The Traumschreiber System

Enabling Crowd-based,

Machine Learning-driven,

Complex, Polysomnographic

Sleep and Dream Experiments

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Abstract

Sleep and dreaming are important research topics. Unfortunately, the methods for researching them have several shortcomings. In-laboratory polysomnographic sleep and dream research is a costly, time-consuming and effortful endeavor, often resulting in small subject counts. Moreover, the unfamiliar sleeping environment can lead to distorted measurements as compared to the natural sleep environment at the subject's home.

Conducting sleep and dream experiments in the field by a crowd of subjects could be a solution. However, complex experiment paradigms cannot be investigated this way, because there are no tools available, which enable naive subjects to carry out complex polysomnographic studies on their own.

The *Traumschreiber* system, which is developed and evaluated in this dissertation, offers a solution to this problem. It consists of a high-tech sleep mask and a minicomputer, and enables naive crowd subjects to perform complex polysomnographic sleep and dream experiments at home. On the one hand, it instructs the crowd subject, what to do when. On the other hand, it controls the experiment during the time the subject is asleep, analyzing the data in real-time using state-of-the art machine learning techniques. The rationale behind is to enable a big data approach to sleep and dream research, using the data recorded by a crowd of subjects for large-scale investigations about sleep and dreaming, with low costs for the researcher.

After describing the development process of the Traumschreiber system, its usefulness regarding crowd-based automated polysomnographic field studies is evaluated. First, it is validated against a commercial medical polysomnographic sleep laboratory system, demonstrating its good polysomnographic data recording capabilities – including measurements of EEG, EOG, EMG and ECG –, which enable the researcher to identify typical sleep patterns like slow waves or rapid eye movements as well as sleep stages in the recorded data.

Furthermore, two field studies show, that the Traumschreiber system can be used successfully by naive subjects to conduct complex sleep experiments at their homes. This includes acoustic stimulation of the sleeping subject as well as sleep stage dependent activities of the system. The sleep staging algorithm implements a Keras/Tensorflow based neural network approach, which demonstrates the system's readiness for state-of-the-art machine learning techniques. However, the currently used neural network is kept very simple and can determine the sleep stage not very reliably; it should be further developed and trained on more data of more subjects.

The Traumschreiber system will be made available under an open source license, enabling any researcher to use, modify or further develop it. A description, how to produce arbitrarily many entities of the Traumschreiber system, is given in this dissertation and shows that one system can be produced at low costs in a short amount of time.

Taken together, the Traumschreiber system is a new tool for sleep and dream research, which enables a crowd-based and machine learning-driven approach to gathering polysomnographic data from complex sleep and dream experiments.

Deutsche Zusammenfassung

Schlaf und Träume sind wichtige Forschungsthemen. Leider sind die Methoden, mit denen diese Phänomene wissenschaftlich untersucht werden, mit zahlreichen Nachteilen verbunden. Polysomnografische Studien im Schlaflabor sind ein teures, zeitintensives Unterfangen, was sich oft in einer geringen Probandenzahl widerspiegelt. Zudem kann die für die Versuchspersonen ungewohnte Schlafumgebung die Messungen negativ beeinflussen. Eine Lösung könnte es sein, die Schlaf- und Traumexperimente von einer großen Menge an Probanden selbstständig zu Hause durchführen zu lassen. Jedoch können komplexe Fragestellungen auf diese Weise nicht untersucht werden, weil es keine technischen Mittel gibt, die ungeübte Versuchspersonen dazu befähigen, komplizierte polysomnografische Experimente eigenständig zu Hause durchzuführen.

Das Traumschreiber-System, das in dieser Dissertation entwickelt und getestet wird, bietet für dieses Problem eine Lösung. Es besteht aus einer Hightech-Schlafmaske und einem Minicomputer, und ermöglicht es ungeübten Probanden, eigenständig komplexe polysomnografische Schlaf- und Traumexperimente zu Hause durchzuführen. Zum einen instruiert es die Versuchsperson, welche Schritte wann zu erledigen sind. Zum anderen steuert es das Experiment, wenn die Versuchsperson schläft, und analysiert dazu in Echtzeit die aufgenommenen Daten mithilfe von modernen Machine Learning-Algorithmen. Die zugrunde liegende Idee ist, einen Big Data-Ansatz für Schlaf- und Traumforschungszwecke zu ermöglichen, in dem polysomnografische Daten sehr vieler Probanden günstig erhoben und ausgewertet werden können.

Nach Darstellung des Entwicklungsprozesses wird das Traumschreiber-System in dieser Dissertation eingehend bezüglich seiner Eignung für massenhafte, automatisierte polysomnografische Feldstudien getestet. Zunächst wird es dazu mit einem professionellen polysomnografischen Schlaflaborsystem verglichen. Das Ergebnis ist, dass schlaf- und traumtypische physiologische Muster im EEG, EOG, EMG und EKG gut mit dem Traumschreiber-System gemessen werden können.

Zwei weitere Feldstudien zeigen, dass das Traumschreiber-System erfolgreich von ungeübten Probanden genutzt werden kann, um komplexe polysomnografische Experimente eigenständig zu Hause durchzuführen. Dies beinhaltet beispielsweise eine akustische Stimulierung des Schlafes und Schlafstadien-abhängige Aktivitäten des Traumschreiber-Systems. Der eingebaute Algorithmus zur Erkennung von Schlafstadien nutzt ein in Keras/Tensorflow implementiertes künstliches neuronales Netz, welches jedoch nur als Platzhalter zu betrachten ist und mit mehr Daten weiter optimiert werden muss, um zuverlässig Schlafstadien erkennen zu können.

Das Traumschreiber-System wird unter einer open source-Lizenz veröffentlicht und ermöglicht somit jedem interessierten Wissenschaftler, es zu nutzen und an eigene Bedürfnisse anzupassen. Teil dieser Dissertation ist eine Beschreibung des Produktionsprozesses und eine Zeit- und Kostenabschätzung, die zeigen, dass das Traumschreiber-System günstig und schnell hergestellt werden kann.

Zusammengefasst ist das hier vorgestellte Traumschreiber-System ein neues Werkzeug für die Schlaf- und Traumforschung, das massenhaft parallelisierte und zugleich komplexe, Machine Learning-basierte polysomnografische Experimente möglich macht.

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Abbreviations

AI	Artificial Intelligence
ADC	Analog-to-Digital Converter
BLE	Bluetooth Low Energy
CSV	Comma-Separated Values
ECG	Electrocardiography
ECTS	European Credit Transfer System
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
EUR	Euro
FoR	Feeling of Recovery
FFT	Fast Fourier Transform
GUI	Graphical User Interface
HEOG	Horizontal Electrooculography
IC	Integrated Circuit
ICSD-3	International Classification of Sleep Disorders – Third Edition
InAmp	Instrumentation Amplifier
JSON	JavaScript Object Notation
LED	Light-Emitting Diode
N1	Sleep Stage N1
N2	Sleep Stage N2
N3	Sleep Stage N3
NDR	Norddeutscher Rundfunk
OpAmp	Operational Amplifier
PCB	Printed Circuit Board
Ph.D.	Doctor of Philosophy
POSIX	Portable Operating System Interface
RAM	Random-access Memory
REM	Rapid Eye Movement Sleep
SF-A	Schlaffragebogen A (Sleep Questionnaire A)
SQ	Sleep Quality
SWS	Slow Wave Sleep
UART	Universal Asynchronous Receiver Transmitter
UDP	User Datagram Protocol
USB	Universal Serial Bus
USD	US Dollar
VEOG	Vertical Electrooculography
XML	Extensible Markup Language

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Preface – Reflecting on my scientific activities

The highest academic degree, the Ph.D., is awarded for scientific achievements and proves that the holder of the degree is able to conduct elaborated scientific works on his or her own[1]. Before starting with the actual dissertation, I would like to briefly reflect on my scientific activities during the past four years.

It all started by following a personal interest of mine – lucid dreaming. I started researching it in my leisure time using a low-budget one-channel sleep EEG device. One year later, I created a student initiative about sleep and dreaming at my university in 2012. I motivated fellow students to conduct our own research in the field of sleep and dreaming using portable high-tech sleep devices, applied for funding from the general students' committee, and organized regular meetings. Subsequently, I wrote my master's thesis about how it is possible to communicate with (sleeping!) lucid dreamers in real-time.

Fortunately, Prof. Dr. Pipa offered me the possibility to extend my research during a Ph.D.. I organized two university rooms and raised a large equipment donation of a medical device manufacturer, enabling me to conduct research in my own fully-equipped sleep laboratory. I went to the Max Planck Institute of Psychiatry in Munich as a visiting researcher, where I took part in a research project on lucid dreaming using a high-density 128 channel EEG, and learned, how to conduct professional sleep and dream research. This knowledge I then transferred to my sleep laboratory in Osnabrueck, and passed it on to fellow students of the student initiative, as well as during seminars I taught. Besides conducting research, life in academia also includes teaching. I offered courses worth 40 ECTS points in total; sometimes more than 100 students participated in my seminars. I supervised 19 bachelor's and master's theses and a one-year study project of ten master students.

The before mentioned student initiative grew steadily and became the largest young scientists sleep and dream research group in Germany, if not worldwide. We conducted workshops and experiments in the sleep laboratory and went on three scientific excursions, e. g. one week in spring 2016 to sleep researchers in Finland. More details about the student initiative can be found in the article "Kurzvorstellung der Studentischen

1 Osnabrueck University Ph.D. regulations "Promotionsordnung des Fachbereichs Humanwissenschaften der Universität Osnabrueck für die Verleihung des Grades Ph.D. in Cognitive Science" (2011), § 1.

Initiative Sleep & Dream Osnabrueck”, published in the journal “Somnologie” (Appel, 2017, see appendix).

There were several research projects of mine, which I conducted during the last years. I validated the sleep communication from my master’s thesis using polysomnographic recordings in my sleep laboratory at Osnabrueck university with experiment subjects from all over Germany. I recorded and analyzed lucid dreams with a high-density EEG at the Max Planck Institute Institute of Psychiatry in Munich. I conducted an online study about the success rate of a lucid dream induction technique, for which I used a self-developed website as a platform. I analyzed a dietary supplement regarding its effect on sleep and dreaming. I carried out a sleep laboratory study investigating the role, which sleep plays for memory processes. I conducted another questionnaire study about the public perception of lucid dreams. I successfully replicated the results of a recent study about a new lucid dreaming induction technique in my sleep laboratory, and started a study investigating the effects of lucid dreaming smartphone apps. I wrote a review paper about lucid dreaming, and an article about the same topic for the “DGSM Kompendium Schlafmedizin” of the German Sleep Society, which is used for educating purposes of sleep laboratory staff and medical doctors. I summarized a German dissertation about event-related potentials during lucid dreams and published it in a scientific journal in order to make it available to the English speaking scientific community. In many of these projects, I instructed and supervised undergraduate students, who carried out the experiments together with me as a part of their theses. Other smaller projects are not mentioned here.

I made most of this research available to the scientific community, e. g. at scientific conferences. Some of the research is already published in scientific journals as well, with the other not yet published works to follow after finishing my Ph.D.. A list of publications and conference presentations is attached at the end of this preface. Besides publishing my research in the scientific literature, it was important to me to transfer the new knowledge to the non-scientific public as well. I presented my research twice on television (NDR), in an international pop-sci magazine (The New Scientist), was interviewed by a large German internet magazine (Netzpiloten), and by journalists from Finland to Brazil (see appendix for examples).

Finally, I carried out other scientific tasks throughout my Ph.D.. From obtaining funds for my experiments (in total nearly 10.000 EUR), to writing and defending four complete ethics proposals, to acting as a reviewer in peer-reviewed journals four times. I connected the new Osnabrueck sleep and dream research to well-known researchers from various institutes, such as the Donders Institute (Nijmegen, The Netherlands), the Central Institute of Mental Health (Mannheim), the Max Planck Institute of Psychiatry (Munich), the Charité Sleep Competence Center (Berlin), the Muenster University Hospital, and Bern University (Switzerland), and cooperated with them in common research projects.

One project was not yet named in this reflection of my scientific activities: the Traumschreiber project. It is the main project of my Ph.D., and is described in larger detail in this dissertation.

List of scientific publications and conference presentations

Appel, K., Pipa, G., & Dresler, M. (2017). Investigating consciousness in the sleep laboratory - an interdisciplinary perspective on lucid dreaming. *Interdisciplinary Science Reviews,* 1-16.

Appel, K., Pipa, G. (2017). Auditory evoked potentials in lucid dreams: a dissertation summary. *International Journal of Dream Research*, 10(1), 98-100.

Appel, K. (2017). Kurzvorstellung der Studentischen Initiative Sleep & Dream Osnabrueck. *Somnologie*, 21(3), 252-254.

Kern, S., Appel, K., Schredl, M., & Pipa, G. (2017). No effect of alpha-GPC on lucid dream induction or dream content. *Somnologie*, 21(3), 180-186.

Appel, K., Leugering, J., Pipa, G. (2016). Kommunikation mit Klarträumern in Echtzeit – aktuelle Möglichkeiten. Oral presentation at the 24rd Annual Conference of the German Sleep Society, Dresden, Germany.

Leugering, J., Appel, K. (2016). Traumschreiber: Eine Open Source Schlafmaske, die Hirnaktivitäten messen und beeinflussen kann. Oral presentation at the MetaRheinMainChaosDays of the Chaos Computer Club, Darmstadt, Germany.

Appel, K., Leugering, J., Pipa, G. (2016). “Traumschreiber”: Measuring and manipulating human sleep with a portable high-quality but low-cost polysomnographic system. Poster presentation at the 23rd Congress of the European Sleep Research Society, Bologna, Italy.

Appel, K. (2016). The Student Initiative Sleep & Dream Osnabrueck. Oral presentation at the 33rd Annual International Dream Conference, Kerkrade, Netherlands.

Appel, K., Kern, S. (2015). Phänomenologie luzider Träume und Induktionstechniken. Schulz, Geisler, Rodenbeck (Hrsg.) *DGSM Kompendium Schlafmedizin.* Ecomed Verlag, Landsberg, XVIII-3.9.1

Appel, K. (2015). The Student Initiative Sleep & Dream Osnabrueck. Oral presentation at the 23rd Annual Conference of the German Sleep Society, Mainz, Germany.

Appel, K., Pipa, G. (2015). Sleep Communication. Poster presentation at the Worldsleep Conference, Istanbul, Turkey.

Kern, S., Appel, K., Schredl, M., Pipa, G. (2015). Lucid dream induction using L-alpha glycerylphosphorylcholine. Poster presentation at the Worldsleep Conference, Istanbul, Turkey.

Appel, K., Pipa, G. (2014). Bidirectional, voluntary and conscious communication with arbitrary message content between a sleeping person and the waking world is possible. Poster presentation at the 22rd Annual Conference of the German Sleep Society, Cologne, Germany.

Appel, K., Erlacher, D., Pipa, G. (2014). Sleep Communication. Poster presentation at the Interdisciplinary College, Guenne, Germany.

1 Introduction

1.1 The basic ideas

All humans sleep on a more or less regular basis; sleep is one of the basic human needs. Moreover, everybody dreams, and even though some people have more trouble remembering their nightly hallucinatory experiences than others, dreaming is a core element of everybody's sleep (Nir & Tononi, 2010).

If sleep or dreaming are disordered, this leads to undesired effects to the individual well-being on the one hand. On the other hand, the society as a whole is affected negatively by sleep disorders: The economic damage to the German national economy due to sleep disorders, for example, accumulated to 1.027 billion EUR in the year 2015 (Federal Statistical Office Germany (Destatis), 2017).

Viewed from the perspective of a sleep scientist, since everybody sleeps and dreams, everybody is a potential subject for scientific sleep and dream studies, too. But recording many subject in a sleep laboratory is a costly, time consuming and effortful endeavor, as will be shown later in this introduction. Thus, a crowd-based approach to researching this topic seems to be an idea worth investigating. The term "crowd-based" as used in this dissertation describes the idea to use the efforts and data of masses of subjects. The aim is to "crowd-source" (as in "outsource") many of the tasks conducted by professional sleep researchers to the naive subjects, so that by far more data can be collected using this parallelized approach than is possible the standard in-laboratory way. Importantly, crowd-based sleep and dream research does not necessarily mean, that the crowd has to consist of many semi-professional sleep experts. It suffices to *somehow* enable a large group of naive subjects to conduct complex, state-of-the-art sleep and dream experiments with professional, polysomnographic methods on their own at home.

Why was this not done before? Actually, several approaches to measure sleep in larger subject populations outside the laboratory have been undertaken in the past, as will be described in greater detail later in this chapter – ranging from online questionnaire studies to dream diary studies to actigraphy studies. Without going too much into detail here already, it can be summarized that these approaches have several advantages and several disadvantages over measuring sleep in a sleep laboratory. Complex sleep and dream experiments, however, which manipulate the sleep acoustically, which rely on sleep stage-dependent paradigms or which need other ways of interaction between the subject and the experimenter, cannot be conducted by naive subjects on their own at home.

Recent technological developments could be a game changer. Everybody knows, that electric components are getting smaller, cheaper and at the same time more powerful. The knowledge, how to construct complex technical devices, is made available in open source projects on the internet, e. g. for building an electroencephalograph (EEG) in the OpenEEG project[2]. More and more powerful algorithms are developed in the field of artificial intelligence and one of its core disciplines, machine learning, as will be described later in this introduction.

Combining these developments, a system can be built now at low costs, which enables crowd subjects to conduct complex, state-of-the-art sleep and dream experiments with professional, polysomnographic methods on their own at home. Such a transportable system needs to be capable of explaining to the inexperienced crowd subject, which experiment step to do when, for example how to record the brain activity using electroencephalography (EEG). Moreover, and equally important, it needs to be capable of conducting some parts of the experiment autonomously on its own, e. g. during the time the subject is asleep. Lastly, in an ideal case, setting up scientific experiments and programming this system would be very simple and not require a lot of time or programming knowledge of the sleep scientist. As a result, with such a system, large-scale, crowd-based sleep and dream research with complex experiment paradigms are possible.

In the following theoretical part of this dissertation, the backgrounds of modern sleep and dream research will be characterized: its variety, its methodology and limitations. Afterwards, the technological progress in the field of artificial intelligence and machine learning will be briefly recapped, and it will be shown, how these technologies are used in the scientific study of sleep and dreaming already today. Ultimately, building on top of this theoretical work, a system will be developed and evaluated, which makes possible crowd-based polysomnographic sleep and dream experiments: the Traumschreiber system.

2 www.openeeg.sourceforge.net

1.2 The importance and variety of sleep and dream research

Scientific research about human sleep and dreaming is an important field with many facets, as can be seen from the following examples:

- In the field of memory consolidation, scientific sleep studies explore, how memory processes are influenced by sleep, e. g. how sleep helps to better memorize vocabulary, to consolidate freshly learned motor tasks, or to even rearrange existing memories and, thus, gain new insights into current problems. Moreover, it is researched, how these memory processes can be influenced and supported, for example using acoustic stimulation during sleep (for an overview, see Diekelmann (2014)).
- In the field of chronobiology, sleep researchers investigate, which biological processes cause sleep and wakefulness, how sleep is influenced by light exposure, by shift work, or by trans-meridian travel, how jet-lag can be reduced, and other related topics (Sack et al., 2007).
- Recurrent nightmares are just one out of around 60 sleep disorders, which the International Classification of Sleep Disorders lists (ICSD-3, American Academy of Sleep Medicine, 2014). About 5% of the population suffer from recurrent nightmares (Schredl, 2013), and a multiple of this suffer from sleep disorders in general, such as insomnia, sleep related breathing disorders, narcolepsy, or restless legs syndrom (Luyster, Strollo, Zee, & Walsh, 2012), underlining the importance of experimental human sleep research for clinical and therapeutic purposes.
- Lucid dreaming research is one of the most spectacular and fascinating subfields of sleep science – especially to laymen –, as can be seen by the occurrence of this topic in popular scientific journals and television shows (see examples for this in the appendix). Lucid dreams, in which the dreamer realizes that he or she is dreaming whilst staying asleep, offer fantastic opportunities not only for hedonistic purposes, but also as a tool used in several other academic disciplines, ranging from philosophy to sports science to psychotherapy (Appel, Pipa, & Dresler, 2017).

Depending on the exact matter of investigation and the available resources, sleep can be assessed in multiple different ways.

1.3 Assessment of sleep and dreaming in the sleep laboratory

One way to assess sleep – and connected to it, dreaming – is to record it in a scientific sleep laboratory. The standard method is to conduct polysomnographic (from Greek “polus”: many, much, Latin “somnus”: sleep, Greek “graphein”: to write) measurements of a subject’s sleep, i. e. to record multiple physiological sleep parameters: brain activity measured by electroencephalography (EEG), muscle tension at the chin measured by electromyography (EMG), and eye movements measured by electrooculography (EOG).

