shows the flow of the user throughout the app. In general, the users do not have to go deep into the navigation stack to find the information for which they might be looking. The majority of all pages elements is reachable within three taps. The only information deeper in the stack are topics related to the version of the app or general information about the developer. Additionally, preferences which are changed very rarely are more hidden than other functionalities. The Aura tabbed page is the page that holds the different root pages. Therefore, users can switch between the pages directly and do not have to navigation to the tab page itself.

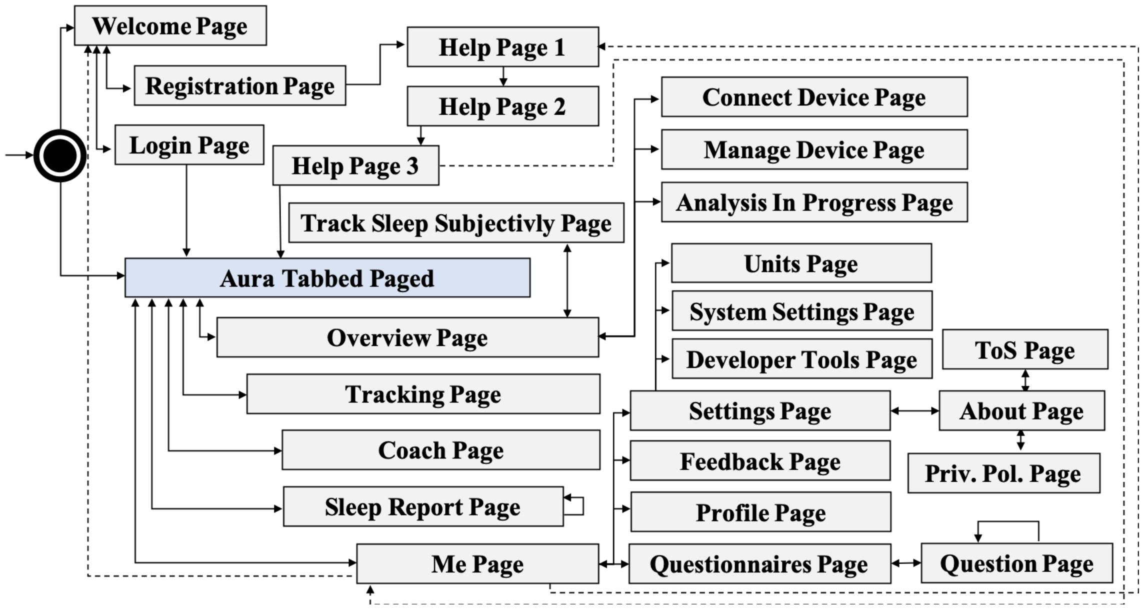


Figure 5.10: The diagram shows the flow between the different pages of the Aura app and the starting point.

5.2.3 Backend

The backend which we developed currently consists of two primary services. One service stores all the datasets recorded by the user with their device. The other service handles the user account. This setup ensures that personal data (e.g., e-mail addresses) stays separated from the health data.

5.2.3.1 Technology

To implement the backend, we use *Node.js* with JavaScript and leverage the *koa* framework [66, 50]. The main advantage of *koa* compared to established frameworks such as *Express* is that it is smaller, more expressive, and robust [27]. Instead of having to use callback functions, *koa* encourages to use asynchronous functions which makes error-handling a lot better. As our database framework, we use *MongoDB* [60]. We deploy the two services by creating *Docker* images that we host on virtual machines at our lab's server infrastructure [26]. Using *Docker* containers ensures that we could move the services to, e.g., *Amazon Web Services* if we would have to handle larger loads [4].

5.2.3.2 Architecture

In Figure 5.11, we present the architecture of our backend. The authentication service serves for registering and logging in. With the accompanying database, we hold all the relevant information related to a user. On successful login, the service returns a JWT (JSON Web Token) and which the app uses for authenticating against the dataset service that holds all the data linked to dataset records. Additionally, we defined an AMQP (Advanced Message Queuing Protocol) messaging queue with *RabbitMQ*, which serves as an asynchronous channel for services to hook [74]. Once new data is available, the purpose of this messaging queue is to notify, e.g., classification services that process datasets that write back their results. We could also define a flow of services with this queue. For example, this would include smoothing data and then passing it to another service that handles the actual identification of, e.g., sleep apnea events. Services will be independent of programming language, and we can, therefore, pick the ideal programming language or framework for any task. Currently, no services are in place. We also add a web socket abstraction layer to our database access layer for real-time collaboration in a data labeling tool which we do not cover in this thesis.

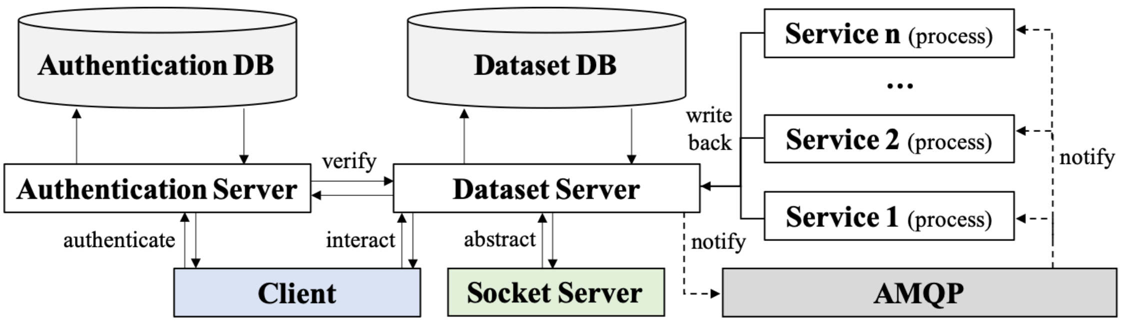


Figure 5.11: The diagram shows how the different services interact with each other. The AMQP queue serves for notifying about new events. A socket server provides abstractions for real-time collaboration on dataset labeling.

5.2.3.3 Database Schema

In Figure 5.12, we show a simplified version of our database schema. The central element is the dataset which references the user identifier it belongs to and also references a set of time series corresponding to the recorded data signals of the device. We decided not to store every data point of a time series as a single record because this would create much overhead. Instead, we store sensor data as a single stream of bytes. A specific device corresponds to every dataset which can have a set of sensors and a firmware. Additionally, for tracking events for, e.g., the behavioral root cause mining, a dataset has a reference to a collection of events. By adding labels to time series, we can add meaning to data (e.g., apnea events). These labels can either be added manually, e.g., with a labeling tool or with an automated service which is why every dataset labeling has a reference to the creating service. If a specific application requires to fuse a set of series into a single object, a fused series encapsulates multiple time series (e.g., when displaying two data streams at once). Finally, we also defined a reference to a video which we could record during experiments. Only a reference to the video's uniform resource locator is stored, and any blob storage provider could store the actual file (e.g., *Amazon S3 Glacier* [3]). The database schema shown here does only correspond to the database that holds medical records. The database which contains the user data is straightforward, and only stores the metadata, as well as information about keys generated for the user (access tokens and refresh tokens). We, therefore, have not created a database schema diagram.