Recording these parameters allows for specialized data analysis, for example, a classification of discrete 30-second time intervals into the commonly used sleep stages, which helps to get an overview of the macrostructure of the sleep of a specific subject or larger populations: Besides the stage Wake, there is, on the one hand, rapid eye movement (REM) sleep, on the other hand, the non-REM sleep phases N1 (which mainly describes the transition period directly after falling asleep), N2 (“light” sleep), and N3 (“deep” sleep, also called slow-wave-sleep, SWS) (Rama & Zachariah, 2013). Standardized rules have been developed for classification purposes (Rechtschaffen & Kales, 1968; Iber, Ancoli-Israel, Chesson, & Quan, 2007), which are usually applied to the recorded data by manual (visual) scoring, or, lately, by using automatic sleep staging algorithms (Penzel et al., 2007). However, the historically evolved approach of using 30 second based sleep stage bins is criticized, as it has many drawbacks and as the digitalization of sleep recordings makes more advanced analyses possible, for example frequency-based analyses of the data using wavelets or Fourier transformations (Schulz, 2008).

When determining the above mentioned macrostructure of sleep, the occurrence of local patterns in the polysomnographic recordings is analyzed, so called graphoelements, which form the microstructure of the sleep. To these belong sleep spindles, K-complexes, slow waves, rapid eye movements, and several more (Rama & Zachariah, 2013).

Furthermore, often additional polysomnographic characteristics are recorded, such as the heart rate or the heart rate variability using electrocardiography (ECG), movements of the legs, respiration, oxygen saturation levels, infrared camera videos, body movements, or snoring (Rama & Zachariah, 2013)).

Studies about the effect of auditory, visual or other stimulation of sleep on the sleep itself, on the occurrence of arousals or on cognitive performance during following waking phases belong to the first scientific experiments of modern sleep research (Davis, Davis, Loomis, Hervey, & Hobart, 1939; Dement & Wolpert, 1958) and are still a widely used tool in modern sleep and dream research (for a literature review, see (Braumann, 2016)[3]).

The recorded data are then used to answer specific research questions in order to find out more about sleep or dreaming, both from theoretical as well as practical viewpoints, e. g. “Do sleep spindles and occur more often after learning a declarative task?” (Gais, Mölle, Helms, & Born, 2002), or, “How does the intake of alcohol affect the sleep macrostructure and the sleep fragmentation?” (Williams, MacLean, & Cairns, 1983).

Polysomnographic sleep laboratory studies have a number of disadvantages. One of them is the limited availability of research-oriented polysomnographic sleep laboratories with adequate technical and personnel equipment (Ghegan, Angelos, Stonebraker, & Gillespie, 2006), not only in Germany and other Western countries, but to a much larger extent in less developed countries.

Furthermore, conducting polysomnographic sleep laboratory experiments is an effortful, resource-demanding and time-consuming activity (Van De Water, Holmes, & Hurley, 2011), as is illustrated in the following excerpt of the paper “Investigating consciousness in the sleep laboratory - an interdisciplinary perspective on lucid dreaming” (Appel, Pipa, & Dresler, 2017, full text in the appendix):

> *“3. A night in the sleep laboratory*
>
> *[…] Subjects with frequent lucid dreams, which in addition have to be long enough to conduct scientific experiments within them, are hard to find. It is thus not uncommon to invite participants from the whole country or even from abroad for a lucid dreaming study, requiring effort for advertisement, recruitment, payment and traveling.*
>
> *Preparation and performance of actual lucid dreaming experiments in the sleep laboratory are complex as well - besides the usual extensive procedures necessary to conduct sleep laboratory studies, including as a minimum*

3 Bachelor’s thesis of Sophia Braumann, supervised by the author of this dissertation. See online appendix.

polysomnographic measurements of the brain activity by EEG, of eye movements by electrooculography (EOG), and of muscle activity by electromyography (EMG). For these measurements, electrodes are fixed on the scalp and in the face of the subject. […] As a result, preparation for the experiment can take several hours before the subject is sent to bed. In lucid dreaming studies with high-density EEG for topographical analyses or source localization of brain activity, for example, it takes two experimenters about three hours to instruct and prepare the subject, including fitting of the 128 EEG electrodes and measuring their positions and orientations.

Then the actual sleep recordings begin: In contrast to daytime EEG studies, where the subject usually sits still in front of a computer screen, sleeping subjects are turning around frequently, moving their heads, rubbing them into the pillow, pulling cables, and so on. Thus, lucid dreaming experimenters usually need to stay awake for the whole night in order to continuously supervise the quality of the recordings and to intervene in case of bad signal quality. There is nothing more frustrating for a lucid dream researcher than a bad EEG signal during the critical few minutes of a lucid dream. […]

The necessity to wake up subjects in case of a lucid dream without self-initiated awakening requires the experimenter to continuously monitor the eye recordings on the computer monitor throughout the whole night. While unfortunately still no automatized solutions for lucid dreaming LRLR eye signal detection in the sleep laboratory exist, some researchers have recently started developing such tools by applying methods from the field of machine learning and pattern recognition to automatically detect lucidity-indicating eye movements or bad EEG signals in real-time (e. g. Appel, 2013).

In the morning, when the subject declares that he or she cannot sleep any more, recordings are stopped, and it usually takes another one or two hours to let the subject fill out more questionnaires, to tidy up and clean the equipment, or to take a few other measures depending on the experiment. For example, a classical study protocol for motor skill training during lucid dreaming needs performance measurements of the chosen skill both in the evening and in the morning. All in all, the whole experimental procedure of recording one night including preparations and follow-up usually takes from 8 PM until 11 AM the *next day – for a few recording minutes of data of interest in the best case scenario, i. e. the subject experiencing an actual lucid dream. In many cases, two or three consecutive nights are recorded in a row in order to reduce traveling demands on the subject, resulting in an extensive workload for the lucid dream researcher. Given all these efforts and constraints, it is not surprising that lucid dreaming studies often suffer from a limited number of participants – if exceeding the character of case-studies of single subjects at all."*

Even though this kind of sleep laboratory study is probably one of the extreme ones – in most cases subjects can be invited from the local area and often most of the recorded nights result in useful data – this insight into a lucid dreaming sleep laboratory study illustrates the immense resource needs of sleep laboratory studies:

- Time-wise for the experimenter or a commissioned person (e. g. a night watch), as he or she has to a) spend the evening in the laboratory preparing the experiment, b) stay awake the whole night in order to supervise the signal quality and to conduct the experimental tasks at night, such as collecting dream reports, applying stimuli, or waking up the subject at specific time points, c) in the morning for uncabling the subject, for collecting more questionnaires, and for cleaning up.
- Time-wise for the subject, as it a) has to spend the evening, night, and (sometimes) morning in the sleep laboratory, instead of sleeping at home, b) needs to travel to the experiment location and back, which might be in a different city, c) might be sleep deprived and thus needs more sleep the following night, due to the unfamiliar clinical sleep laboratory surrounding.
- Money-wise, as the sleep laboratory needs to be heated, cleaned, needs electricity and water, for washing the blankets, replacing materials from time to time, and – especially – for all the sleep laboratory equipment, which can cost several thousand EUR. Moreover, the personnel has to be paid, i. e. the night watch, cleaning personnel, and eventually additional research assistants.
- Infrastructure-wise, as suited rooms have to be allocated for sleep research use.

Besides all these high resource investments, it might, even worse, be the case, that the sleep laboratory environment influences the sleep to such an extent, that it is not comparable to the “natural” sleep at the subject’s home anymore, which one originally planned to study. One reason for this is, that individual needs of the subject such as their preferred time to go to bed are often hard to meet in the standardized procedures of sleep laboratory recordings. Another reason is the so called “first night effect”, which states, that the first night of sleep in a sleep laboratory usually contains more awake periods, and less REM sleep, than in consecutive nights (Agnew, Webb, & Williams, 1966). Hobson, Pace-Schott, & Stickgold (2000) explain nicely, why sleeping in the laboratory is less comfortable, more difficult and less deep for the subject:

> *“To appreciate this point, the reader need only imagine going to an unfamiliar place in an inner city neighborhood of dubious safety, encountering a technician who is a stranger and often of the opposite sex, having ten electrodes affixed to the scalp with cement that smells like airplane dope and then being bid ‘goodnight’ and ‘pleasant dreams.’”*

Furthermore, as Waterman, Elton, & Kenemans (1993) argue, can differences between home and in the laboratory recorded dreams occur. This is due to environmental factors such as the artificial setting or due to the interpersonal, communicative relationship between the experimenter and the subject in the laboratory, which might influence qualitative and quantitative aspects of dream recall and report.

Hobson et al. (2000) suggest, that there are three ways to deal with these limitations of sleep laboratory studies: a) by extending the number of nights for each subject to around seven, which has the disadvantage of increasing the efforts severely, b) by recording only one to four nights, and thus accept possible influences on sleep architecture and dreams, or c) to conduct the experiments as field studies at the subjects’ homes, using portable technology.

1.4 Conducting sleep experiments as field studies at the subjects’ homes

1.4.1 (Online) questionnaire studies

The simplest form of gaining data about sleep is the use of questionnaires or sleep diaries. These can either be used on their own, e. g. for collecting data in epidemiological studies, or in combination with further instructions for the subject, for example when assessing the effect of behavioral tasks on sleep.

As Goril & Shapiro (2013) point out, the main reasons for using standardized questionnaires and rating scales are a) that they are quick and accurate for finding a population of interest, e. g. with a specific sleep disorder such as recurrent nightmares, b) that they enable the researcher to monitor change and progress over longer periods of time, c) that they are quick and easy to evaluate and, in the case of standardized questionnaires, deliver validated results regarding the target they have been developed for, and d) that they allow for direct comparison of subject groups between different study locations and laboratories, for example in multi-site experiments. Moreover, they are relatively inexpensive in comparison to sleep laboratory studies, at least if no license fees have to be paid, and need far less resources.

There exist more than one hundred standardized sleep scales for assessing various kinds of sleep habits and disorders (Shahid, Wilkinson, Marcu, & Shapiro, 2012). Three exemplary and widely used scales in sleep research are

- the *Pittsburgh Sleep Quality Index* (PSQI), which measures the sleep quality and disturbances over a period of one month (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989),
- the *Epworth Sleepiness Scale* (ESS), which measures daytime sleepiness (Johns, 1991),
- the *Morningness-Eveningness Questionnaire* (MEQ), which assesses the chronotype of a subject (Horne & Ostberg, 1976).

A German language questionnaire, which is designed for a differential diagnosis of sleep disorders and is used by the Osnabrueck sleep research group for excluding sleep disordered subjects from study participation, is the *Landecker Inventar zur Erfassung von Schlafstörungen* (LISST). The LISST is based on the *International Classification of Sleep Disorders* (ICSD) and discriminates between sleep disorders such as sleep-related breathing disorders, insomnia, narcolepsy, restless legs syndrom, and circadian rhythm disorders (Schürmann et al., 2001).

Besides using standardized questionnaires, it is of course also possible to develop own questionnaires based on the research question one wants to investigate, however, with the disadvantage that it is not possible to compare the results to norms then.

Questionnaire based studies can be conducted in an online fashion over the internet, saving time and resources. One example of such an internet based study with self-developed questionnaires (conducted by the author of this dissertation) is depicted in figures 1.1 and 1.2.

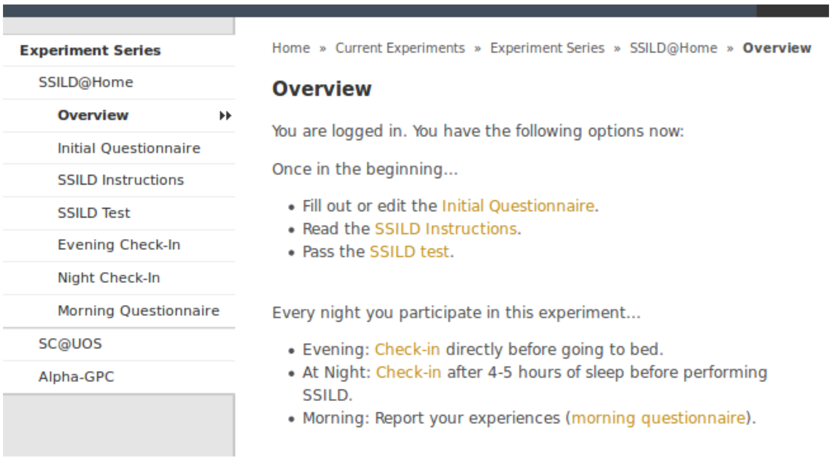

Figure 1.1: Screenshot of an online study navigation, instructing the subject what to do when.

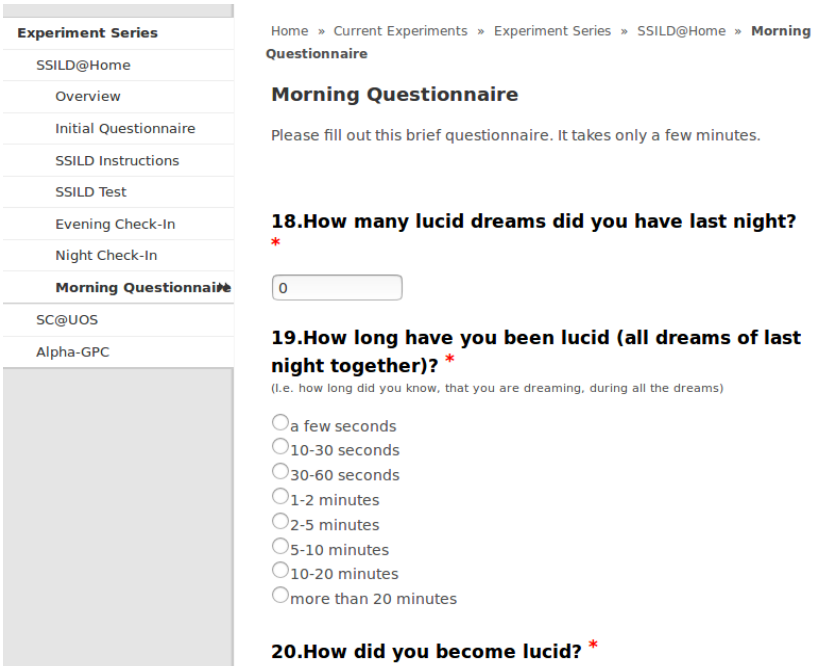

Figure 1.2: An exemplary sleep experiment online questionnaire.

It is possible to extend the idea of questionnaire-based home studies, by supplying the subjects with further experimental materials, such as substances for intake (e. g. drugs or dietary supplements), measurement tools (e. g. saliva sampling) or stimulating tools (e. g. glasses filtering out blue light to be worn in the evening). These tools can be of electronic nature or non-electronic. Electronic tools are discussed in the next section of this chapter.

One exemplary questionnaire based field study analyzed the effect of a special type of self-administered dietary supplements on sleep and dreaming (Kern, Appel, Schredl, & Pipa, 2017, see appendix)[4]. In this experiment, the subjects had to wake themselves up using an alarm clock after a given time period, open a letter containing either placebo or verum pills, continue sleeping, and, in the morning, report their dreams. The whole procedure was then repeated two more times. Even though this study is rather complex, it has to be noted, that drawing conclusions about sleep stages or other sleep characteristics – except the subjectively experienced ones assessed by the questionnaires – was not possible with such a design.

1.4.2 Field studies using electronic tools

Electronic devices exist, which measure sleep outside the laboratory environment at the subject's home. There is a large variation, ranging from consumer products (smartphone apps, watches, but also devices capable of recording sleep EEG), to medical devices such as actigraphs and even portable polysomnographic tools similar to those in the sleep laboratory.

1.4.2.1 Portable medical sleep recording devices

Actigraphy and portable polysomnographic devices are the two main technologies in the field of medical sleep recording devices for home use, even though other approaches like bed sensors are developed as well (Van De Water et al., 2011).

Actigraphy is one of the most widely used medical devices in home-based sleep research (Slater et al., 2015). In most cases, actigraphy consists of a watch, which the subject wears around the wrist day and night, even though other places on the subject's body have been tried out with less recording success, too (Zinkhan et al., 2014). The watch contains an accelerometer, which measures arm movements in all directions. Most modern actigraphy devices measure additional parameters as well, for example brightness or pulse. It is possible, to infer from the recorded data, whether the subject is asleep or awake – at least to some degree (Marino et al., 2013). Actigraphy is often used to study

4 Originally conducted as the bachelor's thesis of Simon Kern, supervised by the author of this dissertation.

circadian rhythms or sleep illnesses like the shift work disorder. However, it is not recommended as a diagnostic tool for routine diagnoses (Kushida et al., 2005; Morgenthaler et al., 2007). The advantages of actigraphy as compared to in-laboratory polysomnography are, that it is less expensive, less complicated to use, ubiquitously available, and most likely without a first night effect (Ancoli-Israel et al., 2003). The disadvantages of actigraphy are, that it cannot measure the brain activity (EEG), eye movements (EOG) or muscle tension (EMG), that it tends to overestimate the amount of sleep and underestimates the amount of wakefulness, and that not all devices have been validated against polysomnography (Ancoli-Israel et al., 2003; Lichstein et al., 2006; Sadeh & Acebo, 2002).

Portable polysomnographic devices, which measure EEG, EOG, EMG and often also ECG, are available, too, and can be used successfully for unattended sleep recordings at the subject's home (Bruyneel & Ninane, 2014). Subjects usually cannot put on the devices on their own (Myllymaa et al., 2016), a trained sleep technician is necessary for connecting the subject to the device in the evening, which is a major disadvantage in comparison to actigraphy or to the consumer devices described below. Moreover, this technology is more expensive, complex and time-consuming than other portable sleep recording technologies. The main advantage over other portable sleep recording devices is that it allows complete sleep evaluation including EEG, EOG, EMG and often more. Compared to in-laboratory polysomnography, the subjects' sleep tends to be better at home, and the costs are lower, however, the data quality is slightly worse (Campbell & Neill, 2011).

Only few data are available regarding the material costs and the cost of actually using home-based polysomnographic devices compared to in-laboratory recordings (Bruyneel & Ninane, 2014). Based on the expenses at the University Osnabrueck sleep laboratory and based on personal communication with several exhibitors at the sleep technology exhibition of the 24th Annual Meeting of the German Sleep Society, 2016, it can be estimated, that state-of-the-art actigraphy watches can easily cost more than 600 EUR, a complete polysomnographic equipment costs several thousand to tens of thousand EUR, with portable polysomnographic sleep recording devices lying in between. The costs for personnel and other expenses are not included in this, but can reach several hundred EUR per night as well. However, this strongly depends on the country, in which the recording takes place (Bruyneel & Ninane, 2014).

The before described medical sleep recording devices are sold commercially, are proprietary (closed) technology and do not allow real-time access of the raw data, displaying further disadvantages of this type of technology.

1.4.2.2 Sleep recording consumer products

A large number of consumer products, which claim to measure human sleep characteristics, are available on the market or preparing a market entry. Even though it was not able to actually measure sleep, the NovaDreamer sleep mask (based on the DreamLight sleep mask described in (LaBerge, Levitan, Rich, & Dement, 1988)) was probably the first commercially available technical sleep consumer product. Its purpose was to influence the subject's sleep and to induce lucid dreams using visual stimulation (blinking lights).

It took until 2009, when the first consumer product was developed, which could actually measure sleep. Furthermore, it was capable of sleep staging the data in real-time and was even sleep laboratory validated: the Zeo system (Griessenberger, Heib, Kunz, Hoedlmoser, & Schabus, 2013; Shambroom, Fábregas, & Johnstone, 2012). The Zeo system consisted of a wireless headband with textile electrodes, which recorded a one-channel prefrontal EEG, and a small station, which received the data in nearly real-time and calculated and displayed the sleep stages. Moreover, it was possible to access the raw data by connecting a cable to the station, and it was very inexpensive (around 150 EUR). However, due to a not working business model, the Zeo went out of business in 2013 (Orlin, 2013).

Nowadays, several products have filled the gap, which was left after the Zeo shutdown. Leaving smartphone apps and fitness trackers aside, which are very popular, but at the same time have very poor quality for measuring sleep and wakefulness (Kolla, Mansukhani, & Mansukhani, 2016), these can be divided into two branches. On the one hand, there are devices, which mainly aim at actual sleep recording. On the other hand, consumer products exist, which mainly aim at measuring brain activity in general, but could be used for measuring sleep as well. Both types of devices cost around 300-800 USD[5] and most of them are produced by small startups, which are financed via crowdfunding campaigns.

5 Please see the companies' websites for the latest price.

The consumer products, which are targeted at measuring brain activity during wakefulness or mediation, are not suited well for recording sleep data: Either because they are uncomfortable to wear a whole night long due to a rigid corpus (OpenBCI[6], Emotiv EPOC+[7]), because they are not designed for unattended use during sleep experiments in the field (OpenEEG[8]) or because the batteries last only around three hours (Muse[9]). A sleep recording subproject exists for the OpenBCI, which aims at enabling professional sleep research experiments with the device. However, the costs for setting up this sleep measuring version are comparatively high (almost 950 USD)[10] and actually measuring sleep data is complicated, if not impossible for not inexperienced subjects.

Ten consumer devices could be identified after an extensive internet research, which claim to be able to record sleep data (see table 1.1). Most of them focus on lucid dream induction, relaxation in general, or improving the sleep quality. However, as of November 2017, most of them are not (yet) available. It has to be noted, that the development of most of the devices, which are not available until the date of writing this, was delayed by months or even years. It can thus only be speculated, when these devices can be bought. Furthermore, it has to be noted, that crowdfunding campaigns were canceled in at least two cases before the development of the devices was finished, even though several hundred thousand EUR were collected.

Major disadvantages of the consumer sleep recording devices are, that the data quality is questionable, especially since most of them record only one or two electrophysiological channels. Moreover, nearly all of the devices for conducting sleep experiment measurements at the subject's home are sold by commercial companies for profit[11]. As a result, the systems are proprietary technology, i. e. not open, which means that the exact way, how they function, is kept secret. Consequently, the researcher has to believe the manufacturer about what is being measured and cannot know in detail, how the signal is processed (e. g. filtered) inside the system. Additionally, a way to access to the raw data in real-time is available only in a few cases, and also the software for analyzing the data is

6 www.openbci.com

7 www.emotiv.com

8 www.openeeg.sourceforge.net

9 www.choosemuse.com

10 www.spisop.org/openbci

11 This is especially the case for the medical portable devices, and also applies to sleep laboratory systems.

often proprietary. This makes it often impossible for researchers to adapt the software to specific experimental needs, which exceed the standard data processing pipeline.

Name Website	Available?	Price (including discounts)	Recording channels	Sleep stimulation built in?	Raw data accessible in real-time?	Software open source?	Sleep laboratory validated?	Comment
LdreamM *ldreamm.com*	yes	360 USD	8x EEG	magnetic stimulation, auditory stimulation	yes	no	no	Seems to be a one-man project of a lucid dreaming and meditation hobbyist, with a small community of users. Uses wet EEG electrodes, which are complicated to use by naive subjects. The project has an unscientific touch, e. g. the developer describes measuring energy levels during meeting his dead wife's soul during wakefulness.
Dreem *dreem.com*	no	399 USD	6x EEG, accelerometer, pulse oximeter	auditory	no	no	no	Extensive testing with hundreds of subjects took place. Not financed via crowdfunding. Strong research collaborations ongoing. Unclear shipment date (postponed several times).
Aurora *sleepwithaurora.com*	no	299 USD	at least 1x EEG, claims to measure EOG, EMG and ECG as well, accelerometer	visual	No (not specified)	no	no	Unclear shipment date, delayed for years since 2014.
iBand+ *ibandplus.com*	no	309 USD	1x EEG	visual, auditory	yes	yes	no	A special developer version has to be bought for accessing raw data in real-time. Unclear shipment date (postponed several times).
kokoon *kokoon.io*	no	239 EUR	1x EEG, accelerometer, microphone	auditory	no	no	no	Unclear shipment date (postponed several times).
neuroonOpen *neuroonopen.com*	no	199 USD	1x EEG, pulse oximeter, thermometer, accelerometer	visual, auditory	yes	yes	no	There was a previous version before (not produced anymore). Unclear shipment date of the new version.
LucidCatcher *kck.st/2qoxywq*	no	380 USD	2x EEG	electric stimulation	No (not specified)	No (not specified)	no	Shipment date unclear (development since 2014). Developer version costs extra.
Lucid Dreamer *luciddreamer.com*	no	-	-	-	-	-	-	canceled due to ineffectiveness regarding lucid dream induction
LUCI *(no website)*	no	-	-	-	-	-	-	canceled, fraud allegations mentioned
iBrain *neurovigil.com*	no	-	1x EEG	-	-	-	-	Device is not commercially available for everybody, but only to special partners. Several prominent people support this device.

Table 1.1: Comparison of consumer sleep recording and stimulation devices.

Even though no exceptions to this are available regarding devices designed for actual sleep recording, the OpenBCI project and the OpenEEG project show an alternative way, by open sourcing their hardware specifications and software code. Open hardware and open software in this context mean, that all the knowledge needed for reproducing the system is made publicly available, even though specific licenses can apply e. g. for commercial usage. Similar open developments take place in other contexts as well (see figure 1.3), for example in the scientific literature (open access journal articles) or in projects like Wikipedia (open knowledge).

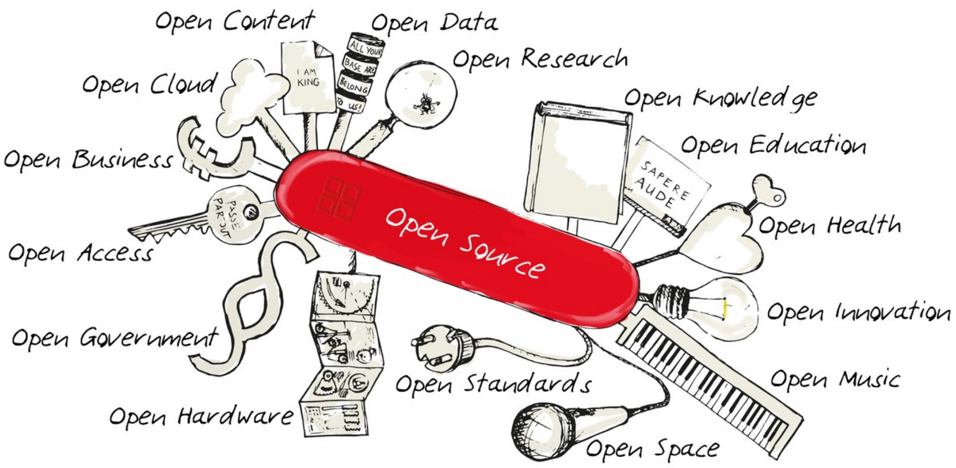

Figure 1.3: Overview of open source fields. *Author: Johannes Spielhagen, Bamberg, Germany - CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=27179850*

1.5 Artificial intelligence

If a researcher wants to let naive crowd subjects conduct complex, interactive polysomnographic sleep or dream experiment at their home, he or she cannot just hand out sleep recording devices to the subjects. Instead, each subject needs to be instructed how to use the device, and someone has to control the experiments during the time the subject is asleep. For example, in a sleep stage dependent experimental paradigm, in which the subject is woken up during a specific sleep stage in order to fill out a questionnaire, someone needs to classify the sleep data in real-time.

Artificial intelligence (AI) is a buzzword, which is used in all kinds of contexts. As the Stanford *One Hundred Year Study on Artificial Intelligence* states, there are many definitions of what AI is, with none being universally accepted (Stanford University, 2016).

The authors write that “a useful one” by (Nils J. Nilsson, 2009) is the following: “Artificial intelligence is that activity devoted to making machines intelligent, and intelligence is that quality that enables an entity to function appropriately and with foresight in its environment.”

Transfered to machines, which are used in complex polysomnographic sleep and dream experiments, AI could be used to take over those tasks, which are normally conducted by a human intelligence (in this case, the sleep researcher or night watch). For example, an AI, which features machine learning algorithms, could be trained to detect sleep stages and to carry out specified experiment tasks based on this, replacing the human intelligence by an artificial counterpart. Before describing, in how far AI is used in the sleep and dream research context nowadays already, some background information on AI and one of its most important subfields, machine learning, is given.

1.5.1 Brief historical overview

The foundations of AI have been laid a long time ago (for a more detailed overview, see for example Russell, S. & Norvig (1995)). Philosophers like Aristotle, who lived in the ancient Greece, already discussed the idea, that the mind is in some ways like a machine, which operates on knowledge encoded in an internal language. By using thought, it can be decided, which actions should be taken. Later, mathematicians like George Boole, Thomas Bayes or Gottfried Leibniz started to develop tools to manipulate statements of logical certainty as well as uncertain, probabilistic statements, and the idea to use algorithms for reasoning purposes was born. Again several centuries later, scientists from other academic fields such as psychology and linguistics contributed to the foundations of AI by adding insight about the mechanisms of human intelligence, already demonstrating this area of research’s multidisciplinarity.

The term *artificial intelligence* itself was first coined in the proposal for the famous Dartmouth workshop written in the year 1955 (McCarthy, Minsky, Rochester, & Shannon, 1955), which was held one year later in summer 1956. This workshop is generally seen as the official birth date of modern AI research. A huge AI hype followed, after the first “intelligent” systems were developed (e. g. ELIZA, an interactive program, which was able to carry on a dialogue in English language on any topic (Joseph Weizenbaum, 1966)), and huge promises were made by prominent AI researchers ("machines will be capable, within twenty years, of doing any work a man can do." - Herbert Simon, 1965 (Goble, 2012), “In from three to eight years we will have a machine with the general intelligence of an average human being.” - Marvin Minsky, 1970 (Darrach, 1970)). At that time, the first expert system was developed as well, automating the decision-making process and problem solving behavior of organic chemists by using detailed, task-specific knowledge as a source of heuristics and seeking generality through automating the acquisition of such knowledge (Lindsay, Buchanan, Feigenbaum, & Lederberg, 1993).

However, after James Lighthill (1973) reports to the British Science Research Council that “in no part of the [AI research] field have discoveries made so far produced the major impact that was then promised”, governmental support for AI research was reduced dramatically. What followed, is generally called the “AI winter”, describing this period of time with disappointed and lost public interest in the field and very limited funding. However, over the years, new approaches occurred. Probabilistic methods were found to function better than rule-based systems, for example in the area of language translation (Brown et al., 1988). In 1997, the IBM computer Deep Blue beats a reigning world chess champion for the first time. Similarly, the quiz show “Jeopardy!“ was won by an AI in 2011 using a huge knowledge base, and an AI based on artificial neural networks and tree search defeated the best human Go player in 2016. Modern AI research has many facets, ranging from understanding human speech, to competing at a high level in strategic games, to controlling autonomous cars.

Figure 1.4: Example of an autonomous car controlled by an artificial intelligence. *Image source: https://www.digitaltrends.com/cars/chicago-may-ban-autonomous-cars/*

As can be seen by this brief historical overview, and as is concluded by (Russell, S. & Norvig, 1995), too, the field of artificial intelligence research underwent several cycles of success and cutbacks, and new methodological approaches were developed constantly, how to create intelligent machines. Interestingly, the border of what can be seen as being “intelligent“ was moved further and further, never being reached. Only a short time after a task was accomplished by an artificial intelligence, which was previously being stated to require intelligence to solve, this point of view was changed, creating the so called AI effect (McCorduck, 2004). Until today, all forms of AI have rather been experts in a specific field or kind of task (e. g. playing chess) – the so called weak form of AI. The opposite, a strong AI displaying all forms of human intelligence (similar: artificial general intelligence) has not been created, and a valid question is, how such a form of intelligence could be tested (Goertzel, 2014). A number of tests have been proposed for this, with the so called Turing test being one of the most prominent ones. In brief, it tests, whether an AI is able to show intelligent behavior, which is indistinguishable from human behavior, by letting human interrogators ask written questions simultaneously to a human and an AI, trying to figure out from the answers, who is who (Turing, 1950).

1.5.2 Machine learning and deep neural networks

Recent AI research has seen a lot of progress in the field of machine learning. This subfield of AI describes the computer’s ability to learn without being explicitly programmed (Samuel, 1959). Even though other promising machine learning approaches exist, for example the decision tree-based random forests (Breiman, 2001), one extremely powerful technology are the so called deep neural networks (Lin, Tegmark, & Rolnick, 2017).

Artificial neural networks (for a detailed, formal introduction and a broader overview of the topic, see Schmidhuber (2015), Yegnanarayana (2009) or Goodfellow et al. (2016)) are based on the idea of modeling natural neural networks in computers – an approach, which foundations were laid by McCulloch & Pitts (1943). Like their natural counterparts, these digital neuron networks can receive inputs, transform the input and generate outputs. The transformation of the input takes place both in the neurons themselves (e. g. by summing up all inputs and applying a mathematical activation function to it in order to obtain an output value) and due to the complex, non-linear interplay between the neurons, with the output of one neuron being used as input to other neurons.

The strength of this approach arises, when the artificial neural network is modified according to certain rules – a process called learning. The goal of this is to let the neural network learn to generalize over different inputs, in other words, to be able to create meaningful output values also for before unseen data. Supervised and unsupervised learning are two categories of this, with supervised learning describing the idea of presenting input-output pairs to the network, making the network learn to calculate a specific output for given inputs, e. g. for pattern recognition purposes. In the case of unsupervised learning, the network is only presented inputs, and tries to describe a hidden structure in the input, e. g. finding clusters in the data.

The first idea, how a learning rule for modifying a network during the learning process could look like, was introduced by (Hebb, 1949), suggesting that “cells that fire together, wire together”, i. e. if neuron A in a network often causes neuron B having a high output value, the connection between them is strengthened. Important other learning algorithms like the backpropagation algorithm followed (Rumelhart, Hinton, & Williams, 1986), enabling the neural networks to learn more complex functions than was possible with the Hebbian learning rule.

Organizing the learning process is commonly subdivided into two parts: training and testing. During training, the network is presented a subset of the available data (training data set), and for each data point, an error function compares the network’s output with the target output values. Based on these deviations, the modifications of the network are applied. Simultaneously, a second subset of the available data (validation data set) is used in order to validate the neural network’s performance on unseen data, which helps prevent the so called *overfitting*, i. e. preventing the neural network from learning only the exact training examples, but not generalizing over them. Finally during testing, after the training and validation process resulted in a sufficiently good performance of the neural network on the validation data set, it is tested on the third part of the available data (the test data set), in order to estimate the neural network’s ability to handle completely new, unseen data.

Various types of neuron models, activation functions, learning rules, error functions and network architectures have been developed, resulting in more and more powerful artificial neural networks, which are capable of solving a manifold of problems[12]. Moreover, several open source frameworks such as Keras (Chollet, 2015) or tensorflow (Abadi, Barham, et al., 2016) exist for developing. Additionally, due to the increasing computational power of nowadays computers, and due to further theoretical improvements in the field, extremely

12 For the sake of brevity and since these details are not of the greatest importance for the rest of this dissertation, the interested reader is referred to the literature cited at the beginning of the chapter for further information.

large artificial neural networks can now be constructed and trained successfully (LeCun et al., 2015). This lead to the phrase “deep learning”, as the neural networks can consist of dozens or even hundreds of layers. Moreover, massive amounts of training data for many different problems is available nowadays due to the internet, smart sensors and devices, increasing the performance of neural networks further, succeeding human performance in many fields. One example for this is the success of deep neural networks at image classification, exceeding human performance in describing what can be seen in a picture (He, Zhang, Ren, & Sun, 2016).

Figure 1.5: This figure from (He et al., 2016) depicts image labels generated by an artificial neural network (numbered 1 to 5) as well as the "ground truth" (GT), i. e. the official label of the image from the image recognition competition.

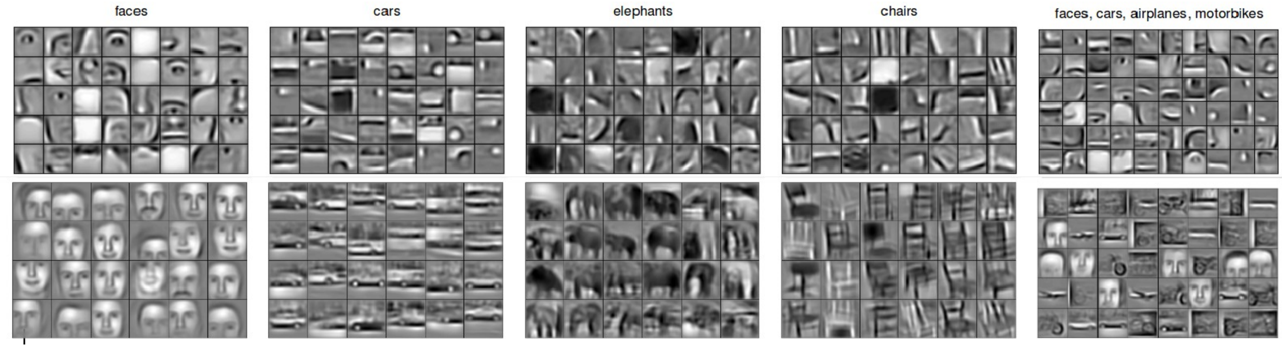

Figure 1.6: This figure from (Lee, Grosse, Ranganath, & Ng, 2009) depicts the features learned by so called convolutional neural networks, which have been trained on images of faces, cars, elephants, chairs, and a combination of faces, cars, airplanes and motorbikes, respectively. The first row shows the features learned by the neurons of an early layer of the network, the second row those of a later layer. It can be seen, that convolutional neural networks can learn hierarchical representations of images, i. e. identify common local patterns in the data (e. g. eyes or noses in the case of faces), as well as combinations of these, in order to classify before unseen pictures into one of the categories.

Figure 1.7: This example of a picture (right) created by an artificial neural network based on two input images (left) illustrates, that by understanding and combining the conceptual elements of a data structure (in this case: an image), new creative data representations can be formed. Image source: https://www.boredpanda.com/inceptionism-neural-network-deep-dream-art/?media_id=419452

1.6 Sleep and dream research and artificial intelligence

Several ways can be thought of, how artificial intelligence and machine learning can be used in the field of sleep and dream research. And also vice versa, AI can benefit from the knowledge created by sleep and dream researchers. In fact, research in both directions has been conducted already, as the following non conclusive list shows:

- By studying the nightly brain, mechanisms can be identified, which could lead to significant improvement of artificial neural networks, e. g. as used for unsupervised neural networks in (Hinton, Dayan, Frey, & Neal, 1995) or, regarding the function of sleep for memory consolidation processes or for restructuring knowledge, by (Walker & Russo, 2004). In these cases, artificial neural networks were trained in a similar way like natural neural networks learn, increasing their performance.
- Expert systems have been developed, which aid physicians in diagnosing sleep disorders (Ohayon, Guilleminault, Zulley, Palombini, & Raab, 1999), as well as astronauts in recording sleep data (Callini, Essig, Heher, & Young, 2000).
- Numerous approaches to AI-driven sleep stage classification using machine learning exist, which use as different AI methods such as linear discriminant analysis (Fell, Röschke, Mann, & Schäffner, 1996; Kayikcioglu, Maleki, & Eroglu, 2015), artificial neural networks (Hsu, Yang, Wang, & Hsu, 2013; Oropesa, Cycon, & Jobert, 1999; Park, Pa, & Jmn, 2000; Robert, Guilpin, & Limoge, 1998), support vector machines (Crisler, Morrissey, Anch, & Barnett, 2008; Koley & Dey, 2012; Lajnef et al., 2015), or genetic algorithms combined with a rule-based expert system (Kim & Park, 2000).
- AI methods were also found useful for automatically detecting microstructures in the sleep recordings, e. g. sleep spindles (Schimicek, Zeitlhofer, Anderer, & Saletu, 1994; Sinha, 2008; Ventouras et al., 2012; Wallant, Maquet, & Phillips, 2016).
- Furthermore, even approaches to measure the sleep quality in real-time based on AI-driven analysis of the ECG signal using support vector machines exist (Bsoul, Minn, Nourani, Gupta, & Tamil, 2010).
- Lastly, AI-driven approaches are also used for sleep medical purposes, e. g. for detecting sleep apnea in ECG sleep recordings (Babaeizadeh, White, Pittman, & Zhou, 2010).

No attempt could be found to automate complex sleep laboratory studies in the field, in order to enable naive crowd subjects to conduct them on their own in the field. Most likely, this is due to the unavailability of suited polysomnographic recording devices. As seen in chapter *1.4.2 Field studies using electronic tools*, tools which give access to raw data, which are cheap enough for crowd experiments, and which have been shown to have a good polysomnographic data quality are not available on the market. Logically, as long as there is no suited hardware, it makes no sense to develop specialized software, which enables naive crowd subjects to conduct polysomnographic experiments on their own and which uses a machine learning based approach for real-time sleep staging and other experiment control.

In order to change this, two things need to be developed for crowd-based polysomnographic sleep and dream experiments:

- a polysomnographic recording device, which is cheap, easy to use, has real-time raw data access, and which makes interactive sleep experiments in a sleep laboratory fashion possible at the subject's home,
- a piece of software, which enables naive crowd subjects to conduct the sleep and dream experiments on their own at home, i. e. which instructs the subject and which takes over the experiment control when the subject is asleep using state-of-the-art machine learning algorithms.

1.7 Aim of this dissertation

The aim of this dissertation is to develop and to evaluate such a portable sleep and dream experiment system consisting of hardware and software, which enables a crowd of naive subjects to conduct complex polysomnographic experiments at home. In other words, the goal is to make automated, interactive, crowd-based polysomnographic sleep and dream experiments possible. The name of this new system will be the *Traumschreiber* system (from German words “Traum” (dream) and “Schreiber” (writer)).

In order to test the suitability of the Traumschreiber system for complex crowd-based automated polysomnographic sleep and dream experiments, it will be evaluated regarding its data quality in comparison to sleep laboratory polysomnography, its usability, its production process and production costs, and its overall applicability for this type of studies.

2 Methods

2.1 Overview

An iteration based approach was chosen for developing the Traumschreiber system. This means that the system was repeatedly improved and tested, until the point was reach, at which a prototype was ready to be evaluated in a sleep laboratory and in field studies. In this chapter, the methods of the development process are described first, and afterwards the methods of the evaluation of the Traumschreiber system are presented.