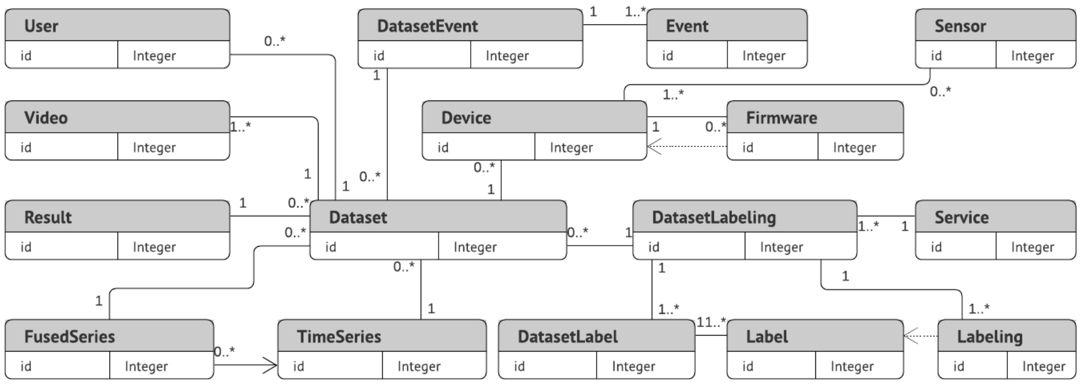


Figure 5.12: The diagram above shows the simplified database schema without attributes. The whole schema can be found in the appendix of the thesis.

5.2.3.4 Implementation

Now that we designed the architecture, the schemas, and the interplay between the different components, we executed our plan. We translate the database schema introduced earlier to a mongoose schema which corresponds to the model of the database. We add subroutes for all the endpoints that we want to have for our API and define controllers which manage the access to the database. They ensure that the correct parameters are passed and also return error codes (e.g., 500 if a request has the wrong parameters). We apply mongoose schema validation directly on the database, which secures the integrity of the data on a low level. Errors that do not follow this schema propagate in the stack. The actual REST API follows the *OpenAPI* standard and is documented using Swagger [70]. The documentation is served together with the actual implementation, which makes it very easy to start developing applications that rely on the backend. For the majority of endpoints, we define GET, POST, DELETE, and PUT operations. In total, this results in a little more than 100 endpoints. Additionally, we set up the infrastructure on our lab's servers. Based on our design a working student did the actual implementation.

5.2.4 Firmware

Finally, we would like to present the firmware that we implemented for the wearable device. It combines access to sensors, storage management, Bluetooth characteristics, and state handling.

5.2.4.1 Technology

For implementing the firmware, we use "*Arm Mbed OS* [which] is a free, open-source embedded operating system designed specifically for the things in the Internet of

Things" [59]. It has everything we need for developing our *Arm Cortex-M* based microcontroller. As the development environment, we use *Visual Studio 2019* [104]. We write the firmware of the device in C++.

5.2.4.2 Architecture

In Figure 5.13, we illustrate the architecture of our firmware. It follows a state design pattern with a state holder used for transitioning between the different states. We have the four states idle, record, advertise, and send. In the idle state, the device is doing nothing except for waiting for any requests by a connected device. In the recording state, data is recorded from sensors and stored on the device using the storage manager. Sensors can either use polling or interrupts depending on the actual hardware device. We can define filters directly on top of the sensors. Additionally, sensors follow the observable pattern, and we, therefore, can be notified in the record state once data is available for any of the sensors and also, e.g., downsample in software. To efficiently use the storage of the embedded device, we apply compression. Furthermore, the storage manager encrypts data after the recording finishes. In the sending state, we use Bluetooth GATT functionality to transfer encrypted packages to the device [16]. The advertising state serves for waiting for connections. If after 120 seconds no phone is connected the device switches back to the idle state. In the real implementation, the recording state separates into two states where we also provide live streaming of the data if the app requests this, however the device switches to the normal recording state after five minutes to ensure that no data is exposed continuously throughout the night. Connected devices can request to go back to this state any time, e.g., once the user opens the app in the morning.

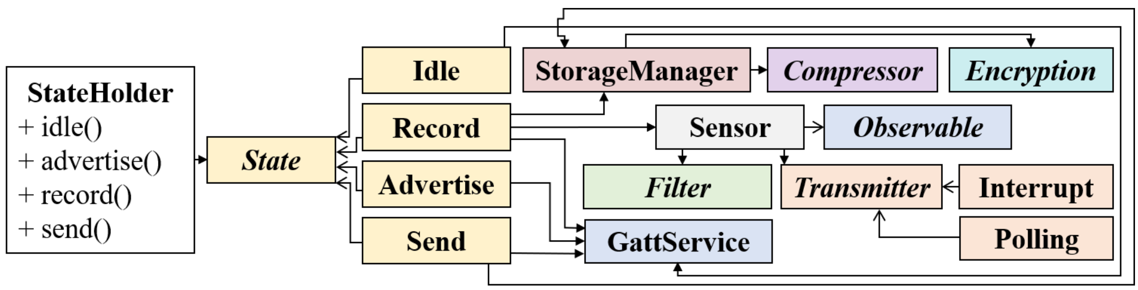


Figure 5.13: The diagram above shows the architecture of our firmware with different states and dependencies on functionalities. Cursive classes are abstract.

5.2.4.3 Implementation

A working student of our lab implemented the architecture that we conceptualized. He also looked into different filtering, compression, and encryption mechanisms. As he will be transitioning to a thesis student and further investigate those topics in his work, we do not go into any further details here. In general, we started by defining abstractions for every sensor and then integrating them one by one into the overall flow of the firmware. Filters and their frequencies are implemented according to specifications from literature. Suitable compression algorithms are implemented for every sensor type independently.

Bluetooth Protocol

We defined a set of GATT characteristics that can be either read, written, subscribed, or a combination of all three by devices such as the user's smartphone [16]. The set of characteristics enables transitioning between states, receiving recorded data packages, and also capturing live data for showing inside the app. Additionally, we make use of the standard characteristics defined by the *Bluetooth SIG (Special Interest Group)* for battery charging level and also the battery state.

6. Evaluation

This chapter provides an evaluation of the mock-up hardware devices and the app. Study participants tested the two different mock-up hardware prototypes, which we presented earlier. For the app, we performed so-called think-aloud sessions. The functional devices which we introduced earlier were still undergoing development during the time of starting to wrap up this thesis. We, therefore, decided to focus on the usability aspects of the devices and software we built. However, we were still interested in assessing measurements of physiological parameters. We got access to a set of a stable third-party platform called eSense [48] which are earphones equipped with an inertial measurement unit. We implemented a data pipeline to determine if head-worn IMUs are suitable for tracking respiration rates. If so, this would be an even less obtrusive solution than our current approach.

6.1 Mock-Up Device

This section presents the evaluation of the mock-up device, which we introduced in the previous chapter.

6.1.1 Participants and Design

We decided to distribute the mock-up device to twelve participants. Due to the number of subjects, we decided to collect qualitative feedback only with an online questionnaire that they had to fill in the next morning after standing up by using their smartphone. We encouraged them to reply extensively for all the free-form text fields. The questionnaire included what they liked and disliked about the wearable, what they would like to keep and discard of the prototype, and also how they perceived the materials that we used. Additionally, we asked them how comfortable the device was. To learn more about their acceptance, we also asked them what they would think about wearing the appliance for several nights, and if they kept it on throughout the night. To learn more about their visual perception, we also asked how they like the optics of the device. For understanding more about the comfort we also asked if they felt disturbed in any way by the prototype (e.g., pressure feeling). We also asked them if their sleep was any different from their regular nights. Finally, we also collect demographic information (age and gender). After showing participants how to wear the device, we instructed them to take it home. Every participant had to wear each version once for a night (nose clip vesion one first, strap version two that wraps around nose second). We did not change the order in which participants did try the two different versions. For the nose clip version, participants can adjust the length by pulling or pushing in the cable through a hole in the 3D-printed case. The strap around the nose can be adjusted by changing the width and then fixing it with a clasp pin. We instructed participants to configure the prototypes according to their comfort.

6.1.2 Results

We recruited twelve participants of whom four were female and eight male. The mean age was 21 years.

6.1.2.1 Version 1 (Nose Clip)

The results we present first correspond to the device with a nose clip that goes inside the user's nose.