2.2 Development

2.2.1 Defining the requirements towards the Traumschreiber system

Based on the experiences from own sleep laboratory and field studies, it was first defined, what the new Traumschreiber system had be able to do in order to fulfill its main purpose – i. e. enabling complex crowd-based automated sleep and dream experiments, including polysomnographic recording of EEG, EOG, EMG and ECG with good data quality, and real-time stimulation of the sleep. The requirements were regularly updated based on the testing during development, and based on the feedback obtained at conferences or of researchers, who tried out the Traumschreiber system (see chapter *2.2.2 Iteration-based development*).

The Traumschreiber system was designed to consist of

- a Traumschreiber sleep mask, which is worn by the experiment subject during the night, and which records and stimulates the subject's sleep,
- a Traumschreiber experiment station, which is placed next to the subject's bed, and which assists the subject, e. g. gives instructions and analyzes the recorded data in real-time,
- a Traumschreiber data analysis software package, which enables the researcher to perform the most important analysis steps in a standardized way after the data are recorded. Further details are depicted in the figures 2.1, 2.2 and 2.3[13] for each part.

13 The mind maps were created using the open-source WiseMapping tool.

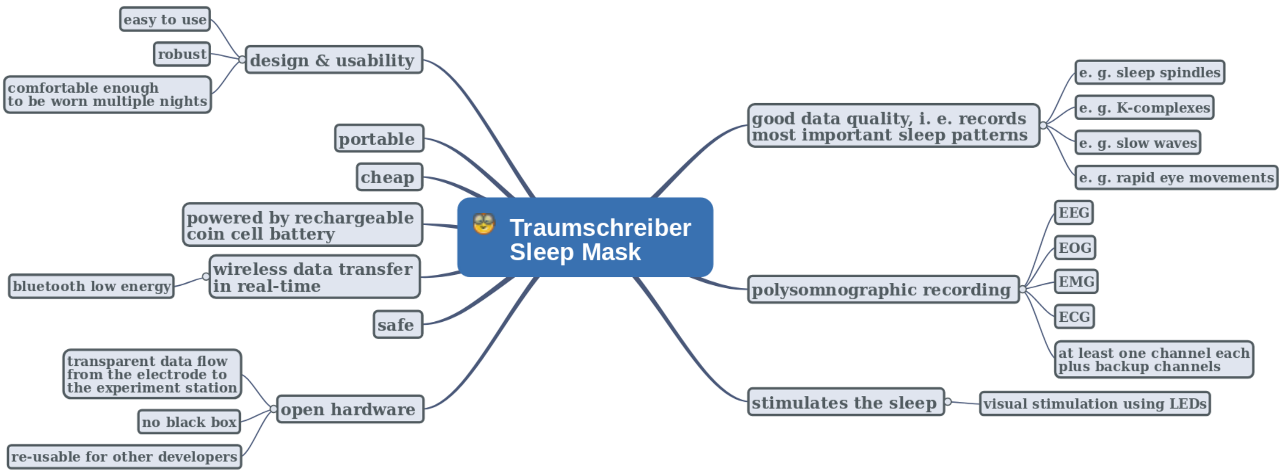

Figure 2.1: Requirements towards the Traumschreiber sleep mask.

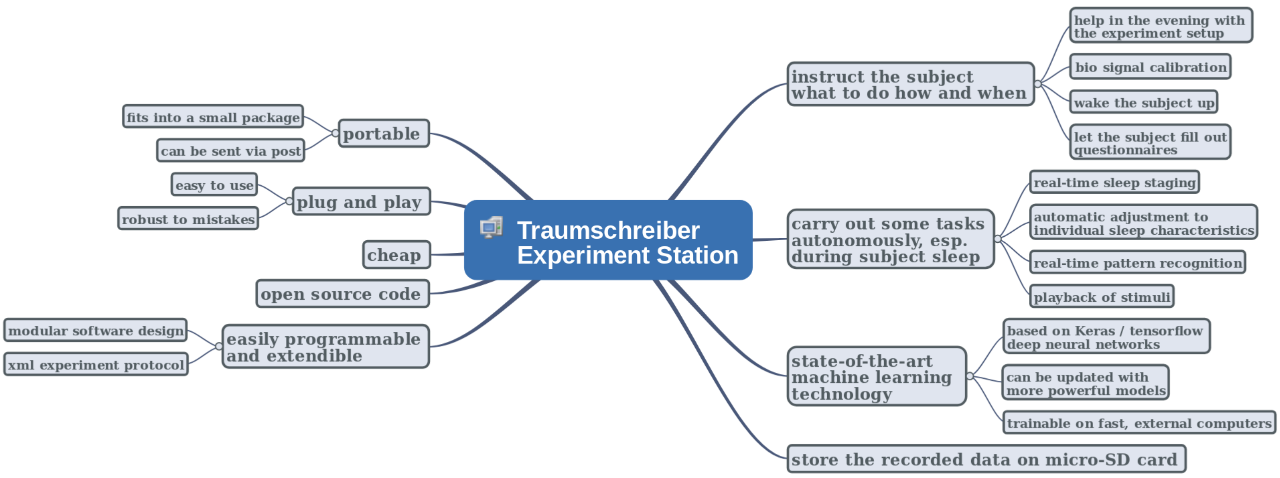

Figure 2.2: Requirements towards the Traumschreiber experiment station.

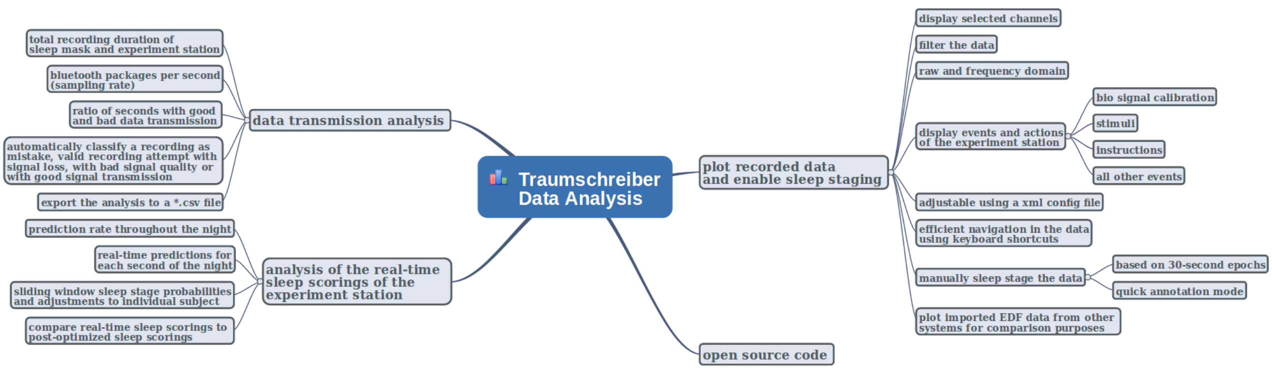

Figure 2.3: Requirements towards the Traumschreiber data analysis package.

2.2.2 Iteration-based development

During development, several decisions had to be made, how to best achieve the features depicted above. Should multi-usable conductive cloth be used as an electrode material, single use sticky electrodes, cup electrodes, a standard EEG cap, or some sort of a plastic helmet? How many channels are necessary for recording sleep physiological data; should there be backup channels in case some channels have a bad signal? How shall the data be transferred between the sleep recording device and the experiment station: via wi-fi, bluetooth, or bluetooth low energy? Should the experiment station rather be a Raspberry Pi minicomputer, a smartphone, or directly integrated into the sleep mask? Should acoustic stimuli and instructions be delivered to the subject via speakers or headphones? Should the recorded data be processed locally, or directly transferred to a server via internet? In what kind of format should the data be stored? Which programming language should be used for programming the experiment station? Which frameworks are suited best for implementing the artificial intelligence part of the system? Not even mentioning all the electric engineering decisions, e. g. regarding the hardware filters, the placement of the components on the PCB, the selection of the optimal microcontroller considering costs, energy consumption, availability, price, and of course technical properties (speed, ADC, connection types, etc.), and many more – in the end, a complete EEG was constructed from scratch. And where should this be produced (China, Germany)? How should it be financed?

These questions illustrate well, how many different decisions had to be made during development, ranging from textile design, to electric engineering, to machine learning, to sleep and dream research. Trying to answer all questions at once right in the beginning of the project was not possible. Instead, an iteration-based approach was chosen.

Each iteration consisted of four main steps:

1. Defining / adjusting the requirements towards the new version of the system, and setting priorities. On the one hand, this was based on the experiences gained from testing the previous version in self-experiments. On the other hand, input from other sleep researchers and clinicians was obtained. Some of these researchers tried out prototypes of the system, others gave feedback at oral or poster presentations about the system at scientific conferences[14]. Furthermore, interested hobbyists

14 23rd Annual Meeting of the German Sleep Society 2015 - oral presentation at the young scientists workshop: “The Traumschreiber Project”; Hofgeismar Young Scientists Workshop of the German Sleep Society 2016 - oral presentation: “Updates on the Traumschreiber Project”; MetaRheinMainChaosDays 2016

(mostly lucid dreaming enthusiasts experienced with other consumer devices such as the Zeo) suggested features to be included in the next development cycle. Last, but not least, the experiences of the author of this dissertation from the sleep experiments at the Osnabrueck University sleep laboratory and at the Max Planck Institute of Psychiatry, Munich, inspired the development of new features, and helped setting the priorities.

2. Finding ways, how to implement the needed features, or how to improve the existing solution. This depended strongly on the type of task, which was conducted, and was done via internet research (e. g. finding new electric components), trial and error (e. g. trying out different approaches to make the sleep mask more comfortable), measuring and electrical engineering using an oscilloscope, by-hand calculations and specialized software (e. g. designing hardware filters, drafting the electrical circuit diagrams and PCB layouts), programming and refactoring (e. g. new software features or the microcontroller code), and group discussions (e. g. which tasks should have priorities or whether to choose a more expensive but better electrical component or not). Furthermore, the autodidactic learning part should not be underestimated, as no professional electrical engineer or product designer was involved in the development, and most skills were obtained in a self-taught way.

Figure 2.4: Picture of the technical development process (Johannes Leugering)

of the Chaos Computer Club - oral presentation: “Traumschreiber: Eine Open Source Schlafmaske, die Hirnaktivitäten messen und beeinflussen kann”; 23rd Congress of the European Sleep Research Society 2016 - poster presentation P214: “‘Traumschreiber’: measuring and manipulating human sleep with a portable high-quality but low-cost polysomnographic system”.

3. Obtaining finances for the production of the new prototype. In the beginning, the Neuroinformatics department of Osnabrueck University funded the project, as well as the Institute of Cognitive Science at Osnabrueck University. In later development stages, when the production became more and more expensive, also external financial sources had to be acquired, e. g. the Hans-Mühlenhoff-Stiftung Osnabrueck (2,000 EUR) and the German Sleep Society (5,000 EUR).
4. Producing a new prototype based on the current iteration's developments, and testing it. In the very beginning of the project, the electric parts of the sleep recording device were soldered on a breadboard and directly tested. In subsequent development stages, the printed circuit board was designed in Osnabrueck, produced in a factory in Germany, and assembled with the electric components in Osnabrueck, as well as tested in Osnabrueck. During the last three developments iterations, the printed circuit board was designed in Osnabrueck, produced and assembled at much lower costs in China, then imported to Germany, and tested in Osnabrueck. The textile parts were completely self-designed in the very beginning. Later, ready-to-use sleep masks were bought in Germany and processed further in Osnabrueck, and finally much cheaper (and at the same time even more comfortable) sleep masks were imported from China and processed further in Osnabrueck, i. e. working the electric parts into the sleep masks. Testing consisted of a) wearing the device during self-recordings for several nights and then analyzing the data quality by plotting and visual inspection, b) analyzing the comfort of the sleep recording device, and c) analyzing the necessary work steps for an experimenter to conduct an experiment. If the new features of the system worked well, they were kept for the next development iteration, if not, they were either changed or removed in the next development round.

During all the above mentioned work steps, external advice or work force was acquired – in some development iterations for the one step, in other iterations for another step. For the textile development, for example, a cooperation with the study program “Textile design” at Osnabrueck University was established, and cognitive science and textile design students drafted and produced several textile designs, how high-tech sleep masks should look like. Moreover, some work packages have been “outsourced” to bachelor's theses of cognitive science students, supervised by the author of this dissertation (all attached in the online appendix): a literature review of sleep stimulation experiments (Braumann, 2016), testing the EOG capabilities of the sleep recording device (Laubisch, 2016), conducting a sleep laboratory validation (Nienhaus, 2017), testing the usability and functionality of the system (Mandt, 2017), and programming a first version of an Android app (Jäkel, 2017).

#	Features, comments	Date	Production place
v0.0	Breadboard based EOG measurement with oscilloscope, inspired by OpenEEG project	07/2014 to 09/2014	At home
v0.1	First PCB, measures EOG and transmits the signal via cable to computer	10/2014 to 07/2015	PCB: produced in German factory, equipped by hand in Osnabrueck
v0.2	Measures sleep EEG, transmits the signal via bluetooth 2.0, has LEDs on external board, which can be controlled via bluetooth, limited auditory stimulation via headphone plug onboard	08/2015 to 11/2015	PCB produced in German factory, equipped by hand in Osnabrueck
v1.0	Uses self-designed signal amplifiers (op-amps instead of IAs), LED board split up into driver board and satellite LED boards, used during textile design seminar	12/2015 to 03/2016	PCB produced in German factory, equipped by hand in Osnabrueck
v2.2	BLE implemented (but does not work), eight channels instead of four, uses IAs again for signal amplification, has flat connectors for the cables, first field study	04/2016 to 12/2016	PCB produced and equipped in China
v2.4	BLE works, LED onboard, battery onboard, DIN cable connectors, sleep laboratory validation, most boards faulty due to bad production quality of new Chinese manufacturer	12/2016 to 03/2017	PCB produced and equipped in China
v2.5	Slightly changed LEDs, ordered at first Chinese manufacturer again (good production quality) **Final version**	03/2017 to 08/2017	PCB produced and equipped in China

Table 2.1: Overview of the main electric development iterations

In total, seven development iterations were conducted. Especially obtaining the finances (by applying for small grants), university and customs bureaucracy, production abroad and testing in experiments were very time consuming. The final version of the system (including the sleep recording device), as well as the exact work steps, how to produce it, are described in chapter *3.1 Development* and *3.2.3 Third study: Preparing polysomnographic crowd experiments*.

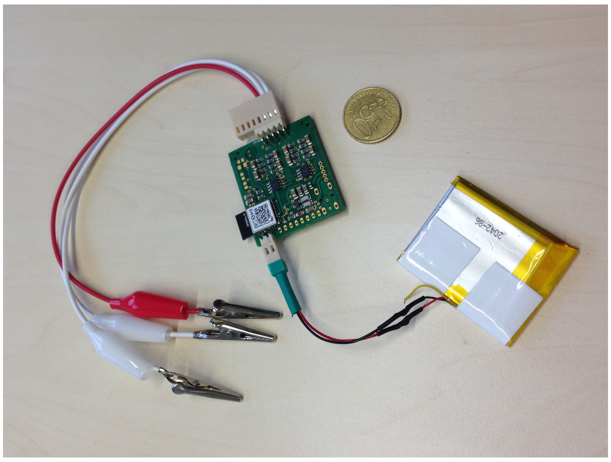

Figure 2.5: Electric prototype version 0.2. It had to be connected to an external battery, it had only four data channels and used bluetooth 2.0 instead of BLE for data transmission.

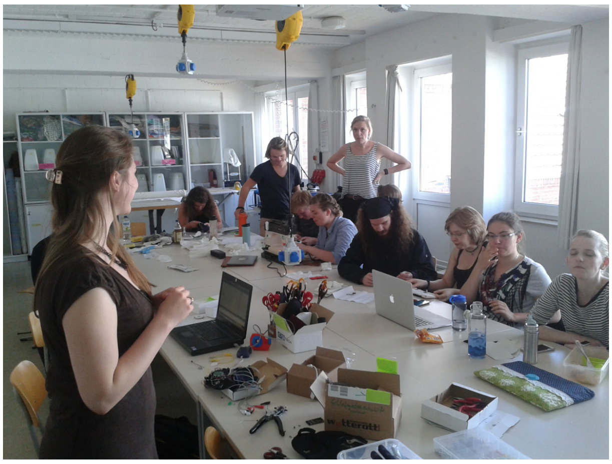

Figure 2.6: Picture of the textile design seminar.

Figure 2.7: One intermediate result of the textile development process.

Figure 2.8: The first self-made prototype of the textile part of the sleep mask. Note that it is flat, i. e. moving the (closed) eyes under this sleep mask is uncomfortable.

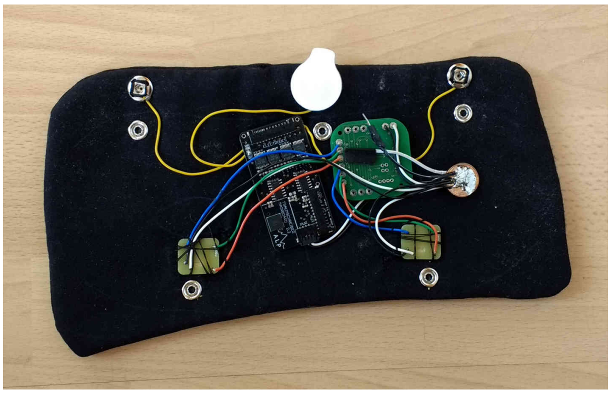

Figure 2.9: Traumschreiber sleep mask version 1.0. Note the several boards for measuring sleep, for LED control and the actual LEDs, all connected via cables.

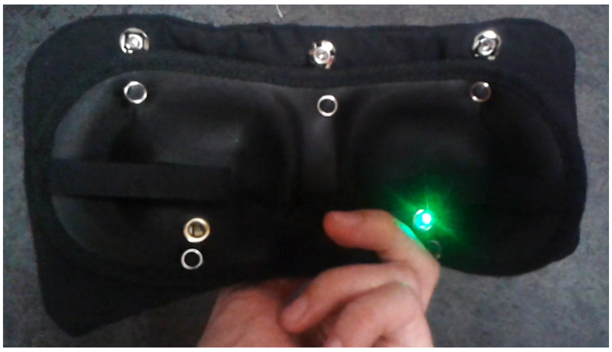

Figure 2.10: Traumschreiber sleep mask 1.0 together with the eye cover. Note that the light of the right LED shines through the eyelet.

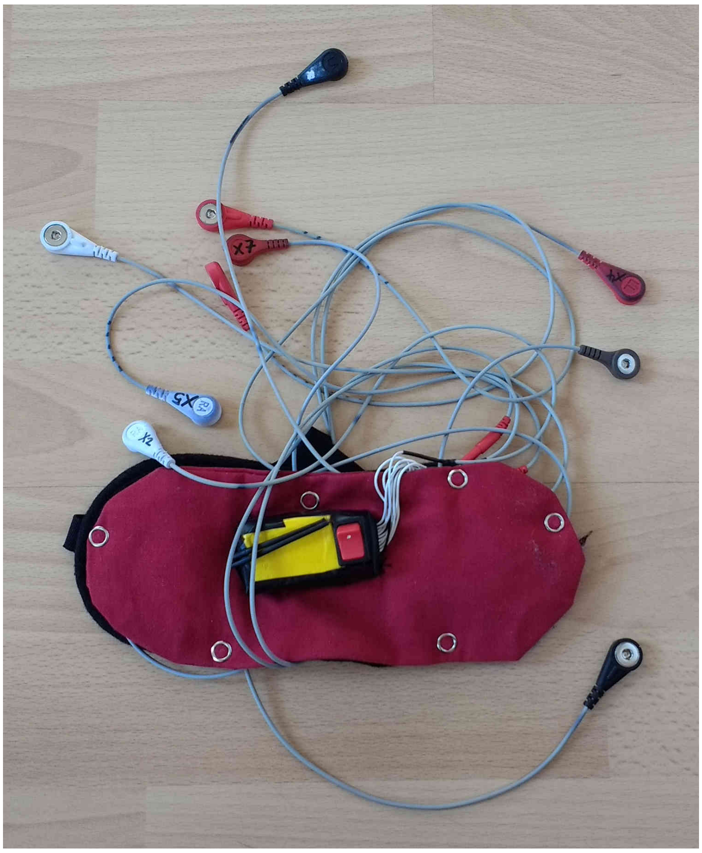

Figure 2.11: Traumschreiber sleep mask version 2.2. Note that the cables are far too long (making the sleep mask heavy and uncomfortable) and that the electronics are not hidden inside the mask.