Comfort Six participants reported that they enjoy the comfort of the headband. One participant explicitly expressed that he likes that the device is in the front center, which avoids disturbing during sleep. Another participant mentioned that the prototype is enjoyably light. However, ten participants reported being disturbed by the nose clip (more on that in one of the following paragraphs). Three users said that the velcro stretched their ear when the strap sat too low. Two users reported that they felt the device causes an uncomfortable pressure feeling on their forehead. Three participants report having taken off the device before the morning because of discomfort.

Fitting Three participants mentioned that they enjoyed the adjustable size of the head strap with velcro. Three participants also expressed that the strap did not hold for the entire night. One subject said that she could not find any enjoyable size configuration no matter how she adjusted the strap.

Looks Two participants expressed that they enjoy the simplicity of the device. One subject said he liked the approach even though it is noticeable that it is a prototype. Another user said she thinks that the device looks premium only that the clip disturbs the overall look. One participant also raised that the device is too big. Finally, one participant also expressed that she would enjoy having other color options.

Hygiene One participant said that he felt uncomfortable because he was sweating, which resulted in the foam soaking. Another participant said that she would be worried about skin irritations on her forehead after wearing the device for several nights.

Effects on Sleep Seven users said that the device did not affect their sleep. Two participants noted that the device caused them to fall asleep later. Another subject expressed that he slept more on the back than usual. Two participants reported being woken up by the nose clip several times.

Nose Clip Seven participants explicitly reported that they thought that the nose clip is uncomfortable. One user said that he felt that his nose is clogging because of the clip. Another user expressed that he had a cold and the nose clip made it hard to blow his nose because he had to take it off every time.

6.1.2.2 Version 2 (Elastic Strap)

The following paragraph will present additional findings reported by the same participants as for the previous study. We do not cover comments which we received again (e.g., about the head strap). We focus on new aspects which we got from this prototype test for a sleep tracking system. We specifically encourage users to compare between the two versions.

Comfort Ten participants said they did prefer the comfort of this version compared to the previous one. Only one user reported having taken off the device before the next morning. Three participants explicitly expressed that they would hope to get rid of any nose attachment in general.

Fitting Two participants mentioned that the strap on the nose did not stay in place. Also, two participants reported having lost the headband during sleep.

Looks Three participants reported preferring the looks of the device mainly because it looks less medical, seems to be more stylish and also thoughtfully designed.

Effects on Sleep Ten users said that the device did not affect their sleep. One participant who especially felt stressed out by the strap in her face said she could not fall asleep until she took it off.

6.1.3 Discussion and Limitations

Overall, the second implementation of the headband was accepted better than the first one. The nose attachment for both versions, however, is troublesome for the majority of users. We should think further about ways to improve on this aspect because it will likely yield the highest comfort increase. Additionally, we need to find ways that ensure that the head strap does not get lost during sleep by finding materials that hold better onto the user's head, such as rubber.

The subjects we had in our study do not report severe sleep problems. Insights we might get from patients already struggling with sleep problems are likely to be different. Additionally, users that have spent a night in a sleeping lab might have a different perception of our device because they can compare state-of-the-art polysomnography. Overall, future tests with a functioning prototype will also reveal more insights because users will then receive an immediate benefit from wearing the device.

6.2 App

After looking into the wearability of the device, we now like to investigate how users interact with our app. We apply a think-aloud study which generates qualitative feedback on usability.

6.2.1 Participants and Design

We decided to recruit eight participants through a sample of convenience for our think-aloud study. According to literature, it is recommended to recruit around four to five participants for a relatively simple application. However, due to diminishing returns, we decided to have more participants which increase the probability of revealing usability errors [52]. We planned to have the users interact with the app naturally and let them explore all features. We placed them in a quiet room and made sure they could settle comfortably. Additionally, we emphasized that we are interested in their problem-solving strategies, and not in unconscious emotions and hidden thoughts [103]. Before the study, we gave them a small tour of the app. Then we had the user go through the on-boarding process and asked them to register. Before the study, we also encouraged them to start a sleep recording which required them to connect the device and start an analysis. After finishing, they will also see mocked results showing on the sleep report page. We also told them to explore any of the other pages. For the study, a functional device was placed next to the user, ready to be connected. We did not ask them to wear it. As another student is currently working on a thesis for evaluating the tracking features, we do not cover them in our evaluation and exclude them from the app. While users perform these different interactions, we take a transcript and encourage them to emphasize what they are doing continuously. If a participant stops talking for a while, we ask them to keep talking. The study wraps up with the participant filling out a form about demographics (age and gender) and signing a document which asks for their consent for us to use their data. Due to the low number of participants we decided to not collect quantitative data.

6.2.2 Results

Six subjects were female and two male. The mean age was 30 years. The following paragraphs summarize the findings for different aspects of our app that we could draw from the transcripts. Additionally, we aggregated general feedback that we got for the overall interface. Comments that we got that go beyond usability errors (e.g., individual responses to sleep questionnaires) have not been included in this summary.

On-Boarding Process Participants all were able to complete the onboarding process without hurdles. When entering their details, three users were unsure if they should enter their full name, first name, or a pseudonym. Additionally, three participants entered a password which was not full-filling the requirements (more than eight characters). We should add this information visually and not show it only after entering a wrong password.

Device Management All participants succeeded in connecting the device. One participant said it was not visually apparent that the device in the top corner is an interactive button immediately. Another user reported dissatisfaction with the cryptic unique device identifier (UUID) that he could not directly get a connection with why it would be his device. Instead, he would expect the product name of the device and maybe a number. Four participants were confused by the small blue icon, which indicates the established connection of the device over Bluetooth. One user expressed he would rather have a green icon show the connect state.

Sleep Analysis Results All participants explored the entire sleep report page. They expressed to find information about their sleep interesting. Three participants mentioned that they have trouble understanding the spider chart and think that the text on the axis of the charts should be more prominent. Five participants were interested in the question mark buttons which helped them to understand the topic of data they were looking at however they all expressed that they would like to learn more than what we provided about the different sleep parameter. In particular, this includes concrete examples of what a deviating parameter means for their health and also adding detailed explanations for specific parameters and abbreviations. Three participants mentioned finding the four weeks trend engaging. However, two participants said that they would wish to have an option where they can view multiple data points over time instead of just average and if the trend is going up or down.

Questionnaires Participants missed a feeling of success after completing a questionnaire. Two seemed to expect additional information about what they can learn about their sleep quality based on what they entered, and two also expected a better feeling of success, such as gamified elements. One participant also figured that he could not go back to change the reply to a question, and we, therefore, should add this option.

Profile The profile page shows the weight and height as well as gender and age of the user based on default values. Five participants expressed that they would prefer to set these parameters during the registration process instead of having to go to the profile page. Additionally, four participants said that they think the standard parameters which we set for weight and height should be higher, e.g., at the average of the population (the app shows the lowest possible value).

General User Interface Aspects In general, the user interface elements were described to be visually appealing by four users and also complimented to be modern looking by two. However, one of the older participants wished to change the font size for the entire app because he thought it is too small. As we are using the font sizing by name resolution of the mobile operating system, the problem resolves after configuring the device correctly. To improve usability, we could still integrate a separate configuration step in the onboarding process of the app. Going through the transcript, we can not conclude that participants ever expressed to be stuck while browsing throughout the app and that they had a continuous flow of interaction.

6.2.3 Discussion and Limitations

We did evaluate our software by investigating how users navigate throughout the app. Our findings suggest that in general, they understand where to find the information for which they are looking. Even though we do provide information about the different sleep parameters, we will have to provide more information on how to interpret them and what they mean for sleep quality. Furthermore, users would also like to have aggregated insights about their sleep for longer times in more detail. Finally, we also have to make sure that users feel like they achieved something when sharing personal information, such as in the questionnaires of our app. The app design is visually appealing for our participants, and they seem to understand the purpose of all functionalities. For the future, we should think about ways that make some interactions more visible such as changing the apnea chart to display the hypopnea events after tapping on them which none of our users did discover.

The majority of users is from a younger generation. They are likely to be more tech-savvy than the older persons which we imagine to be predominantly using our app. Additionally, we can not reveal findings related to interacting with the device or long-term usage usability errors.

6.3 Head-Worn Respiration Sensing

As we can learn from the previous evaluations, a major problem with our current sleep tracking device is the respiration sensor which hooks onto the nose. We, therefore, performed an evaluation with a head-worn respiration sensing device based on IMU data. There is previous work on this topic using, e.g., Google smart glasses [38] for tracking respiration rates on the head. However, as we had access to the eSense earable platform (Figure 6.1), which provides 6-axis inertial measurement data over Bluetooth measured in the ear, we decided to conclude on our own. We implemented a novel processing pipeline to understand how good the results are which we can achieve. We have already published this work at a conference before the finalization of this thesis. We suggest that readers should refer to the paper [79] to learn more about the working principle as the co-authors also supported it. We only showcase the relevant results which we were able to achieve with our implementation and not the parts of the actual processing pipeline. The following paragraphs have been published accordingly.

6.3.1 Participants and Design

To evaluate our system, we recruited twelve participants (two female, ten male) between the ages of 21 and 39 (mean age 26) for a lab study. The mean height was 179 cm and weight 81 kg. We did not pay participants. Our experiment was conducted in a room with a couch to lie on and a chair with armrests to sit down. We placed both *eSense* earbuds [48] into the participant's ears (left earbud equipped with the IMU) and hooked them up to nasal cannulas as ground truth. We did not play any audio during the study.

During the first phase of our evaluation, each participant was asked to breathe normally for one minute each in three different postures (standing, sitting, and lying) while otherwise keeping as still as possible. This step was followed by a

Figure 6.1: The left picture shows a participant wearing nasal cannulas (red, left circle) and the eSense headphones (blue, right circle). The right picture also shows a close-up of the eSense earable platform [48].

second phase, in which we then asked them to perform a short 30-second jumping jacks session before each of the three postures, which we anticipated to result in a more dynamic dataset. After performing the activity, we again recorded respiration data for one minute for every posture.

We used the Williams design generalized Latin squares [107] to balance for first-order carryover effects introduced by a potentially unnatural breathing behavior when asked to breathe on the spot. For the three different postures, this resulted in six different sequences, which we assigned to participants in a round-robin fashion according to their arrival time. The sequence for the first and second phase of the evaluation was identical within each session. After completing these tasks, participants were asked to fill in a short questionnaire, which included demographic questions (sex, age, weight, height) as well as a question inquiring whether participants felt that they had breathed naturally and space for free-text feedback.

The respiration ground truth was collected using a custom made monitoring device: We wired a *RedBear BLE Nano v2* to a pressure transducer that connects to nasal cannulas (see Figure 6.1). The device samples pressure data at a frequency of 50 Hz. We filter the signal with the same data processing pipeline as described in [79]. It also connects to our mobile application, which we installed on an *Apple iPhone X* for our study. Similarly to the acceleration and gyroscope data, we use the arrival time of the Bluetooth packages on the phone as timestamps, which makes it easy to synchronize the data afterward. We also attached the device on the user as displayed in Figure 6.1.

Sensor	**MAE**	**SD**	**RMSE**
Accelerometer	2.62	2.74	3.79
Gyroscope	2.55	2.63	3.67

Sensor	**Standing**	**Sitting**	**Supine**
Accelerometer	3.15 / 2.74	3.10 / 2.80	2.56 / 2.19
Gyroscope	2.45 / 2.22	2.74 / 2.64	2.68 / 2.00

Table 6.1: First table shows the respiration rate performance in cycles-per-minute (CPM). The second table shows modalities and postures (MAE / SD) in CPM.

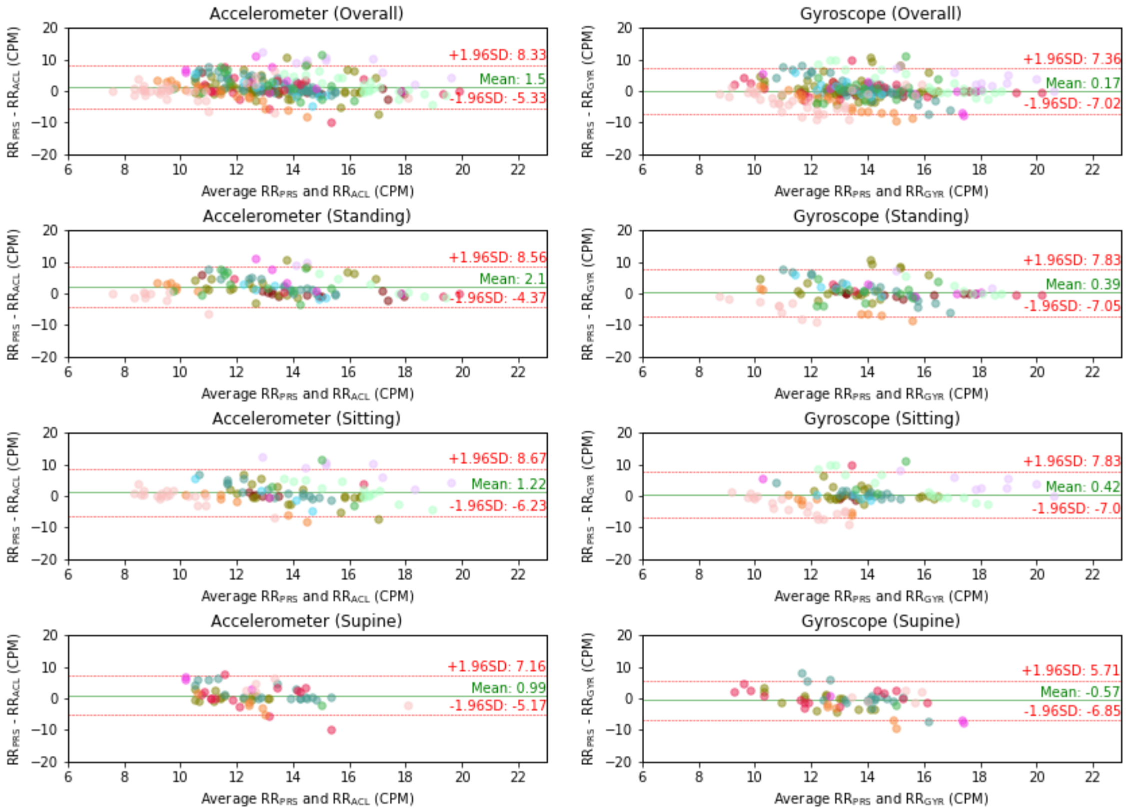


Figure 6.2: The graphs above show Bland-Altman plots for the accelerometer (left) and gyroscope (right) with an aggregated graph for the overall performance and for standing, sitting and lying on the back. Per-user results have different colors.

6.3.2 Results

In total, we collected 72 minutes of breathing data. We shift a sliding window at an interval of 5 seconds over every one-minute data frame. This process yields 669 twenty-second breathing sequences. After removing the ones with too many movement artifacts, 253 remain. Ground truth respiration rates range from 7.6 to 22 in cycles-per-minute (CPM) for those sequences. To evaluate the agreement between our approach and the ground truth measurement, we utilize Bland-Altman plots shown in Figure 6.2. In most settings, the observed differences are centered around zero and show no significant bias, also observable from the displayed mean error. The plots also show the limits of agreement (interval between +1.96SD and -1.96SD) that contain 95% of the measured differences. Additionally, we have computed several metrics for ease of comparison, namely the mean absolute error, its standard deviation, and the root mean squared error shown in Table 6.1 and also broke it down by body posture. Overall, the performance of gyroscope is similar to the accelerometer but varies between postures. We achieve the best results for the accelerometer in the supine position, followed by similar results for sitting and standing. For gyroscope, we achieve comparable results for all three postures.