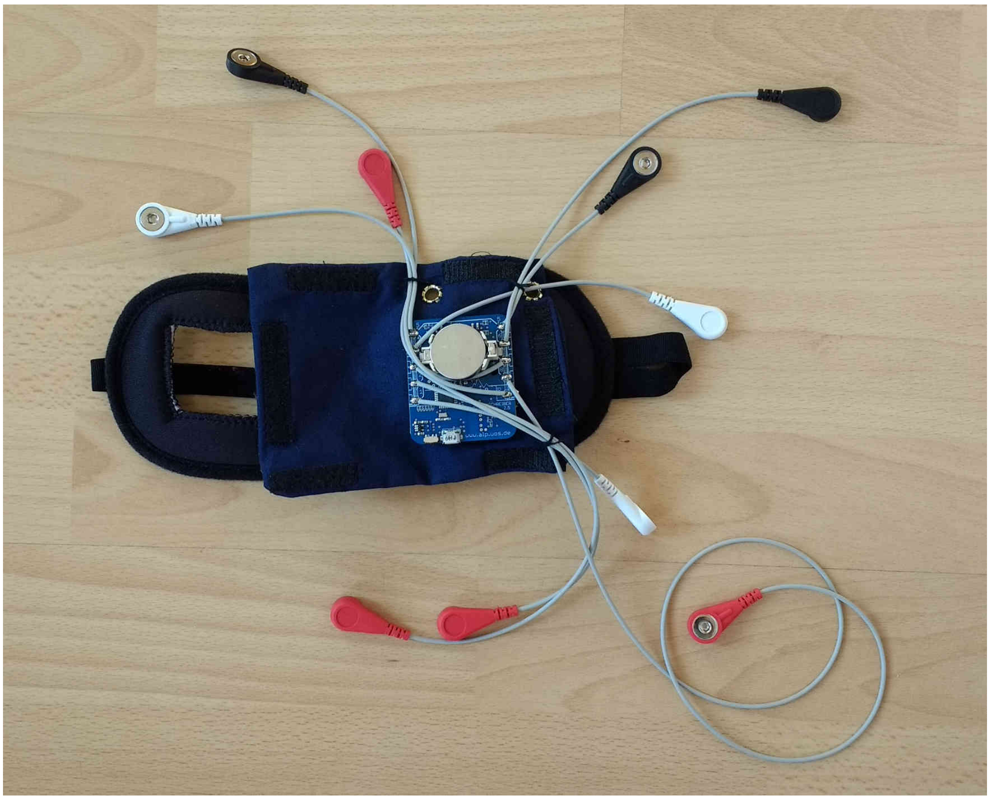

Figure 2.12: The final version of the Traumschreiber sleep mask (open pocket).

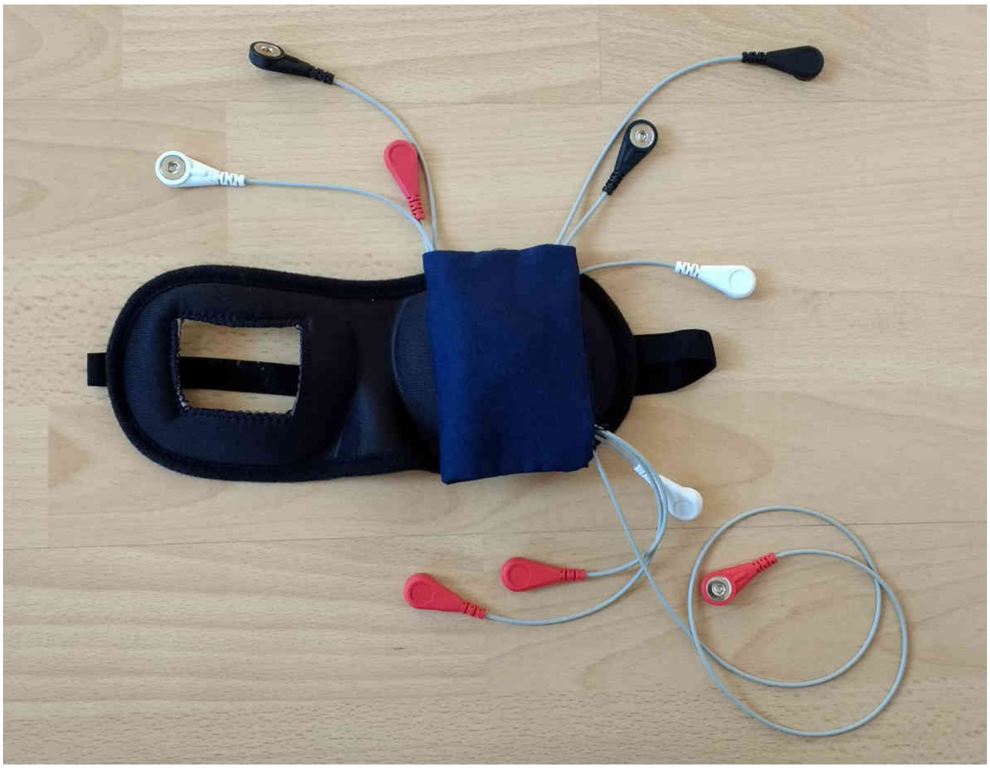

Figure 2.13: The final version of the Traumschreiber sleep mask (closed pocket).

2.3 Evaluation

After developing the system, it was evaluated in several studies. The purpose of this was to analyze, how well the system is suited for real-world usage of sleep researchers. It is suggested to first read the description of the development results (chapter *3.1 Development*) before continuing with reading this chapter.

2.3.1 First study: Sleep laboratory validation

2.3.1.1 Aim

Can the same sleep characteristics be measured using the Traumschreiber system and a commercially available, worldwide used medical polysomnographic system? What are the differences in the recorded data? In order to answer these questions, the Traumschreiber system was validated against such a commercial medical polysomnographic system in the sleep laboratory of Osnabrueck University.[15]

2.3.1.2 Subjects

Seven healthy students (2 female, age between 18 and 27 years) were recruited via email announcement. Exclusion criteria were: younger than 18 years; pregnancy or breastfeeing; suffering from psychic or psychosomatic illnesses, neurologic diseases, hallucinations, or sleep disorders (evaluated using the standardized LISST questionnaire (Schürmann et al., 2001)); taking sleep drugs, psychotropic drugs, pain killers, or antihistaminics. The subjects were asked to not consume any alcohol within the last 24 hours before the experiment, to not nap during the day, and to sleep regularly the night before the experiment. The subjects spent one night each at the Osnabrueck University sleep laboratory. They signed written informed consent and were compensated with 3 subject hours, which they needed for their degree. One subject had to be excluded from data analysis, as the battery of the sleep mask was not charged and recorded only a part of the night.

2.3.1.3 Materials and procedure

Using an ALICE 3.5 commercial medical polysomnographic system, chin EMG, EOG, frontal, central and occipital EEG (2 channels each) as well as ECG were recorded using gold cup electrodes (central and occipital EEG) and single use sticky electrodes (Covidien

15 The study was conducted together with Frederik Nienhaus, who wrote his bachelor’s thesis about this experiment (Nienhaus, 2017, supervised by the author of this dissertation).

Kendall H135SG) for the other recording locations. Simultaneously, the prototype version 2.4 of the Traumschreiber system was used, which did not differ from the final version of the Traumschreiber system regarding the relevant technical specifications of the PCB or its components (same filters, same microprocessor, same bluetooth chip, etc.). The electrodes of the Traumschreiber sleep mask were of the same type as the ALICE system's and were attached directly next to them, with the intention to record similar physiological activity. An exception were the central and occipital EEG electrodes of the ALICE system: Since only single use sticky electrodes are used in the standard Traumschreiber recording setup, which do not hold in hair, no Traumschreiber electrodes were attached near them. Thus, in total 14 electrodes were fixed in the face of the subjects, plus additional 11 electrodes behind the ears (references), in the hair (EEG), and on the chest (ECG) – see figure 2.14.

The subjects were sent to bed around 11 PM, and were woken up around 7 AM, resulting in a total of 8 hours of bed time.

2.3.1.4 Data analysis

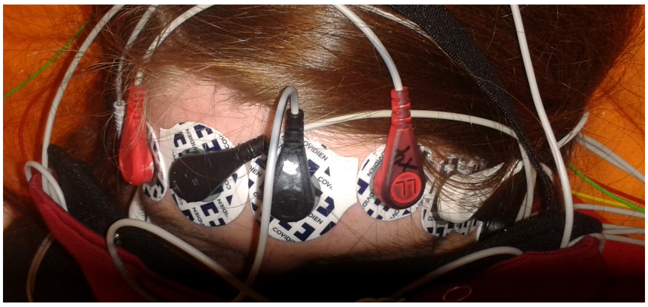

Figure 2.14: Sticky electrodes of both systems were placed on the forehead, recording EOG and frontal EEG.

30-second epochs of the data were plotted in 15 minute intervals using the post_visualization.py script of the Traumschreiber data analysis software package and a modified EDF-compatible version of it for the ALICE data. This means that a snapshot of the recorded data was produced for each of the time points 11:00 PM, 11:15 PM, 11:30 PM throughout the whole night to 6:30 AM, 6:45 AM, 7:00 AM for both systems including all channels. Both systems were synchronized in time using the bio signal calibration markers, i. e. the calibration procedure at the beginning of each night, for example clenching the teeth or moving the eyes in a systematic manner.

The plots of the data of the Traumschreiber system and of the ALICE system were then compared by visual inspection. As a first step, each plot of the Traumschreiber system was analyzed, whether there were clearly recognizable slow waves, sleep spindles, K-complexes, a low amplitude and mixed frequency EEG signal, rapid eye movements, slow eye movements, eye blinks, clearly visible heart beats in the ECG signal, arousals, alpha waves, or vertex waves. Next, the same was done for the plots of the ALICE system. It was then denoted, whether the two systems showed similar elements in each corresponding epoch, or whether some graphoelements could only be seen in one of the recordings. Furthermore, the differences were described in detail by words, if necessary, e. g. if sleep spindles were not detectable in the Traumschreiber system's plot, because they were of central origin. As a second step, every epoch of each system was classified into the categories wake, REM, N2, N3 and ambivalent sleep. It is sometimes impossible to rate, whether a single 30-second data bin depicts wake, N1, N2 or (tonic) REM sleep, because this depends on the classifications of previous epochs, too. For these cases, the *ambivalent* sleep category was used. The classifications of both systems were then compared. Descriptive statistics were used to summarize the results.

2.3.2 Second study: Home-based prototype study

2.3.2.1 Aim

In this study, a prototype (version 2.2) of the Traumschreiber system was tested for the first time at the subjects' homes. The aims were

- to investigate, whether the crowd subjects were able to conduct the study with the Traumschreiber system as intended,
- to check the data quality of the recordings,
- to analyze the effect of the system on the sleep and dreams of the subjects,
- to find out, how easy to use and comfortable the system was for the subjects,
- to determine, how the system should be further developed, and
- to conduct a small scientific study as a side experiment with the new system, namely, to analyze the effect of acoustic stimulation from the Traumschreiber system on sleep and especially on the occurrence of arousals.[16]

2.3.2.2 Subjects

24 healthy students (15 female, age between 18 and 27 years) were recruited via word-of-mouth advertising and e-mail announcements. Exclusion criteria were: younger than 18 years; pregnancy or breastfeeing; suffering from psychic or psychosomatic illnesses, neurologic diseases, hallucinations, or sleep disorders (evaluated using the standardized

16 The study was carried out together with Laura Sophie Mandt, how wrote her bachelor thesis about this experiment (Mandt, 2017, supervised by the author of this dissertation).

LISST questionnaire (Schürmann et al., 2001)); taking sleep drugs, psychotropic drugs, pain killers, or antihistaminics. The subjects were asked to not consume any alcohol within the last 24 hours before the experiment, to not nap during the day, and to sleep regularly the night before the experiment. One subject did not meet these criteria and was thus excluded from further data analyses. The subjects received no financial payment, but three subject hours needed for their degree. All subjects signed written informed consent.

2.3.2.3 Materials

The prototype Traumschreiber system, which was handed out to the subjects of this study, consisted of the sleep recording device, a Raspberry Pi 3 Model B minicomputer with a touchscreen, two small USB speakers “Trust Leto 2.0 USB”, and a sufficient amount of single use sticky electrodes (Covidien Kendall H135SG). The sleep recording device was a sleep mask similar to the final development version 2.5, but with a larger battery pack (three AAA batteries instead of a coin cell battery) and much longer cables (90 cm each), which were connected to the board via a connector and not directly soldered to it (see figure 2.11). The recording locations used in this experiment differed slightly from the suggested electrode positions in the final version of the system (two ECG channels instead of one, only two dedicated EEG channels (Fp1-F1, F1-F2), no reference electrode behind the ear). Moreover, the on-off-switch of the sleep mask was larger and on the outside of the cloth, and the sleep mask textile was larger and had a different color, but was of the same kind of fabric as the final version. The relevant electric parts of the prototype did not differ from the final version of the system regarding the technical specifications of the PCB or its components (same filters, same microprocessor), however, the data were transmitted using an older bluetooth 2.0 chip.

The subjects were instructed verbally and via a written text how to conduct the experiment, and received a demonstration video showing how to attach the electrodes (see figure 2.15). They were also asked to fill out questionnaires during the whole experiment.

2.3.2.4 Procedure

Figure 2.15: Screenshot of the instruction video (Laura Mandt).

The subjects received the materials from the experimenter during the day, and were instructed to record the following night with the Traumschreiber system, i. e.

- to watch the instruction video,
- to switch on the minicomputer and to place the speakers in 2m distance from the pillow,
- to follow the minicomputers instructions, (put on the electrodes at the correct positions, connect them to the sleep mask, switch on the sleep mask, go to bed),
- to conduct the bio signal calibration (e. g. move the eyes in a specific way, clench teeth) according to the instructions of the minicomputer,
- to try to sleep normally,
- to disconnect and switch off everything the following morning,
- to fill out questionnaires about the past night's sleep (Schlaf-Fragebogen A (Görtelmeyer, 1986)) and about the Traumschreiber system (self developed questionnaire "Fragebogen zum Gebrauch des Traumschreibers", see online appendix), as well as a dream report, if they could remember any dream from the experimental night, and
- to return everything the same day.

A control night was conducted one week later, but without the Traumschreiber system, i. e. only questionnaires had to be filled out by the subjects.

The batteries of the sleep recording device were re-charged by the experimenter in between the recordings of the different subjects.

2.3.2.5 Arousal threshold experiment

In order to investigate, how well the system was suited for conducting a small scientific experiment, a “toy” experiment was programmed into the system. The subjects were randomly assigned to one of two groups: one group (N=14) received acoustic stimulation from the system via its USB speakers throughout the whole first night in regular time intervals of 10 minutes, the other group (N=9) received no acoustic stimulation. The stimuli consisted of one second long 1000 Hz sine wave tones of random volume (ranging from not noticeable to room volume level). The goal was to analyze the effect of such a stimulation on the sleep quality, the feeling of recovery in the morning, as well as to confirm the hypothesis, that arousals are more frequent after louder stimuli than after quiet ones.

2.3.2.6 Data analysis

For investigating, whether the Traumschreiber system fulfilled its purpose at the subjects’ homes as intended, the different subfields of the experiment were viewed holistically. This included the following data analyses:

- The data quality of the recordings was assessed descriptively by analyzing the amount of time, during which data was transmitted from the sleep mask to the minicomputer, the sampling rate (number of data points per second), and by visually inspecting the signal quality in each channel for each recording.
- The effect of the system on the sleep of the subjects, as well as on dreaming, was assessed as follows: The Schlaf-Fragebogen A (SF-A) was evaluated as described in the manual by (Görtelmeyer, 1986) and yielded information about the total sleep time, the sleep quality and the feeling of recovery both in the first night and in the control night. For sleep quality, this was based on the time to fall asleep in the evening, the number of awakenings during the night, the length of the awake periods during the night, and a self-assessment of the subject, how constant, deep, restless, relaxed, undisturbed and good the sleep of the previous night was. For the feeling of recovery, this was based on the ampleness of sleep and whether, subjectively, the subject felt even-tempered, drowsy, cheerful, fresh, relaxed, and well-rested the next morning. The data of the first and the control night were then tested for statistically significant differences using Cohen’s effect size d (Cohen, 1992) and permutation tests ((Fisher, 1937), within-subjects), as well as the

differences in the first night between the stimulation and the non-stimulation groups (between-subjects). Dreaming differences were assessed by analyzing the dream reports of the subjects regarding the number of recalled dreams, and the incorporation rates of the experiment and of the stimuli into the dream content, using descriptive and inferential statistics by calculating Cohen's effect size d and permutation tests (between-subjects).

- For finding out, how easy to use and comfortable the system was for the subjects, descriptive statistical analyses were conducted based on the answers to the self developed questionnaire.
- The recorded data were visually inspected for each stimulation, in order to analyze the effect of acoustic stimulation carried out by the Traumschreiber system on sleep and especially on the occurrence of arousals. If the data quality was sufficient, the stimulus was classified as either eliciting no arousal (no change in frequency or amplitude after stimulus onset), or eliciting an arousal (distinct change in the signal visible after stimulus onset). Statistical analyses were then conducted in order to evaluate the stimulus loudness with respect to the classification of an arousal or no arousal applying Cohen's effect size d, and checked for significance using permutation testing.
- Collecting ideas on how the Traumschreiber system should be further developed: This was conducted by summarizing the suggestions of the subjects from the questionnaires, as well as by reporting practical experiences with the system.

For all analyses, descriptive and inferential statistical data analyses were carried out, based on the questionnaires and the recorded data. The recorded data were plotted and analyzed using R and Python scripts (previous versions of the Python data analysis scripts of the final version of the Traumschreiber system).

2.3.3 Third study: Preparing polysomnographic crowd experiments

2.3.3.1 Aim

The goal of this analysis was to collect and describe all tasks, which have to be conducted in order to produce one or more entities of the new system. The preparation of study four (see chapter *2.3.4 Fourth study: A crowd-based polysomnographic experiment*) was analyzed for this purpose regarding production times and production costs. The knowledge obtained by this is especially important for the future usage of the Traumschreiber system in crowd-based projects, for which a beforehand calculation of production times and costs is needed. The description of how to prepare a Traumschreiber study starts with ordering the raw material and ends with handing out the ready-to-use experiment boxes to the subjects. This chapter can also be seen as a short tutorial for setting up a Traumschreiber system study.

2.3.3.2 Description of the preparation steps for a Traumschreiber system study

During the preparation of the fourth study of this dissertation, every preparation step was noted. This included both the hardware production and the necessary tasks for software setup. The tasks summary can be seen as rather independent of the total amount of Traumschreiber systems needed, as every system requires the same tasks to be done in order to obtain a working Traumschreiber system.

For determining realistic production times of each production task, the components of 20 Traumschreiber systems were ordered and put together by a person with amateur skills (at most!) regarding textile and electronic craftsmanship (e. g. sewing and soldering) - the author of this dissertation. The time needed for production was measured for each task. The production times of the work steps, for which a decrease in production time was expected due to learning and practical experience (e. g. soldering, sewing), were assessed for each sleep mask individually. The collected data were then summarized.

For calculating the costs per Traumschreiber system, the real costs for ordering the 20 Traumschreiber systems of the fourth study were noted. Additionally, it was described, whether the costs of the parts of the system stay rather constant regardless of the amount of systems being produced, or whether larger quantities lead to lower costs per system.

The 20 experiment boxes, which were produced in this study, contained the latest development version of the Traumschreiber system: a hightech sleep mask with electrode cables, a Raspberry Pi 3 Model B minicomputer with power adapter, a set of two USB speakers, a package of 50 electrodes, and the paperwork including subject information, consent form and questionnaires.

2.3.4 Fourth study: A crowd-based polysomnographic experiment

2.3.4.1 Aim

The main goal of the Traumschreiber system is to enable naive crowd subjects to conduct complex, interactive sleep and dream experiments on their own at home. The system assists the inexperienced subjects by instructing what to do when, and conducts major parts of the experiments automatically. This makes massively parallelized studies possible. In this fourth study, a demonstration experiment was conducted in order to test, whether the Traumschreiber system is capable of fulfilling its purpose, and if so, how well it is suited and where the pitfalls lie.

During three nights for each subject, a sleep experiment was conducted at the subjects' homes. One aim of recording multiple nights was to find out, whether the subjects became more practiced and secure in how to use the system after a few nights, and if this could be seen in the data transmission success or data quality. Furthermore, it was analyzed whether any first night effects could be found regarding sleep quality or comfort of the system. Another aim was to investigate, whether any signs of wear could be detected after three nights of use.

By recording more than 10 subjects simultaneously, the study also aimed at finding out more about the organizational demands for the scientist (before, during and after the experiment), and whether any problems can be expected because of this parallel design.

The experiment did not aim at delivering new scientific insights about sleep or dreaming in general, but should test the suitableness of the Traumschreiber system for complex automated sleep experiments at the subject's home - including automated real-time analyses of the recorded data. Moreover, the experiment aimed at finding out, how well the simplistic automatic adjustment of the sleep scoring algorithm to individual subject sleep characteristics functions.

An additional exemplary research question was chosen, which was not expected to reveal anything new about sleep or dreaming, but for which the results are mostly well known already. This way, the results of the here conducted experiment could be compared easily to previous studies, in order to see whether it is possible to obtain the same results with this new methodology as in previous studies with full polysomnography in the sleep laboratory. The research question was, in how far REM dreams differ from N3 sleep dreams, regarding how static and thought-like they are, how vivid they are, how bizarre they are, and how entertaining they are, and, additionally, how easily subjects can be woken up from the two sleep stages.

2.3.4.2 Subjects

18 healthy adults (13 female, age between 18 and 31 years) were recruited via the psychology students mailing list of the university. Exclusion criteria were: younger than 18 years; pregnancy or breastfeeding; suffering from psychic or psychosomatic illnesses, neurologic diseases, hallucinations, or sleep disorders (assessed using the standardized LISST questionnaire (Schürmann et al., 2001)); taking sleep drugs, psychotropic drugs, pain killers, or antihistaminics; and having a beard at the chin. The subjects were asked to not consume any alcohol within the last 24 hours before the experiment, to not nap during the day, and to be careful with the materials. Four subjects dropped out before the study started due to personal reasons (the study was conducted during the exam phase of the semester). Thus, 14 subjects collected one experiment box each. One further subject dropped out during the first night of the experiment due to a technical defect of the sleep mask (on-off switch broke), resulting in 13 subjects completing the experiment for three nights each. The subjects signed informed written consent prior to the study and received no payment, but six subject hours, which they needed for their degree.

2.3.4.3 Materials

Each subject received one personal experiment box as described in chapter *3.1.2 The components of the Traumschreiber system*, containing a sleep recording device, a Raspberry Pi 3 Model B minicomputer, which was connected via a USB sound card to two small USB speakers, a sufficient amount of single use sticky electrodes (Covidien Kendall H135SG), as well as printed out questionnaires for all three nights.

2.3.4.4 Time frame

The whole experiment took place within one week, from June 26th to July 2nd, 2017. The subjects were allowed to choose three out of seven nights on their own, during which they wanted to conduct the experiment.

2.3.4.5 Procedure

Before participation, the subjects were informed about the study's goal and methods, and signed informed written consent. Next, the subjects filled out the LISST questionnaire and the subject information sheet, which they then returned together with the consent form to the experimenter. If none of the exclusion criteria were met, the Traumschreiber box was handed out to the subject.

The subjects were instructed to record three out of seven nights with the Traumschreiber system on their own, i. e.

- to watch the instruction video of how to stick on the electrodes, how to put on the sleep mask, how to switch on the sleep mask, how to remove the electrodes and the sleep mask in the morning, and how to recharge the battery of the sleep mask (screenshots of the instruction video in figures 2.16 and 2.17, the whole instruction video can be found in the online appendix),
- to switch on the Traumschreiber experiment station and to place the speakers in 2m distance from the pillow,
- to follow the Traumschreiber experiment station's instructions, (stick on the electrodes at the correct positions, connect them to the sleep mask, switch on the sleep mask, go to bed),
- to conduct the bio signal calibration (e. g. move the eyes in a specific way, clench teeth, etc.) according to the instructions of the Traumschreiber experiment station,
- to try to sleep normally,
- to turn off the Traumschreiber experiment station by unplugging the power cable and to switch off the sleep mask in the morning,
- to recharge the sleep mask batteries by plugging the power adapter of the minicomputer into the sleep mask in the morning, and
- to fill out questionnaires about their sleep (Schlaf-Fragebogen A (Görtelmeyer, 1986)) and about the Traumschreiber system (self developed questionnaire "Fragebogen zum Gebrauch des Traumschreibers", see online appendix).

Additionally, the subjects were woken up up to six times in each experimental night, preferably during REM or N3 sleep (sleep staged automatically in real-time). In case no sleep stage was automatically detected, subjects were woken up after a maximum waiting time (see experiment xml file in figure 2.18, for details about the experiment xml file concept see chapter *3.1.2.2.1 Autonomous, easy to program experiments*). They then had to fill out a brief questionnaire about their dream, in case they had one prior to awakening, and were sent back to sleep again.

Figure 2.16: Screenshot of the instruction video (placing the electrodes).

Figure 2.17: Screenshot of the instruction video (connecting the electrodes to the sleep mask).

```
<root>
    <experiment>
        <sound>welcome.wav</sound>
        <sound>follow_evening_instructions_then_turn_on_TS.wav</sound>
        <wait_for>TS_connected</wait_for>
        <sound>connected.wav</sound>
        <sound>calibration.wav</sound>
        <sound>good_night.wav</sound>

        <wait_for>duration_00:10:00:000</wait_for>
        <wait_for>sleep OR duration_00:30:00:000</wait_for>
        <wait_for>duration_00:30:00:000</wait_for>
        <wait_for>REM OR N3 OR duration_00:45:00:000</wait_for>
        <arousal_procedure></arousal_procedure>
        <sound>night_questionnaire.wav</sound>
        <coding_number></coding_number>


                        ...


        <wait_for>duration_00:10:00:000</wait_for>
        <wait_for>sleep_onset OR duration_00:30:00:000</wait_for>
        <wait_for>duration_00:30:00:000</wait_for>
        <wait_for>REM OR N3 OR duration_00:45:00:000</wait_for>
        <arousal_procedure></arousal_procedure>
        <sound>night_questionnaire.wav</sound>
        <coding_number></coding_number>


        <wait_for>duration_99:00:00:000</wait_for>

    </experiment>
</root>
```

Figure 2.18: The experiment xml file of the fourth study. After the Traumschreiber experiment station played a welcome message, the subject was asked to follow the written and video instructions, and to switch on the Traumschreiber sleep mask, when lying in bed. Next, the subject was informed that the connection was established, and instructed to conduct the bio signal calibration. Next, the subject was wished a good night. Each arousal block consisted of waiting for sleep, detecting REM or N3 sleep, waking up the subject, asking to fill out the night questionnaire, and saying a random number, which had to be noted in the night questionnaire. The three dots stand for four further repetitions of the arousal block.

2.3.4.6 Data analysis

<u>General results</u>

First, the data of all subjects was evaluated, regarding whether the Traumschreiber system conducted its tasks as planned: Were the subjects instructed and enabled to record polysomnographic data on their own autonomously in their natural sleep environment? How reliable were the subjects? The answers to the questionnaires as well as the data of the recordings were summarized using descriptive statistics.

Data quality

The recorded nights were analyzed regarding the total recording duration and the transmission quality using the data_transmission_analysis.py script (see chapter *3.1.2.2.4 Data visualization and data analyses*). Based on the table and the plots created by the script, the nights were classified as “good transmission quality” (good signal quality determined by the script and full night recorded) or “bad transmission quality”. Descriptive statistics and inferential statistics based on Cohen’s effect size d (Cohen, 1992) and a two-sided permutation test (Fisher, 1937) for statistical significance were used to compare the first, second and third recording nights regarding data transmission.

Next, all nights with good transmission quality were further evaluated. First of all, all channels of all recordings were analyzed regarding their data quality: Every channel of every recording was visually inspected, whether any periods of time with bad data quality occurred, and if so, how long they were. The post_analysis.py script was used for this. Next, it was summarized for each of the categories “EMG”, “EOG”, “EEG” and “ECG”, how many channels delivered a good signal in at least 90% of the night. Moreover, the ratio of recordings was calculated for each category, in which at least one channel recorded a good signal in at least 90% of the night (both for only the nights with good signal transmission, and in total over all second and third nights). Finally, the categories were compared between the nights (number of channels with good signal in at least 90% of the night) using Cohen’s effect size d and two-sided permutation testing for significance.

Sleep quality and comfort of the system

The answers of the questionnaires (Schlaf-Fragebogen A and the self developed questionnaire about the system) were evaluated regarding differences in the sleep quality (SQ), the feeling of recovery in the morning (FoR) and the comfort of the system between all three nights, as well as compared to reference groups provided by the questionnaires (SQ and FoR). The sleep quality and feeling of recovery were evaluated as described in the manual to the Schlaf-Fragebogen A (sleep quality items: time to fall asleep in the evening, the number of awakenings during the night, the length of the awake periods during the night, and a self-assessment of the subject, how constant, deep, restless, relaxed, undisturbed and good the sleep of the previous night was, into account; feeling of recovery items: ampleness of sleep and whether, subjectively, the subject felt even-tempered, drowsy, cheerful, fresh, relaxed, and well-rested the next morning). The comfort of the system was based on the single questions of the self developed questionnaire.

Descriptive and inferential statistics applying Cohen's effect size d and two-sided permutations tests for significance were used.

Automatic sleep scoring algorithm and adjustment to the individual subject

Using the plots generated by the script plot_night_predictions.py (for details about the plotting script, please see chapter *3.1.2.2.4 Data visualization and data analyses*), it was first analyzed, whether the system was online and predicted sleep stages during every second of the recorded nights. Next, it was evaluated using the plots of the aforementioned script and the whole-night sleep EEG time-frequency plot of the post_analysis.py script, in how many nights the uncorrected sleep stage probabilities led to a plausible hypnogram. The same analysis was conducted for the sleep stage probabilities, which were adjusted based on the subject-individual sleep characteristics in real-time during the night, and for the post-optimized automatic sleep staging. Furthermore, it was evaluated separately, whether an automatic adjustment to the individual subject was visible at all, and whether it was of benefit, by visually inspecting the generated plots of the nightly predictions.

N3 and REM sleep differences

Using the answers of the nightly questionnaire regarding the dream content ("What describes your thoughts well, which you had before you woke up?": "rather static thoughts, no story", "lively or with an action-packed plot", "it was bizarre", "it was entertaining; I'd like to continue dreaming about it". All four items were rated on a scale from "0-not at all" to "7-very much".), differences between the two sleep stages REM and N3 were determined by calculating Cohen's effect size d and checking for statistical significance using a two-sided permutation test. The sleep stage was determined by (human) visual scoring using the plotting features of the post_visualization.py script.

Furthermore, the same statistical procedure was used to find out, whether subjects woke up faster from N3 or from REM sleep. The answers to the question "Which letter did you hear first after waking up?"[17] were used for determining the time needed to wake up. It was looked up for every nightly wake-up procedure, which number the letter had, which was written down by the subject.

17 Details about the idea to wake up the subjects using a sequence of acoustic letter stimuli are described in chapter *3.1.2.2.1 Autonomous, easy to program experiments* (*Table 3.2*).

Sleep depth

Furthermore, for the first, second and third night it was analyzed, how quickly the subjects woke up by the nightly stimuli, with the hypothesis that during the second and third night the subjects slept deeper and woke up later, because they became used to the sleep experiment situation. Pearson's correlation coefficient was calculated for the night number (1-3) and the number of the first heard letter (1-6). A one-sided permutation test was applied to test for significance.

The same type of analysis was carried out to investigate, whether the subjects woke up faster during later parts of the night (i. e. more towards the morning).

Workload of the experimenter and costs of the experiment

The actual tasks, which remained to be done by the experimenter and were not carried out by the Traumschreiber system, were briefly reported. Moreover, the workload of the experimenter and the costs of the actual experiment were summarized.

3 Results

3.1 Development

3.1.1 Overview

After about 3 years of development, the requirements described in chapter *2.2.1 Defining the requirements towards the Traumschreiber system* are fulfilled. The Traumschreiber system contains a battery-driven hightech sleep mask, which can be connected via bluetooth low energy to an experiment station – a Raspberry Pi 3 Model B minicomputer. The Traumschreiber sleep mask measures the electrophysiological sleep data of the subject on eight channels using single use sticky electrodes. The data is stored and processed in real-time on the minicomputer using Python scripts – including the possibility to use advanced AI algorithms like deep neural networks based on Keras and Tensorflow. During experiments, the Traumschreiber experiment station can instruct and stimulate the subject via two small USB speakers. A simply adjustable xml script can be used to program complex sleep experiments into the system in a very short time. An advanced data visualization and analysis tool as well as several other python scripts make data standardized analyses quick and easy.

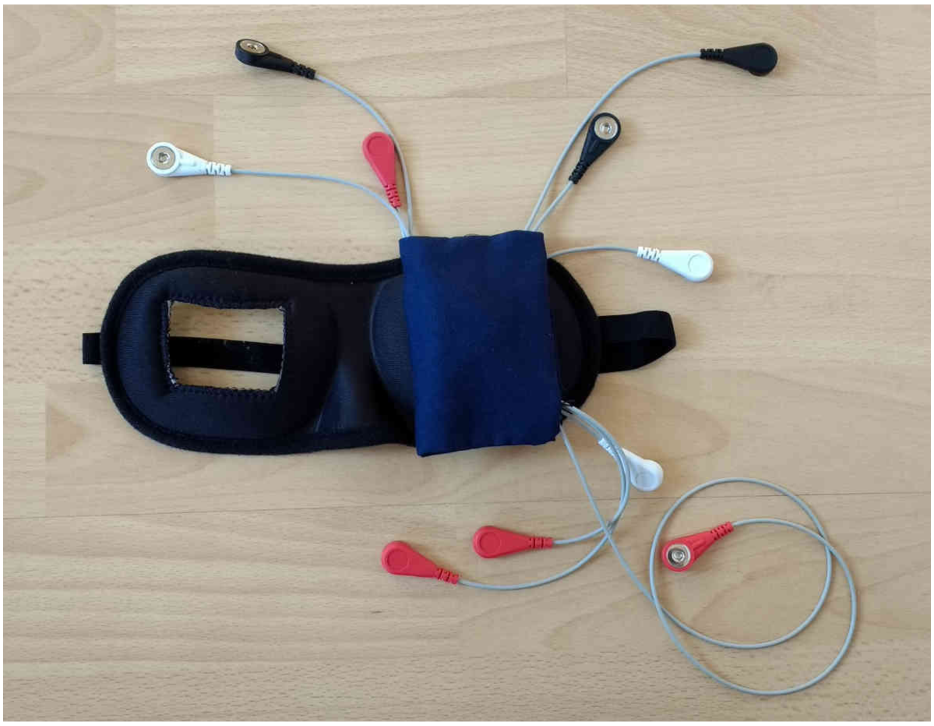

Figure 3.1: The final version of the Traumschreiber sleep mask.

Figure 3.2: One complete Traumschreiber system experiment box, including the sleep mask, the Raspberry Pi minicomputer, the speakers, electrodes and questionnaires. Each subject receives one box, records polysomnographic sleep data at home following the instructions of the Traumschreiber system, and returns the box including the data to the experimenter. No experimenter is needed at the place of recording.

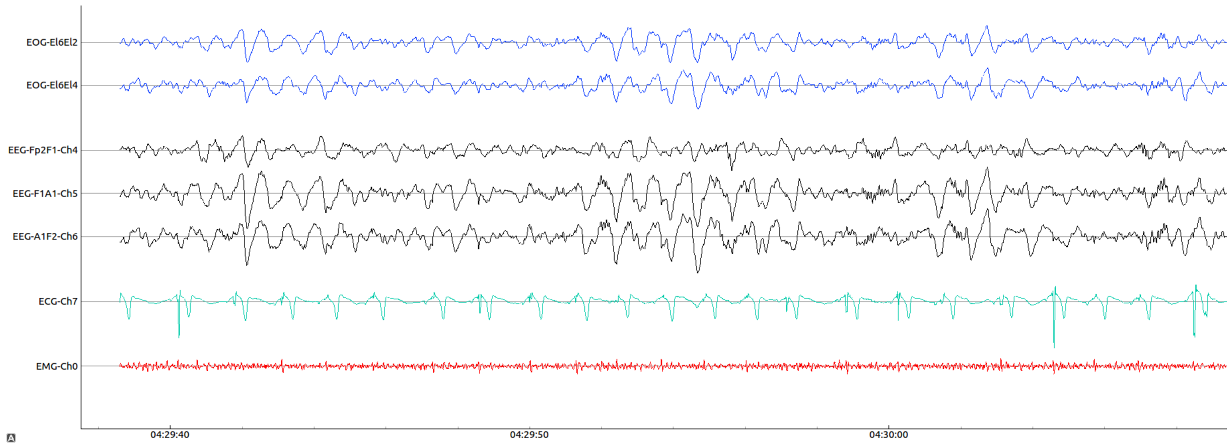

Figure 3.3: N3 sleep (slow wave sleep, SWS) recorded by a subject at home with the Traumschreiber system. Note the clearly visible slow waves.

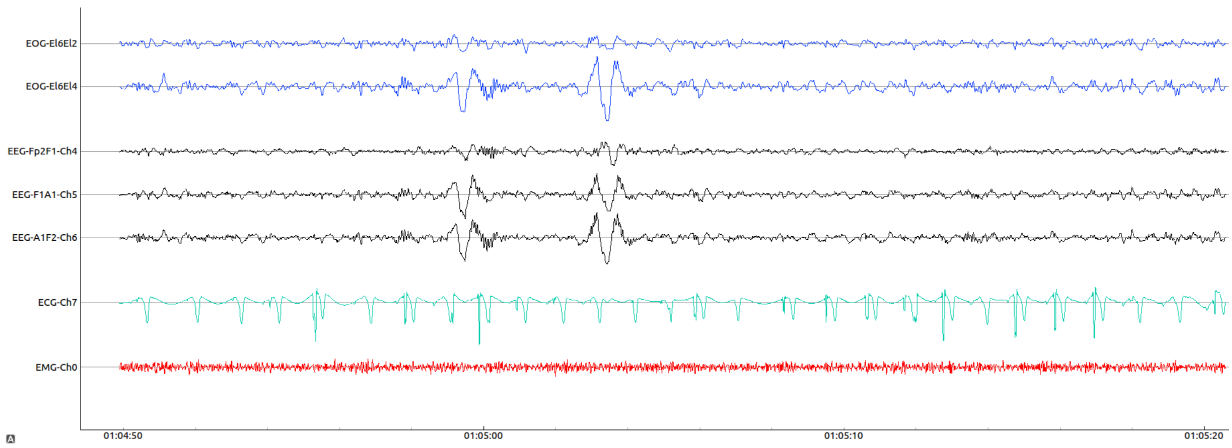

Figure 3.4: N2 sleep recorded by a subject at home with the Traumschreiber system. Note the clearly visible sleep spindles and K-complexes.

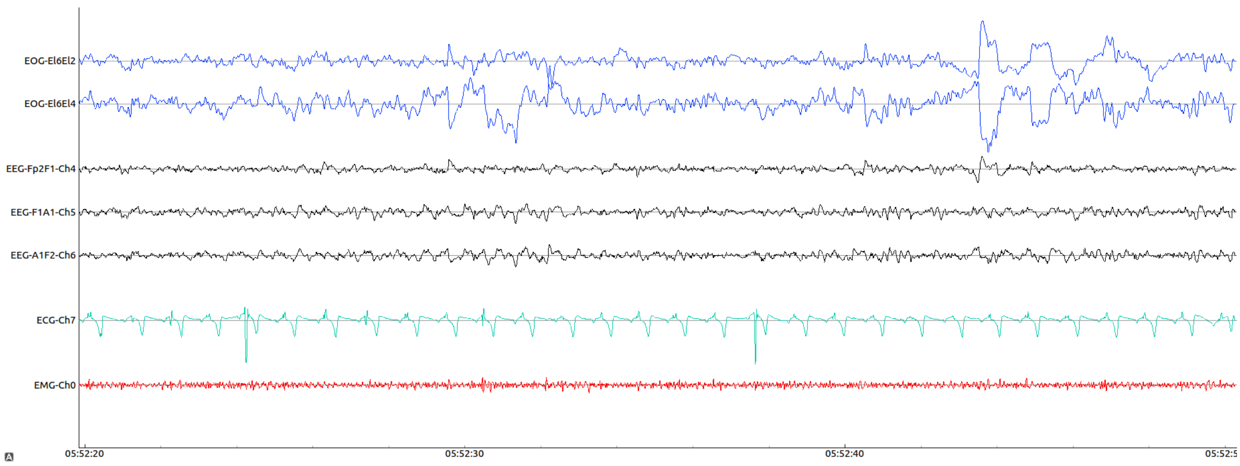

Figure 3.5: REM sleep recorded by a subject at home with the Traumschreiber system. Note the clearly visible rapid eye movements.