6.3.3 Discussion

Generally, we can observe that our method is highly sensitive to motion artifacts. The first row in Figure 6.3 shows that we achieve better results after setting the

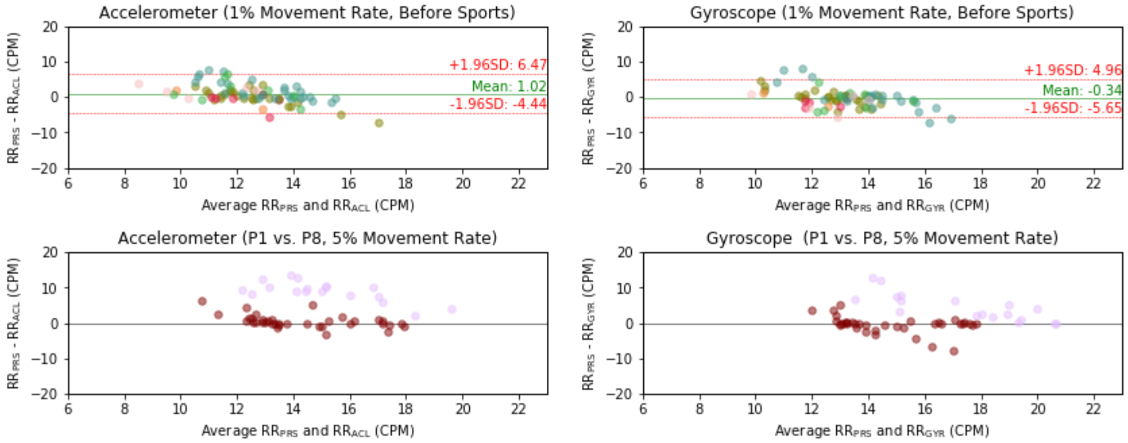


Figure 6.3: The two diagrams in the first row above indicate how strictly discarding segments with movement artifacts and limiting data to restful users increases the accuracy. The diagrams in the second row compare the data of two participants, whereas P1 achieves a much lower mean error than P8 even at a higher movement threshold of 5%. Per-user results indicated in different colors.

motion threshold to 1% and limiting the dataset to non-aroused participants. Introducing this limitation reduces the MAE to 2.09 CPM for the accelerometer and to 1.90 CPM for the gyroscope. Additionally, we see significant differences between subjects. For example, the second row in Figure 6.3 shows that even after raising the motion threshold to 5% participant P1 has much better results than P8 (MAE 1.21 ACC / 1.45 GYR vs. MAE 8.97 ACC / 4.58 GYR). We do not know what causes these differences; however, bad fitting of the earplugs or differences in pose and anatomy could be a reason.

6.3.4 Limitations

For our evaluation, we measured nasal respiration using a pressure transducer. After performing the physiologically straining task of jumping jacks, several participants reported the urge to breathe through the mouth afterward. We did not limit them to nose breathing before the study, but several participants reported that they "felt forced to not breathe through the mouth" (P2). An FDA-cleared chest belt based on respiratory inductance plethysmography is a more suitable methodology, which could support a more natural breathing behavior and therefore positively affect results. To identify relationships between the fit of the earplugs and respiration rate estimation accuracy, we suggest measuring ear sizes and film participants in future studies. Furthermore, our experimental environment left things to explore visually (e.g., posters), which could result in additional motion artifacts.

7. Conclusion and Future Work

We want to wrap up this thesis by summarizing our work. We also provide the conclusions we take from our investigations and showcase what is left to explore and validate for future work.

7.1 Summary

As we figured that sleep labs are struggling with a complex and uncomfortable process, we challenged ourselves to integrate the majority of sensors used during polysomnography into a single device and an accompanying app. We wanted to understand what characterizes human sleep and which disorders there are. We also planned to understand how the current diagnostic process resembles and which alternatives exist. Additionally, we had to find out the relevant user groups and their preferences. Based on the findings we get from those questions, we planned to present an example solution. Finally, an evaluation should reveal feedback which users have about this system.

For answering all these questions, we apply different techniques from literature review to user interviews and studies. We use prototyping tools such as 3D-printing and sketching for developing new hardware and user interfaces.

We introduced the fundamentals of sleep with the different sleep stages wake, non-REM, and REM. Furthermore, we introduced the sleep-regulating processes with the two-process model and also the model of reciprocal interaction which creates pressure to sleep and cause the user to wake up. We also covered various purposes of human sleep which include recovery, saving energy, strengthening the immune system, and performing memory consolidation. Then we presented the different categories of sleep disorders defined by medical experts. We stressed symptoms, therapy, and epidemiology. The diseases include insomnia, sleep-related respiration disorders (obstructive and central sleep apnea), hypersomnia, circadian sleep-wake disturbances, and parasomnias. Additionally, we presented sleep-related locomotory disorders such as restless leg syndrome as well as less severe sleep disorders such as sleep talking. We also introduced previous works which include a respiration sensor we developed and a systematic comparison of sleep tracking products which revealed the lack of a fully integrated solution for at-home sleep sensing. Next up, we looked into how sleep labs measure and assess sleep quality today. We covered the diagnostic process where we identified a set of standardized questionnaires. They include sleep diaries, the Pittsburgh sleep quality index, and the Landecker inventory for Sleep disorders as standard tools for every patient. Additionally, we described the personality traits of the sleep-deprived questionnaire, the sleep-related cognition questionnaire, and the insomnia severity index, which physicians can use for diagnosing insomnia and also tracking therapy progress. Finally, we also stressed the STOP-BANG questionnaire for sleep apnea and the International RLS Study Group Rating for diagnosing restless legs syndrome. Then we introduced polysomnography as state-of-the-art for measuring patients in sleep labs. We showcased how PSG is administered with patient monitoring throughout the night and also biological calibration of the sensors. To understand what is measured, we gave an introduction in the sensors electroencephalography for brain activity, electrooculography for eye movement, electromyography for muscle activity, and electrocardiogram for cardiac events. Pulse oximetry enables recording of blood oxygen saturation. For respiration sensing, we introduced oronasal tubes as well as belts for respiratory effort on thorax and abdomen. For snoring, sleep labs leverage a microphone. An inertial measurement unit with 9-axis is applied to capture the sleep position of the patients. By presenting the different sampling rates and recommended filter frequencies, we also showcased how all the sensor are working. To help with summarizing which parameters we can derive from sleep and PSG, we also presented the different parameters of sleep staging, respiration, cardiac cycle, and movement. We stressed various alternatives to state-of-the-art PSG for sleep staging, breathing, heart rate, blood oxygen, and sleep position. They use vision, depth, accelerometer data, and other sensor inputs. We performed a PESTLE analysis where we interviewed five experts to get an understanding of the current political, economic, social, technological, legal as well as environmental situation of sleep tracking. This revealed many challenges such as regulatory hurdles. Finally, we did a SWOT analysis (strengths, weaknesses, opportunities, threats) to understand how feasible a sleep tracking device would be on the market.

The next big part of our work looked into different design considerations we had to make for our implementation. To understand the user, we did online research, where we collected facts about users from various sources. We got insights into the current adoption of sleep technology and learned that many sleep problems are related to psychological root causes. Users are willing to share their data to improve health. Online stores and health care professionals are most critical for a purchase decision of sleep technology. For a device, comfort, reliability, usability, and location are among the essential factors for a wearable. Furthermore, we conducted interviews with seven users from different age groups. From this investigation, we learned that many of the users we talked to know why they sleep bad and know little about the trackable parameters. However, they are very interested in understanding their sleep and learn more about influencing factors are. We also learned that when sharing data, users would like to keep control of who gets to see their data. Finally, ensuring safety and also, e.g., turning off the device's Bluetooth signals during sleep is beneficial for the user experience and comfort. Based on all the insights we got from our research, we defined five personas who are typical representatives of the sleep technology user group. We also looked at aspects related to the user journey that shows how the user would interact with a sleep tracking system. As we still had questions remaining for how to implement the sleep tracking device, we compared four different implementations (two different straps, a cap, and an eye mask). Based on our findings, we learned that users would prefer a strap entirely made from fabric. We also found out that the desire to improve sleep seems to relate to the willingness of wearing a sleep tracking device. Finally, we were also interested in learning what kind of attachment for a respiration sensor would work best for our users. From a visual perception point of view, users preferred a strap that wraps around the nose. Also, a clip that goes inside the nose seems to be visually acceptable. We studied those findings further in the evaluation part of the thesis.

Then we implemented a system which is supposed to aggregate the majority of all the findings we got earlier. We developed two hardware prototypes which integrate different sensors. The initial prototype had a respiration sensor and inertial measurement unit for movement tracking. The device was attached to the user using adhesive medical tape. The second version of the hardware expands upon the first one by adding pulse oximetry capabilities, electroencephalography, and electrooculography as well as a vibration actuator. The device is a kind of strap which wraps around the user's head, making it easier to apply. With the sensors, we could measure sleep stages, sleep position and agitation, sleep apnea, and other respiratory events. Furthermore, we get insights into the cardiovascular system and the room climate. The learnings we got from both prototypes are about comfort and also attachment. We identified issues with the interaction, e.g., button in the front. We generated insights from the prototyping process, whereas we determined that self-assembling hardware is tough and sometimes impossible to debug. We also learned that connection different PCBs could be challenging as small plugs do not stay in place consistently if conditions are not ideal. To further evaluate our design, we came up with two versions of a mock-up device which straps around the user's head and unites foam, velcro, and fabric. We also implemented software to accompany the hardware device. The app that we implemented follows best practices for cross-platform apps. It connects to our device over Bluetooth low energy and to our server backend using REST. To design our app, we apply a mood board which conveys looks and feel. Based on that, we created a set of interface guidelines that we implemented as shared code elements. We reused these components throughout our implementation and achieved a total of 26 pages. This collection of pages includes a registration and login process, help pages to introduce the user, handling of the device connection process, and also running analysis with real-time data visualization. We have also implemented user interfaces for displaying the sleep quality measures of the users and even a page for tracking daily activities. Besides that, we added the logic for conducting questionnaires with an extensible set of questions. Finally, we realized pages for managing developer settings and also settings which can be configured by the user. We show the flow that the user goes through highlighting that the majority of all pages can be reached with not more than two or three taps. For our backend, we implemented two services - one for the authentication and user data as well as one for handling all the datasets created by the device. We also presented our database schema, which is easily extendable and provides the opportunity for adding more sensor in the future. The firmware we implemented is carefully designed to ensure no issues with unintended device states and also handles storing, compression, and encryption of data.

Our work finalizes with the evaluation which we performed. We tested the mock-up devices with twelve users for two nights in different versions. We revealed additional findings regarding little details about comfort (e.g., scratching velcro) and attachment (e.g., loose fitting), which could further improve our prototype. By applying think-aloud studies for the app, we also got insights into usability. We recruited eight participants. We were able to show that our app is easy to understand; however, users wish for more interactivity for the different elements. Additionally, we revealed small issues mostly related to visual cues which could further smoothen the flow of the users as they utilize our app. Finally, we also evaluated if a head-worn inertial measurement unit could provide an alternative for tracking respiration rates. We showed that it works well for some participants however we had questions remaining for differences between subjects.

7.2 Conclusion

Now that we have summarized the contributions of this thesis, we would like to give conclusions that users should take from our work. Additionally, the grey boxes spread throughout the different chapters already gave outcomes for many aspects we identified.

Sleep is a complex process which fulfills crucial functions for humans. It is challenging to understand the whole set of sleep disorders, and many similarities across the clinical pictures make differential diagnosis a hard task. Finding the right therapy is a tight interplay between physicians and the patient and includes various disciplines such as sleep experts, psychology, and event dentists. However, we can support some of those aspects with software solutions, e.g., identifying behavioral connections to sleep. Additionally, measuring at home will enable patients to continuously monitor their sleep instead of spending just one or two nights at the sleeping lab. Our findings provide insights that will help to shape such an enabling platform and we even propose an example implementation for such a device.

Measuring and assessing sleep quality is also challenging because of the technical complexity with a broad set of different sensors used and high sampling rates which create additional obstacles on constrained embedded hardware devices (e.g., lack of enough storage). The current process of polysomnography is very uncomfortable, and therefore the majority of alternatives focus on improving comfort. However, the regulated medical market makes it hard to establish any other options. That's why our approach focused on using methods related or closely related to the set standards directly measuring on the user, which is likely to be accepted more quickly by a medical community. However, we will have to heavily rely on algorithmic approaches such as machine learning to track the entire set of parameters covered by sleep labs with a constrained device.

The device we developed succeeds in integrating the majority of all sensors of a sleeping lab. We strongly believe that it can support tracking sleep throughout several nights to learn about the user's sleep quality. Due to its integrated form factor, it will be easily attachable by users, and the improved comfort ensures they are less disturbed during sleep analysis.

7.3 Future Work

Our work has shown that it is possible to integrate the majority of all sensors used in sleep labs into a single package for providing sleep tracking. However, there are several things left to investigate in future work. More formative studies will shape the solution, and a summative study will have to assess if a fully-integrated sleep tracking solution meets the goals and requirements of sleep experts.

To further understand how accurate the sensors which we integrated in our prototype can measure the different parameters of polysomnography we will have to perform comparison studies including lab studies, clinical trials and also in-situ studies at the home of the user. We will have to combine the insights we generated from a usability perspective and a technical viewpoint into a single solution. By continuously taking user feedback into account, we will be able to come up with a solution that fulfills requirements for usability and accuracy. Long-term studies with the users will reveal additional problems which we might not even think of yet.

For the app, we will have to look into further supporting the user with aspects that they would like to learn about their sleep. We would also expand by aggregating the questionnaires we collected from sleep science into a single flow that the user could go through. This process, however, would require intensive support by sleep experts. Additionally, we will have to integrate the tracking functionality of daily behavior to have a unified user experience within the app.

Future work will have to investigate how we might be able to measure respiratory effort and also accurate measurements of electromyography, e.g., for chin and leg movement. By coming up with novel sensors or approaches based on the existing sensors within the device, we might be able to get hold of all parameters step by step. We should also think about how we might include head-worn respiration sensing similar to what we presented in the evaluation chapter of this thesis which could get rid of the uncomfortable nose attachment.

We are particularly interested in investigating how users behavior influences sleep. Therefore, we suggest to record a large number of datasets for looking into the correlations between quality of sleep and actions performed during the day. We believe that this could reveal a whole new set of influencing factors on an individual level. Ultimately, we are convinced that the combination of tracking daily behaviors and sleep quality might even reveal new therapeutic approaches for patients that could not find solutions for their sleep problems for days, months, or even year.

A. Appendix

A.1 Personas

A.1.1 Karlo - Struggeling With Health

<table>
<tr><td>
Karlo Krank</td><td rowspan="3">Health: 0% 100%
Money: 0% 100%
Tech Affinity: 0% 100%
Tech Trust: 0% 100%
Sleep Disturbance: 0% 100%
Tiredness: 0% 100%</td></tr>
<tr></tr>
<tr></tr>
<tr><td>Age: 45
Location: Stuttgart</td><td rowspan="2">Personality
- process correctness and conservative
- thinks that when you are sick you should probably see a doctor
- insurance should cover all health related issues
- should use CPAP; thinks it is unsexy and does not want to wear anything
- thinks that a sleeping lab is the place to be when you want a diagnosis

Objectives
- wants to stay healthy but doesn't put effort into it
- "pretends" to improve his health ("This year I will start to work out".)