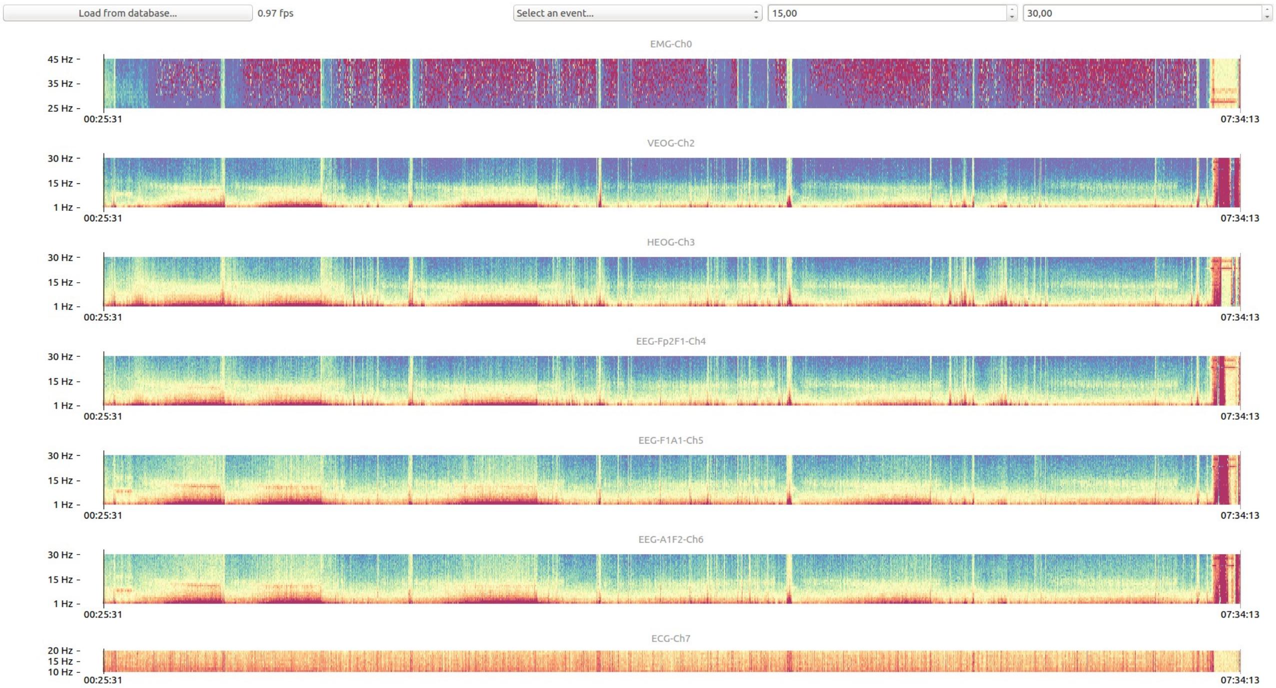

Figure 3.6: Time frequency plots of a whole night recording of the Traumschreiber system of all relevant channels (the channel between the chin and the bottom eye electrode is not depicted). Note the clearly visible activity in the slow wave and the sleep spindle frequencies, and the arousal/movement artifacts, which give the sleep researcher an instantaneous overview of the night.

3.1.2 The components of the Traumschreiber system

3.1.2.1 Hardware

3.1.2.1.1 Sleep mask

The sleep mask is worn on the eyes and is based on a black cotton-synthetic sleep mask with an adjustable, elastic band. A 5x4 cm hole is cut into the right eye of the sleep mask, enabling the subject to look through the sleep mask. A 10x7cm red or blue piece of cloth (a pocket) is sewn on the front of the left eye, which contains and protects the electric parts of the sleep mask, i. e. the PCB. This cotton bag can be opened and closed with a hook and loop fastener, and is connected to the sleep mask with four eyelets. The board lies inside, and is placed in a way that the two LEDs, which are mounted on the PCB, can shine through two of the four eyelets, ready to stimulate the (closed) eyes during the night.

Ten single use sticky electrodes can be connected to the board via cables of different length. In the suggested configuration, two cables are connected to electrodes on the subject's chin (measuring EMG), three cables are connected to electrodes outside and below the left eye, outside and above the left eye, and outside and above the right eye (measuring VEOG and HEOG), three cables are connected to two electrodes on the left and right forehead as close to the hairline as possible and to one electrode on the mastoid behind the left ear (measuring EEG), one cable is connected to an electrode on the left side of the chest (measuring ECG), and the last cable is connected to another electrode on the forehead, which is used as a ground electrode. The cables are adjusted in length and soldered onto the PCB so that they can easily reach the electrode locations, without being too long – thus, reducing the weight of the sleep masks and increasing comfort.

The cable design and the electrode locations can be arbitrarily changed by using different cable lengths and sticking the electrodes to other hairless parts of the skin, allowing for different recording locations, if needed. Table 3.1 displays the channels which are recorded in the suggested configuration. This configuration is suggested as it records EMG, EOG and EEG, which is needed for standard polysomnographic recordings, and additional ECG, which is useful for example for heart rate variability analyses. The channels can be combined, i. e. it is possible to re-reference the electrodes to one common reference.

Electrodes	**Positions**	**Channel number**	**Suggested use**
0 and 1	Chin, chin	0	EMG
1 and 2	Chin, below left eye	1	-
2 and 3	Below left eye, above left eye	2	VEOG
3 and 4	Above left eye, above right eye	3	HEOG (+EEG)
4 and 5	Above right eye, left forehead close to hairline	4	EEG (Fp2-F1)
5 and 6	Left forehead close to hairline, left mastoid (behind the ear)	5	EEG (F1-A1)
6 and 7	Left mastoid (behind the ear), right forehead close to hairline	6	EEG (A1-F2)
7 and 8	Right forehead close to hairline, left side of the chest	7	ECG

Table 3.1: Overview of the electrode positions and recorded channels in the suggested recording layout.

The PCB is equipped with a holder for a 3.6V lithium-ion rechargeable coin cell battery, and a micro-USB recharging plug. The sleep mask can thus be recharged using a standard smartphone recharging cable, or the power cable of a Raspberry Pi. Furthermore, the PCB has a power switch, making sure that no battery power is used, if the sleep mask is not in use. Both the recharging plug and the power switch are hidden inside the cover bag, but can be reached with a little bit of fiddling without opening the cover bag.

Furthermore, the PCB is equipped with dozens of electric components, ranging from simple resistors to microcontrollers. Using the data flow from the electrodes to the minicomputer as a metaphor, the differential signal between two electrodes is first amplified by a factor of 100 by instrumentation amplifiers, then passes hardware-based filters (an active 2nd order Sallen-Key high-pass filter with a gain by a factor of 10 and a cutoff frequency of 0.05 Hz, and a passive 1st order resistor-capacitor low-pass filter with a cut-off frequency of 72 Hz, resulting in an attenuation of the signal by a factor of 10 at roughly 720 Hz (plots of the filter response in the appendix)), is then again amplified (by a factor of 1, which is adjustable in software) and sampled by an analog to digital converter (ADC) at 244 Hz with 12 bit resolution. Both the analog to digital conversion and the last amplification are done by a microcontroller (Atmel XMEGA8E5). The obtained values for each channel can be encrypted by a dedicated chip in hardware (model ATECC508A, not active at the moment) and are then passed via UART to a bluetooth chip (Broadcom BCM20737S), which transmits them via bluetooth low energy to arbitrary BLE-able devices, e. g. smartphones or, as used in the final version of this system, to a Raspberry Pi 3 Model B minicomputer. In case the BLE signal is lost, for example if a subjects goes to the toilet, the connection is automatically re-established once the signal is in reach again. The BLE chip can also receive commands from the paired device, e. g. for setting the color of the two LEDs to different colors. Several pins on the microcontroller are not in use so far, making it possible to add further customized features, e. g. connecting and controlling other stimulating devices. Further technical specifications can be found in the online appendix.

3.1.2.1.2 Experiment station

Besides the sleep mask, a Raspberry Pi 3 Model B minicomputer with the linux derivate Raspbian Noobs as operating system is the second essential part of the Traumschreiber system. The Raspberry Pi is connected to two small USB speakers (Trust Leto 2.0 USB), for which it uses an external USB sound card in order to improve sound quality, since the standard audio jack of the Raspberry Pi produces a noisy audio signal. The minicomputer guides the subject through the experiment by giving acoustic instructions of what to do when. Moreover, the minicomputer saves and analyzes the incoming data from the sleep mask in real-time.

In principle, a smartphone could be used as an experiment station, too. This option was investigated in a bachelor thesis project of Martin Jäkel (Jäkel, 2017, supervised by the author of this dissertation). However, it became apparent, that developing a complex system like the Traumschreiber system for a smartphone is much more complicated and takes much longer time than for a linux-based minicomputer. As a result, despite the promising impressions of the developed Android app prototype (see figure 3.7 for screenshots, complete code in the online appendix), this option was postponed to future developments.

Following this line of thought, the direct data transfer of the recorded data via smartphone over the internet to a web server was briefly investigated as well. The web server analyzes the data in real-time and streams back its real-time calculations to another device – e. g. the sleep researcher's computer (web browser). The idea behind would be to enable the sleep researcher to see the recorded data of all subjects in real-time, or possibly to even combine the data of multiple subjects in new experimental paradigms. Even though this direct data transfer via internet worked well in a demo case, this topic was not investigated further.

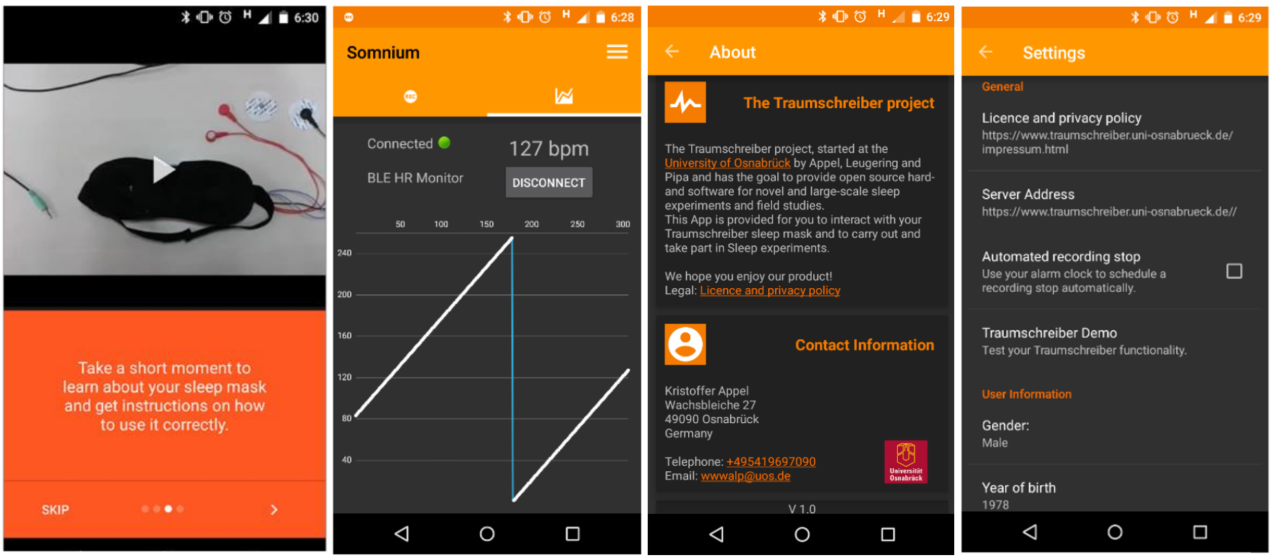

Figure 3.7: Four screenshots of the prototype Android app, demonstrating that an Android smartphone could be used as the experiment station instead of the Raspberry Pi minicomputer, if this line of development is further pursued (image source: (Jäkel, 2017)).

3.1.2.2 Software

3.1.2.2.1 Autonomous, easy to program experiments

Several python scripts are stored on the minicomputer, some of which are executed during startup. The user (experiment subject) only needs to connect the minicomputer to a power plug. After about 30 seconds, the Traumschreiber software is started and the user is welcomed via the two speakers. What happens next, can be specified in the experiment xml protocol file (see figure 3.8 for a simple example, and table 3.2 for further explanation). In a basic experiment setup, the user first receives some acoustic instructions (e. g. to put on the sleep mask and to switch it on), before going to bed and conducting the sleep part of the study. Every experiment action, which the Traumschreiber system carries out according to the experiment xml protocol after the sleep mask is switched on, is time logged, and can be looked up later during data analysis.

```xml
<root>
    <experiment>

        <sound>welcome.wav</sound>
        <sound>follow_evening_instructions_then_turn_on_TS.wav</sound>
        <wait_for>TS_connected</wait_for>
        <sound>connected.wav</sound>
        <sound>calibration.wav</sound>
        <sound>good_night.wav</sound>

        <wait_for>sleep</wait_for>
        <wait_for>duration_07:30:00:000</wait_for>
        <sound>alarm_clock_song.wav</sound>

    </experiment>
</root>
```

Figure 3.8: Example xml experiment file. After a welcome message of the Traumschreiber system after startup, the subject is asked to follow the instructions from the video tutorial and the subject information leaflet. In these instructions, the subject is told how to put on the sleep mask and when to switch it on (when being ready for sleep). Next, when a connection to the sleep mask was established, the subject is informed about this and is asked to conduct the bio signal calibration. Afterwards, the subject is asked to sleep. Next, the Traumschreiber system waits for sleep onset, i. e. that the internal real-time sleep classifier detects either REM, N1, N2 or N3 sleep. 7.5 hours later, the Traumschreiber system wakes up the subject with a melody.

xml element	Function
<root>, </root>, <experiment>, </experiment>	Setting up the experiment xml file.
<sound>abc.wav</sound>	Plays the sound file “abc.wav”, which has to be located in the experiment folder, via the USB speakers.
<wait_for>abc</wait_for>	Pauses the experiment execution, until the condition “abc” is met. “abc” can have various values: • “duration_12:34:56:789”: waits for an arbitrary period of time, in this example 12 hours, 34 minutes, 56.789 seconds • “TS_connected”: waits with any further experiment execution until the sleep mask is connected • “sleep”, “N1”, “N2”, “N3”, “REM”, “wake”: waits until the Traumschreiber system has detected sleep or the sleep stage specified • “LRLRLR”: waits until the Traumschreiber system has detected a left-right-left-right-left-right eye movement pattern It is possible to combine these elements using “OR”. For example, if “abc” is set to “N3 OR REM OR duration_00:30:00:000”, the Traumschreiber system waits until either N3 sleep or REM sleep have been detected or 30 minutes have passed (whatever happens first). Only then the next xml element is carried out.
Customized elements, e. g. <arousal_procedure> or <coding_number>	Any customized element can be used for advanced experiment control, if the action is specified in the python file “eese.py” in the function “action”. For example, the xml element <arousal_procedure> evokes one such customized function. In this function, every five seconds one of the letters 'o', 'b', 'r', 'i', 'h', 'j', 'l', 'v', 'm', 'ä' is randomly selected as an acoustic stimuli, with increasing volume, in total five times. This is followed by six alarm clock-like beeps. This procedure was used to wake up the subjects and to let them write down, at which letter they woke up. As a second example, the xml element <coding_number> leads to the playback of the next element in a list of acoustic stimuli ('4', '9', '6', '7', '8' and '5'). i. e. every time the xml element is reached during the experiment, another number is presented to the subject. This was used to check, whether a subject really woke up and filled out the nightly questionnaire, or just invented some answers the next morning.

Table 3.2: Detailed description of the experiment xml file commands.

3.1.2.2.2 Automatic sleep staging and pattern recognition

The Traumschreiber system supports a simple form of real-time sleep stage classification, and can adjust the experiment accordingly. For example, it is possible to wait for the occurrence of REM sleep and then playback a sound in order to wake up the subject (e. g. for REM sleep deprivation studies, or for collecting REM dream reports). For this, Keras (Chollet, 2015) with Tensorflow (Abadi, Barham, et al., 2016) backend is used, which is one of the best and most advanced frameworks for machine learning using deep neural networks (Kovalev, Kalinovsky, & Kovalev, 2016)[18]. The neural network classifies each second of sleep recording as either wake, N1, N2, N3 or REM sleep. The Traumschreiber system then averages the classifications over the last 20 minutes, and calculates which sleep stage was most prominent in this time window. Based on the individual sleep characteristics of the subject in previously recorded nights and a calculation, how much the distribution of classifications of each night differed from the average healthy human sleep stage distribution found in literature (Rama & Zachariah, 2013), a correction term is then applied to the data. This enables the Traumschreiber system to adjust the sleep stage classifications subject-individually in real-time. For example, if less N2 sleep was detected by the Traumschreiber system for a specific subject in previous nights than would be expected for healthy human subjects, an additive bias term is applied to make the live sleep stage classification more likely (assuming the subject has a healthy sleep). In this example, it might be the case that for this very subject, less EEG activity in a specific frequency band is measured, making the neural network select the wrong sleep stage more often. For a critical review, of how well this procedure works in practice, see chapter *3.2.4.6 Automatic sleep scoring algorithm and subject-specific adjustment*.

A similar simplistic neural network-based approach as for classifying sleep stages in real-time is implemented into the Traumschreiber system for detecting specific graphoelements during recording, e. g. specific eye movement patterns like the lucid dreaming eye signal left-right-left-right-left-right[19]. Note, however, that this real-time pattern recognition algorithm was trained only on few training examples of one subject (the author of this dissertation) and needs further improvements, before it can be used in autonomous experiments. See figure 3.9 for an example of the real-time eye movement detection.

18 Further details on the technical implementation can be found in the appendix.

19 Further details on the technical implementation can be found in the appendix.

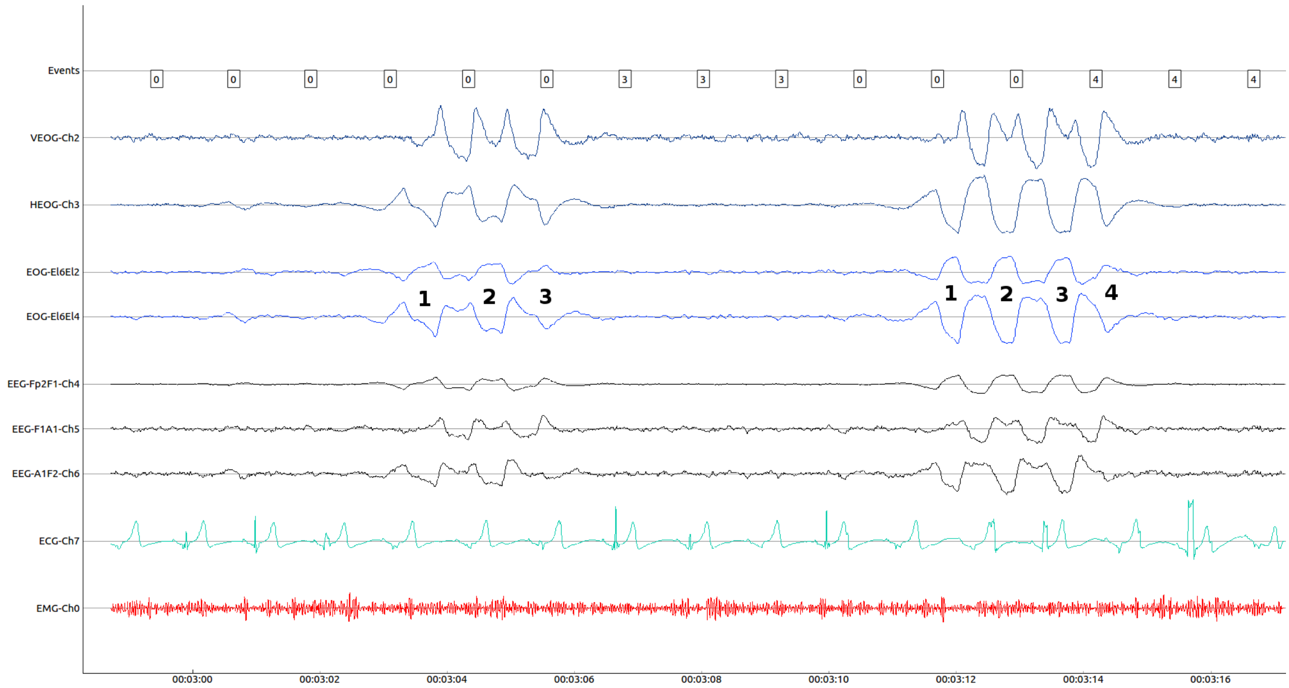

Figure 3.9: Example of the real-time pattern detection using a simplistic Keras/tensorflow neural network approach. Note the 3xLR eye movement of the subject at 00:03:04 and the corresponding real-time classification "3" after the eye signal (top row), and the 4xLR eye movement at 00:03:12 and the corresponding real-time classification "4", as well as the "0" classifications for the rest of the time.

Using state-of-the art machine learning technology, the Traumschreiber system is thus able to not only analyze the macro structure of sleep in real-time (i. e. sleep stages) – it can also detect patterns in the data in real-time. It has to be emphasized though, that it was not the goal (yet) to optimize the performance of the machine learning algorithms, not only as not enough recorded nights are available as training data at the moment. The neural network within the Traumschreiber system should be seen as a placeholder for more elaborated, better trained deep neural networks. Any more sophisticated deep neural networks can then be used instead of the simplistic approaches for sleep staging or pattern recognition developed up to now. They can rely on the same hardware and software layout – future developers only need to exchange two files: the serialized JSON description of the network structure and the serialized weight matrix of the network. In case the input data structure to the network is different, a few more lines of code need to be adjusted in the python file classification_methods.py.

3.1.2.2.3 Real-time data processing using encapsulated, modular scripts

The software is designed that the data coming from the sleep mask via BLE are received by a Python script, which directly broadcasts them using a socket server via the user datagram protocol (UDP). This enables arbitrary many listeners (clients) to receive, store or process the data further – also in independent processes and (in principle) also in any arbitrary programming language that supports sockets and UDP. A second UDP server is created automatically during start of the system, which forwards control messages between all different software modules, enabling a communication between arbitrary scripts written in arbitrary programming languages and running in several processes.

In the final version of the Traumschreiber system, one such modular script (save_data_to_database.py) saves the raw data every 30 seconds into an sqlite database, i. e. the data is stored safely on the microSD card even if the minicomputer is abruptly disconnected from power supply. An experiment subject can thus just unplug the minicomputer in the morning without having to shut down the system.