Needs
- wakefulness, stability and time
- no painful feeling when waking up after a bad night

Motivations
- solve his serious sleep condition
- appear attractive to others (e.g., his girlfriend)</td></tr>
<tr><td>Job Title: shift worker (lead) at automotive company

two children, divorced, not single

serious sleep illness (apnea, insomnia). His job makes the situation worse because he sometimes has to attend night shifts to check stuff with workers.</td></tr>
<tr><td colspan="2">"Status and authority are the results of hard work."</td></tr>
</table>

A.1.2 Sarah - Cares About Loved Ones

Sarah Sorge

Health: 0% 100%
Money: 0% 100%
Tech Affinity: 0% 100%
Tech Trust: 0% 100%
Sleep Disturbance: 0% 100%
Tiredness: 0% 100%

Age: 28
Location: Munich

Job Title: software engineer @ tech company

Half-time career and half-time mum.

Loves to do sport, cooking freshly and healthy and trying to be a role model. Believes in prevention and caution.

Married and one new born baby.

Personality
- tries to optimize her lifestyle and loves to do sport
- family is really important and wants to have a happy family
- loves to help and support and is very curious
- tries to out new trends and technology that is simplifying life
- good connection to her parents

Objectives
- wants to help her father who is in a bad mood because he sleeps bad
- wants to give something back to her parents because they supported her
- wants to stay updated and have a family that is up to date as well

Needs
- regular contact to her parents
- help her parents being happy
- have a healthy grandpa for her son

Motivations
- keep up to date with latest technology
- make her parents happy and not annoying

"If you'll never try you'll never know" "always ask yourself what a hero would do"

A.1.3 Maria - Always Feels Tired

Maria Müde

Health: 0% 100%
Money: 0% 100%
Tech Affinity: 0% 100%
Tech Trust: 0% 100%
Sleep Disturbance: 0% 100%
Tiredness: 0% 100%

Age: 40
Location: Karlsruhe

Job Title: works at an accelerator for energy startups

two children, married

Personality
- hates things that do not make sense or are impractical
- a bit sceptical about sharing her data (especially if employee has access)
- concerned about sleep because she heard from others struggling
- a wearable should look nice and should not cause any smell or pressure
- not too excited to enter information into an app every day

Objectives
- be more rested during the day and have time for herself to relax
- test the device for a couple of days, then buy it if it helps

Needs
- more energy during the day
- external trigger to close the deal for buying a wearable
- some decision time and proof of functionality for the device

Motivations
- tired of being tired and does not want to be an outlier
- maximize the time she can spend with her family

"I love my workplace because my colleagues are really inspiring and creative."

A.1.4 Peter - Senior Supported By His Children

Peter Pensionär

Age: 72
Location: Freiburg

Job Title: retired

Was a workaholic and now enjoys hanging out in the garden.

Tries to stay up to date with the new technology. Regularly goes to the choir. Sometimes goes hiking with friends

Two grown-up children. Three grand-children.

Health: 0% 100%
Money: 0% 100%
Tech Affinity: 0% 100%
Tech Trust: 0% 100%
Sleep Disturbance: 0% 100%
Tiredness: 0% 100%

Personality
- likes technology but would not be an early adopter
- likes to be consulted by his children and nephews in terms of technology
- has bad mood because of bad sleep
- is going for a short walk every day to stay in shape

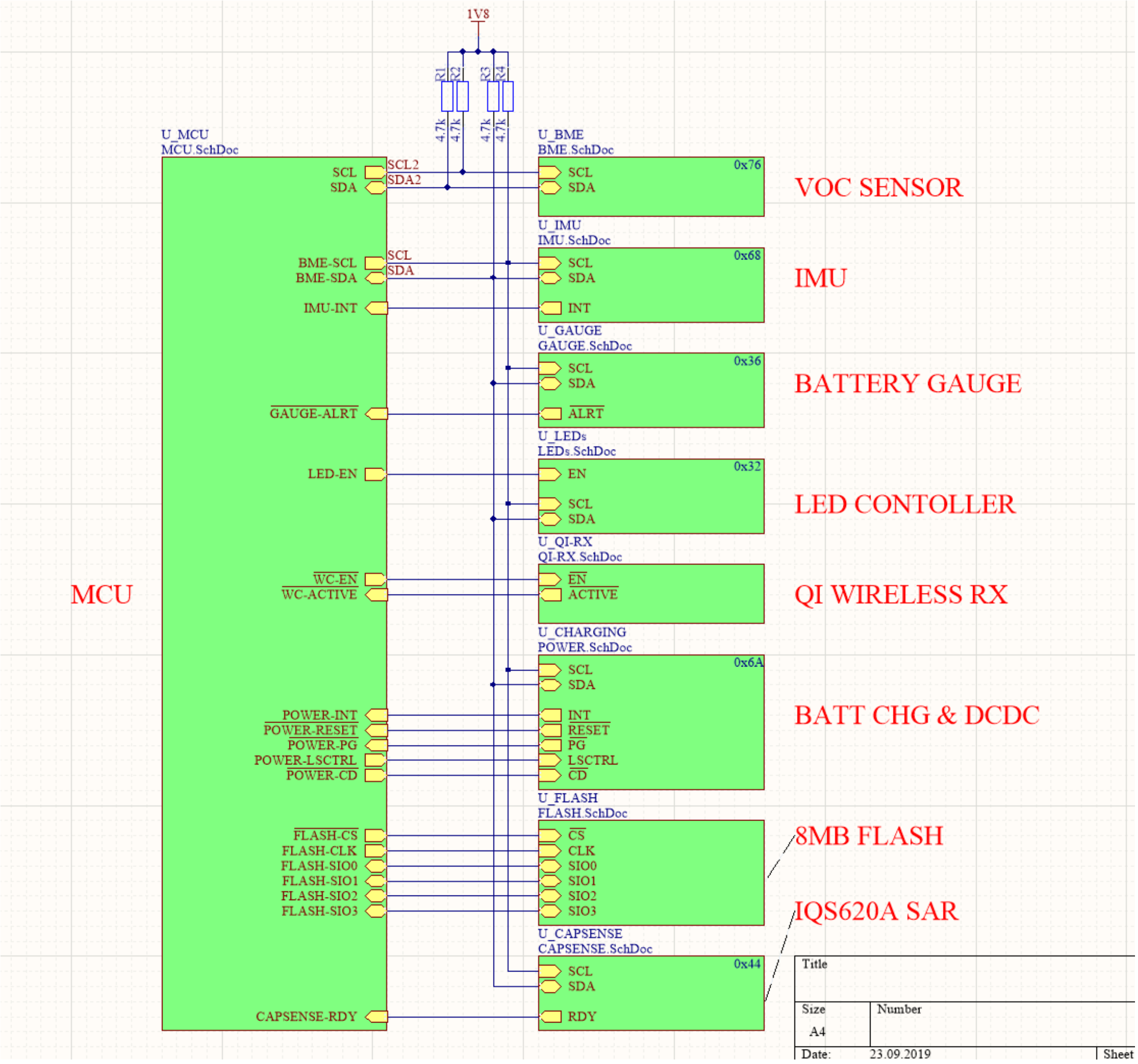
Objectives
- wants to stay updated with technology
- wants to have a relaxed life and enjoy time with his family
- wants to find reasons why he is tired sometimes

Needs
- better sleep so he feels fully energized
- get a better feeling about his health status and understand body signals
- taking care of himself

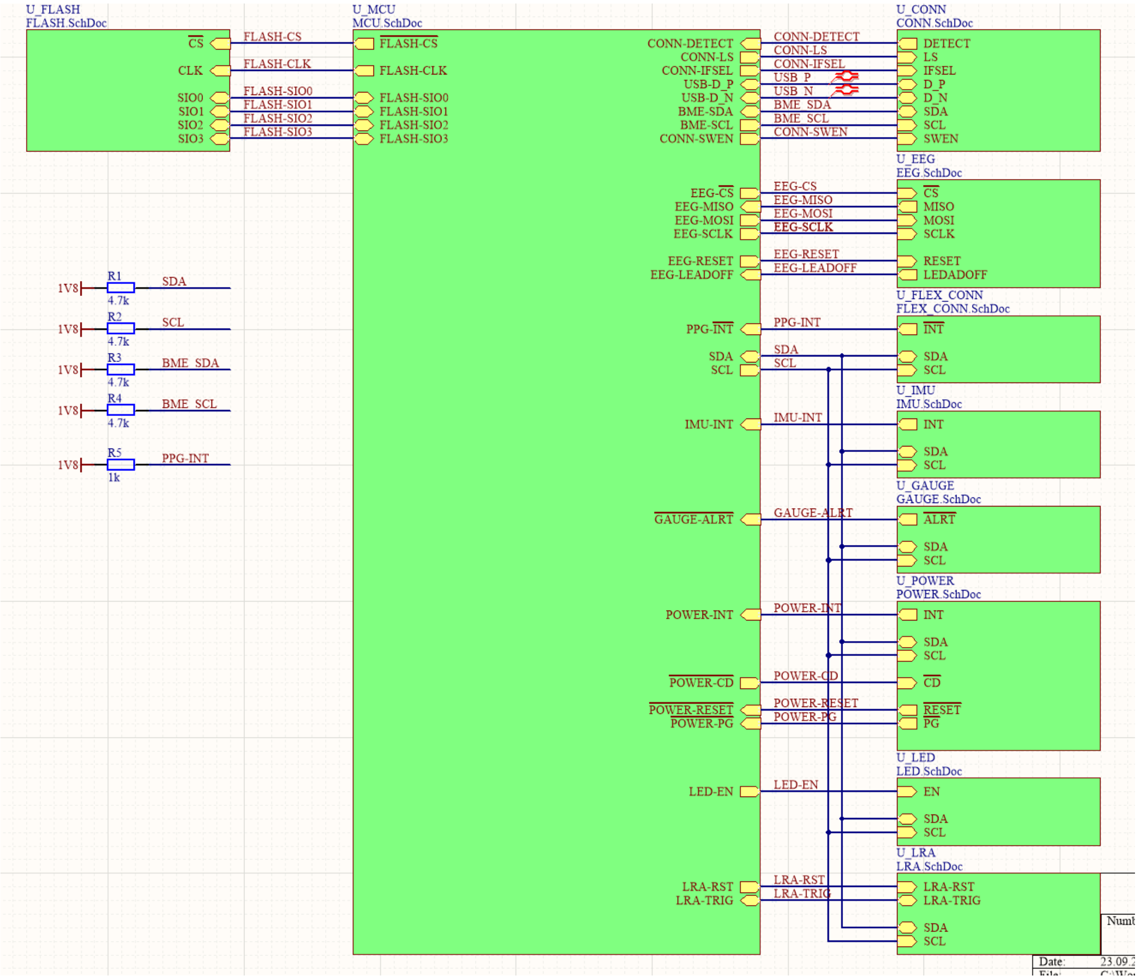
Motivations
- keep up to date with latest trends
- test new things to be not bored
- more relaxed life and stay in shape for his grandchildren

"If you want to go fast, go alone. If you go long, go with others"

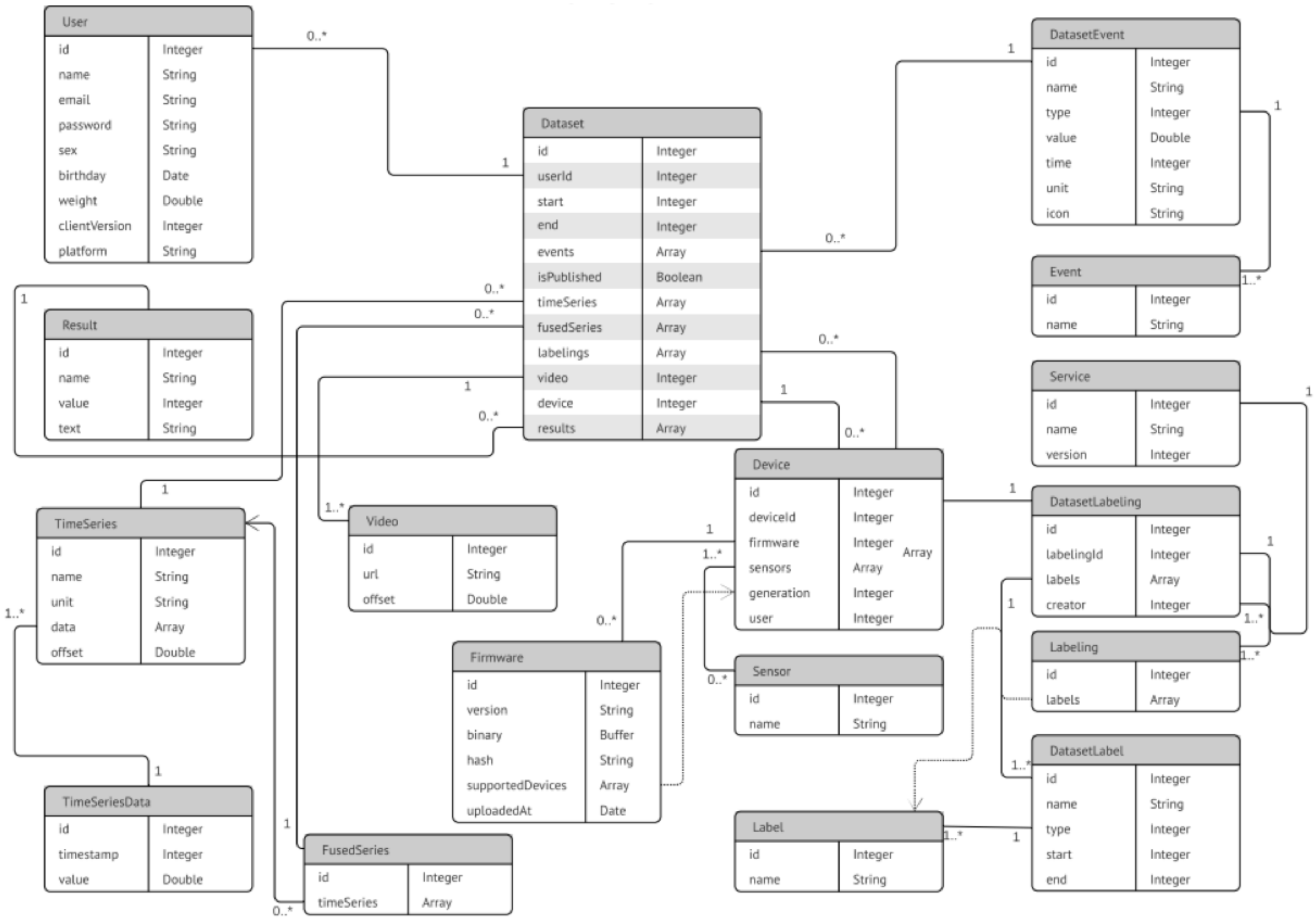
A.2 Block Diagram Functional Prototype 1



A.3 Block Diagram Functional Prototype 2



A.4 Database Schema



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