Another modular script (replay.py) is able to simulate a recording: by sending data via the UDP port, all other software modules can be tested for functionality also during the day, which makes the software development much easier.

A third modular script serves as an event logger. It listens to all messages, which are forwarded by the control server, and identifies events, which are then saved into the sqlite database. That means, that any module can directly save any marker together with a time stamp into the database, without having to know anything about the underlying database filename, structure or type. This feature is for example used for saving the time stamps of acoustic stimuli. Furthermore, it is also possible to save events manually by using the GUI of the script.

3.1.2.2.4 Data visualization and data analyses

Last, but not least, the Traumschreiber system provides several scripts for data visualization and data analysis – both for real-time visualization during a recording, and for later post-analysis.

Data transmission analysis

The stand-alone python script recording_transmission_analyses.py calculates for each recorded database in a given folder,

- when the recording started (timestamp of first data point), and when it stopped (timestamp of last data point),
- the total recording duration, i. e. the difference between the first and last datapoint,
- whether the recording has a total recording duration of less than 5 minutes and should be classified as “mistake”, e. g. for when the subject mistakenly started the experimental recording due to having switched on the sleep mask during preparation and needs to replay the calibration later,
- whether the recording has a total recording duration of more than 5 minutes (classified as “valid recording attempts”),
- the ratio of seconds with no or with bad data transmission (i. e. less than 50 or 232[20] data points, respectively), and the ratio of seconds with good data transmission (i. e. at least 232 data points),
- classified the recording into one of the categories “mistake”, “valid recording attempt with signal loss”, “valid recording attempt with bad signal transmission”, and “valid recording attempt with good signal transmission”, depending on the ratio of no, bad and good seconds regarding the transmission quality,
- automatically finds the related temperature log file for the Raspberry Pi and obtains the temperature development throughout the night, and the time duration the Raspberry Pi was listening for data packages.

The script then plots a data transmission diagram for each database file, in which one can see, how the transmission changed in the course of night. Furthermore, the most important statistics regarding data transmission success and the Raspberry Pi temperature and online time are displayed. Moreover, the script saves the calculated data in a summary csv file, which can then be used for further analyses. Please see figures 3.10 and 3.11 for exemplary plots of a recording with good signal transmission and a recording with signal loss.

20 Why 232? In optimal case, 244 data points are transferred on average every second. Bad data transmission was defined as more than 5% of data loss during data transmission, i. e. less than 232 data points per second.

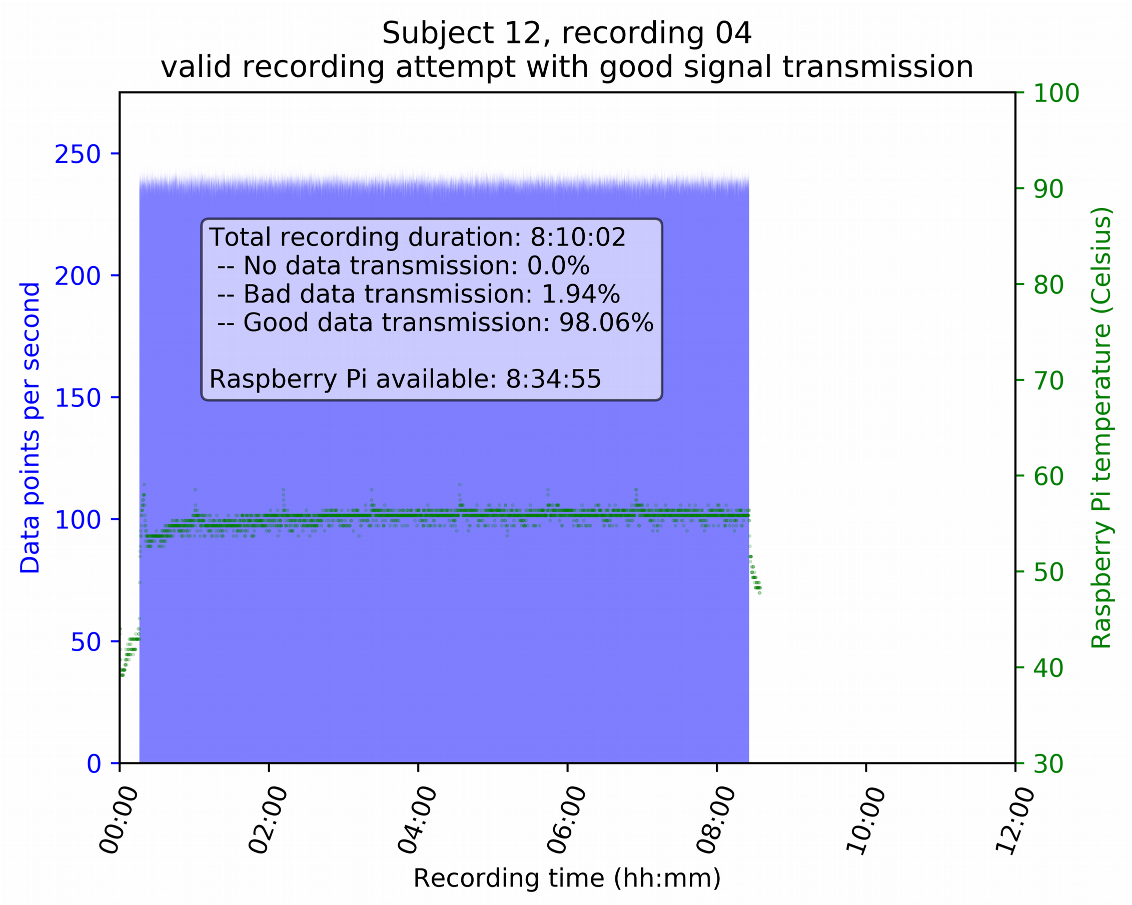

Figure 3.10: This plot, which was generated by the recording_transmission_analyses.py script of the Traumschreiber data analysis package, shows that the signal transmission rate stayed constantly high throughout the whole night, close to the optimum of 244 data points per second. Only for a small amount of time, the signal transmission was bad, i. e. more than 5% of the data points of a second were lost. It can further be seen, that the sleep mask was switched on and started sending data about 15 minutes after the Raspberry Pi was switched on, and switched off a about 10 minutes before the Raspberry Pi. The temperature of the Raspberry Pi stayed constantly at around 57 °C during recording, showing that the Raspberry Pi did not overheat due to potentially too heavy calculations.

<u>Real-time data visualization</u>

The script “standalone_plotting.py” enables the researcher to quickly look at the recorded data in real-time. All eight channels can be bandpass filtered and are displayed (last 10 seconds). This script can be used as a reference of a minimal data processing pipeline, as it also includes the BLE handling and plotting of the raw signal.

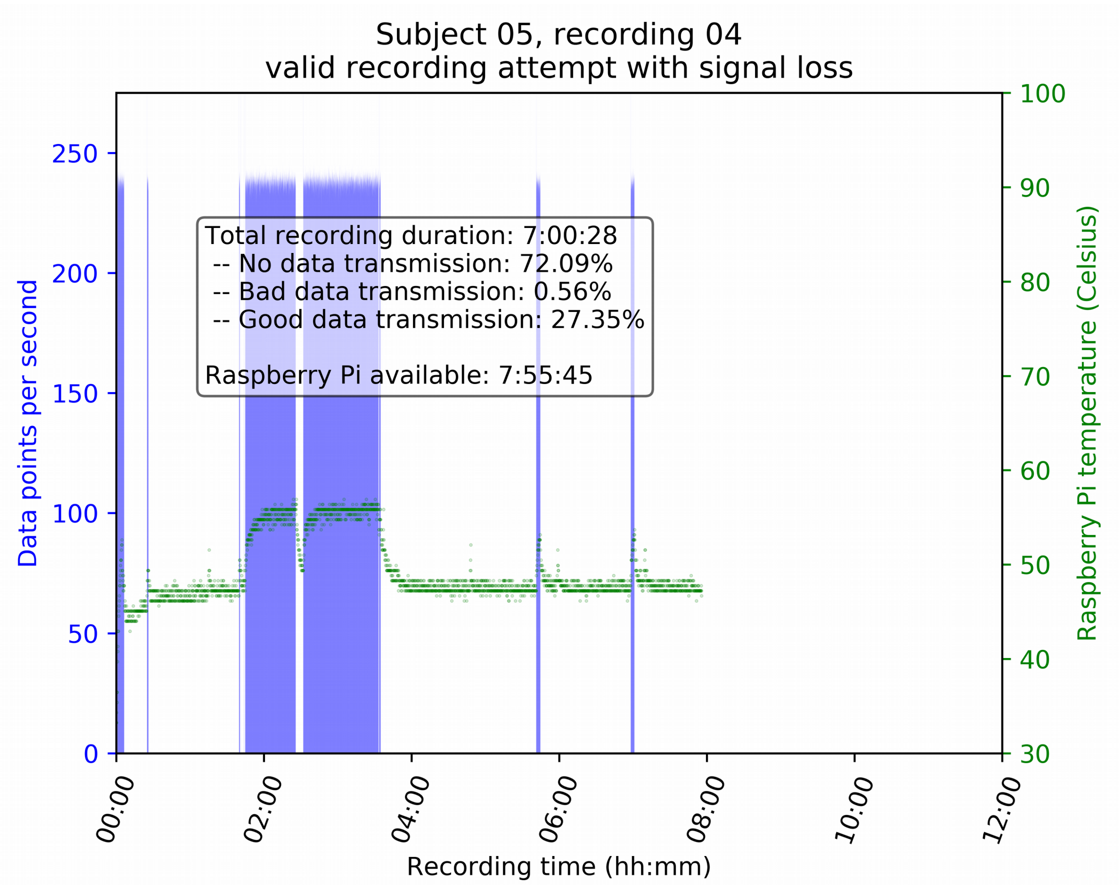

Figure 3.11: This plot, which was also generated by the recording_transmission_analyses.py script of the Traumschreiber data analysis package, shows that no data was transmitted in this recording throughout most parts of the night. The Raspberry Pi was switched on the whole time, as can be seen at the green dots indicating its temperature. Furthermore, it can be seen, that the temperature of the Raspberry Pi went up by 10°C, when it received data packages, but stays far below the threshold of 80°C, at which it reduced the CPU speed in order to prevent overheating. Thus, it seems unlikely, that the data loss of this recording was a reception problem of the experiment station. It is more likely, that the sleep mask did not send data throughout the whole night, probably due to a loose on-off power switch of the sleep mask used in this recording.

Visualizing and manually sleep scoring a recording

A recorded night can be viewed and manually scored by running the script post_visualization.py. After starting the script, a GUI opens and a database can be selected by clicking a button. The data are completely loaded into RAM, which is why this script cannot be executed on a Raspberry Pi 3 Model B (too few RAM for a whole night recording). The advantage of loading the whole data into RAM is that afterwards one can jump to any point in the recording without waiting time.

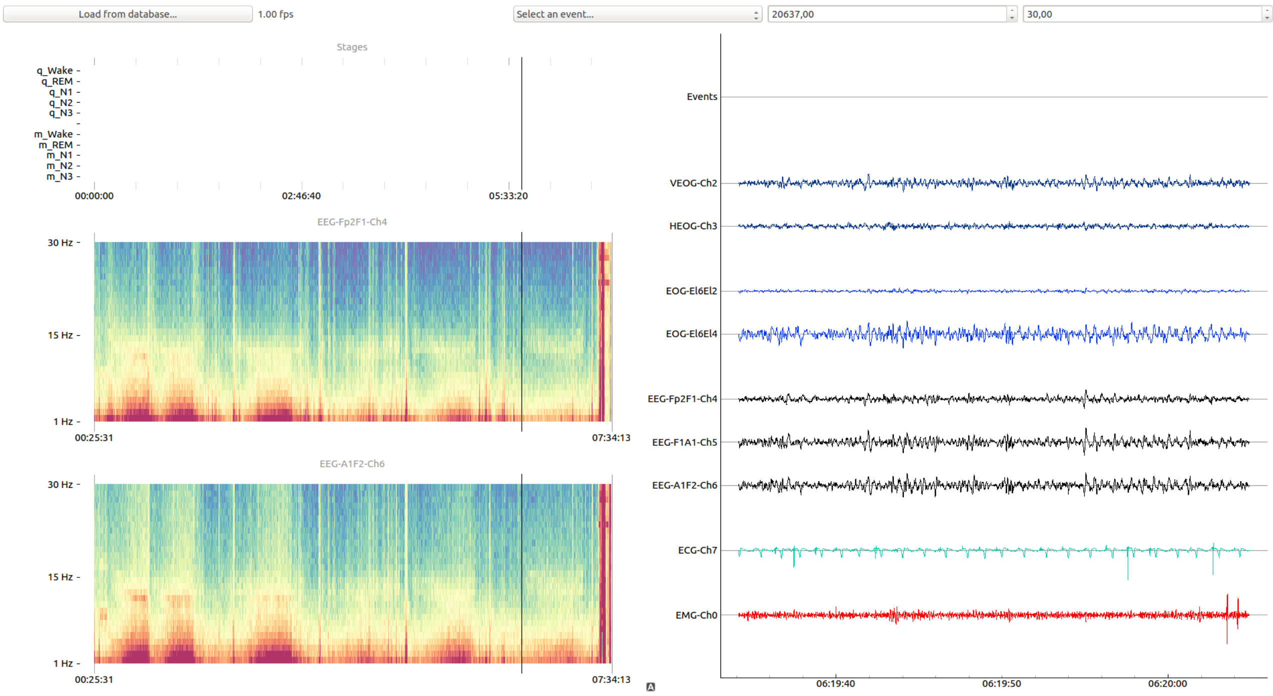

Figure 3.12: The GUI of the post_visualization.py script after loading the data, which was recorded autonomously at the subject's home by the Traumschreiber system. The left side shows an overview of the complete night, here two EEG channels are displayed in a time frequency plot. Above is the (still empty) sleep staging plot. The right side depicts a detail view of 30 seconds length (length can be adjusted in the top right corner). The black lines in the left plots indicate, which time point is selected for the detailed view.

On the right side of the GUI, the raw data are displayed, usually in a 30 second window. This is the detailed view of the data, in which the researcher can look for sleep graphoelements like sleep spindles or REMs. Moreover, the events, which took place during this time window, as displayed in the right plot as well. The length of the time window can be adjusted in the top right corner. On the left side, transformed versions of the data are shown, e. g. a time frequency plot using fast fourier transform (FFT) or complex morlet wavelets. This is useful for getting an overview of the night and channels, and with a bit of practice one can identify periods of time with a lot of slow wave activity (N3 sleep), spindle actitivy (N2) or mixed frequency EEG with REMs (REM sleep). Moreover, one can identify arousals, as they cause artifacts in the signal and its frequency transform. When pressing the keyboard shortcuts Y, X, and C, only the left, both or only the right plots are shown, enabling the scientist to inspect the plots in greater detail.

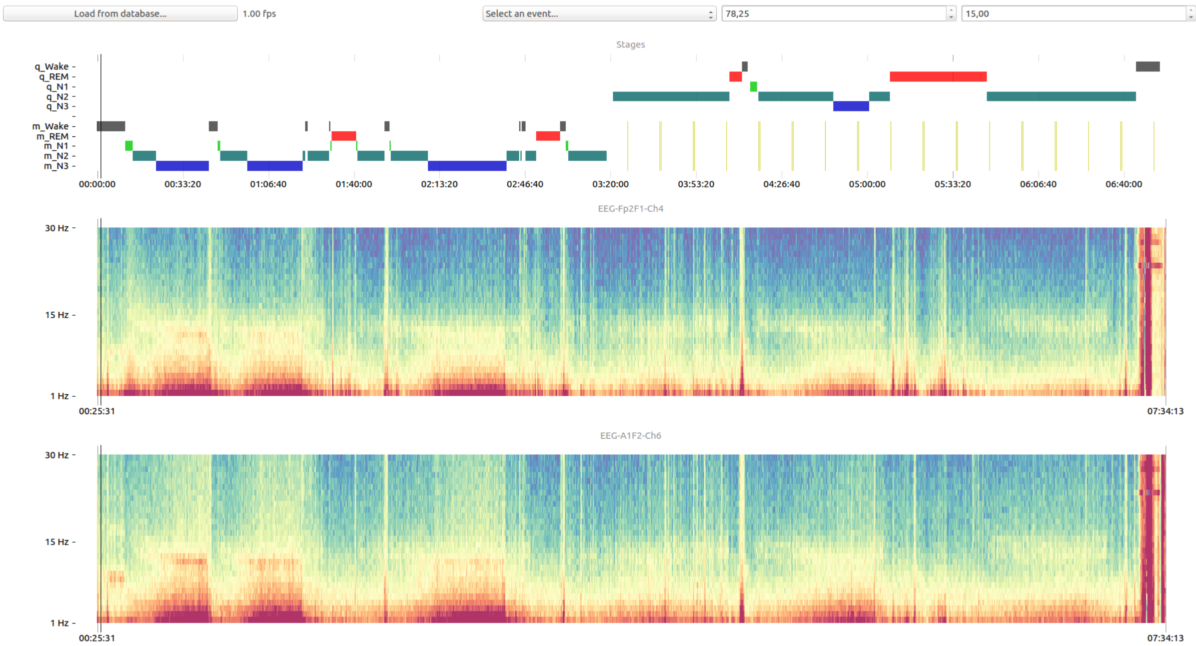

Figure 3.13: After pressing the Y shortcut on the keyboard, the night overview is displayed in full window width. This screenshot was taken after sleep staging (top plot filled, see next pages).

Figure 3.14: After pressing the C shortcut on the keyboard, only the detailed view is displayed, which makes it easier to identify sleep spindles or other sleep grapholements. The following recording channels were selected to be displayed in the config xml file: VEOG and HEOG, a re-referenced channel depicting the voltage between the left mastoid electrode (electrode 6) and the electrode below the left eye (electrode 2), another re-referenced channel (left mastoid vs. electrode above the right eye), three EEG channels, ECG and EMG.

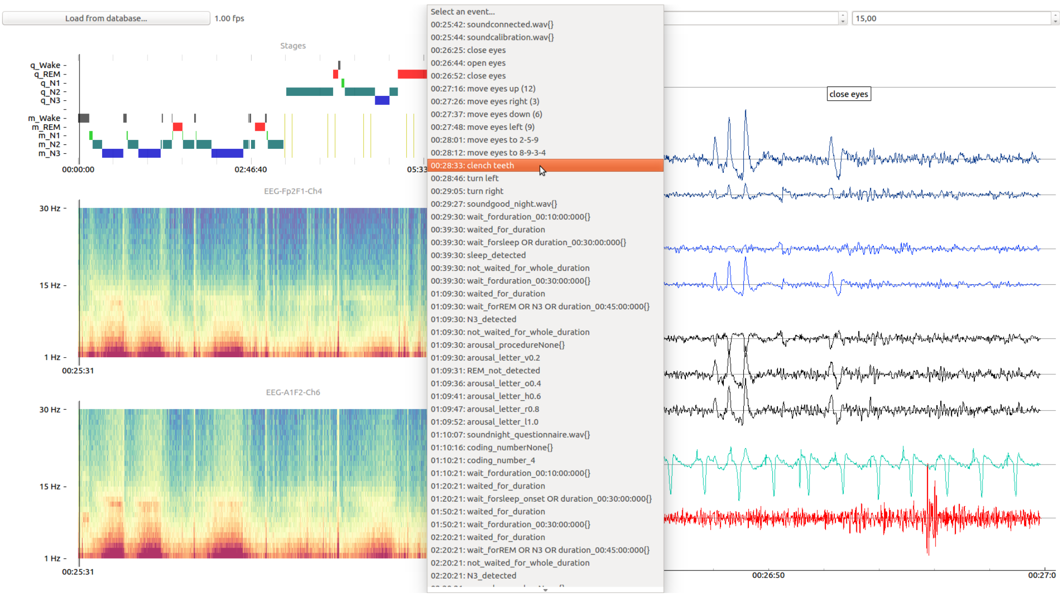

Figure 3.15: The researcher can comfortably jump directly to the time point, at which the Traumschreiber system carried out a specific action or at which other events happened, by using the events dropdown menu.

It is possible to navigate through the data easily in multiple ways. First, the researcher can click into the frequency plots with the left mouse button. The right plots are updated and centered around the selected second from the left plots. Second, one can directly enter either an exact second of the recording or a POSIX timestamp (as used in the database for storing the data and events) in the GUI (top row, second field from the right). Third, one can select one of the events, which have been stored in the database, by clicking on it in the dropdown menu in the top row. The right view is then centered around the timestamp of this event. Last, one can use the keyboard shortcuts N and M for quickly jumping one time window back or next.

The scientist can choose, which channels should be displayed, by modifying a configuration xml file. This also includes combinations of channels, in case one wants to use a common reference for several channels[21]. Furthermore, it is possible to adjust bandpass and median filters for the left and right plots, and to specify plot properties like scaling factor, line color or labels. Lastly, one can also select, which events should be displayed.

21 When combining several channels, be aware that the channels 1, 3, 5 and 7 are inverted due to the technical layout of the instrumentation amplifiers.

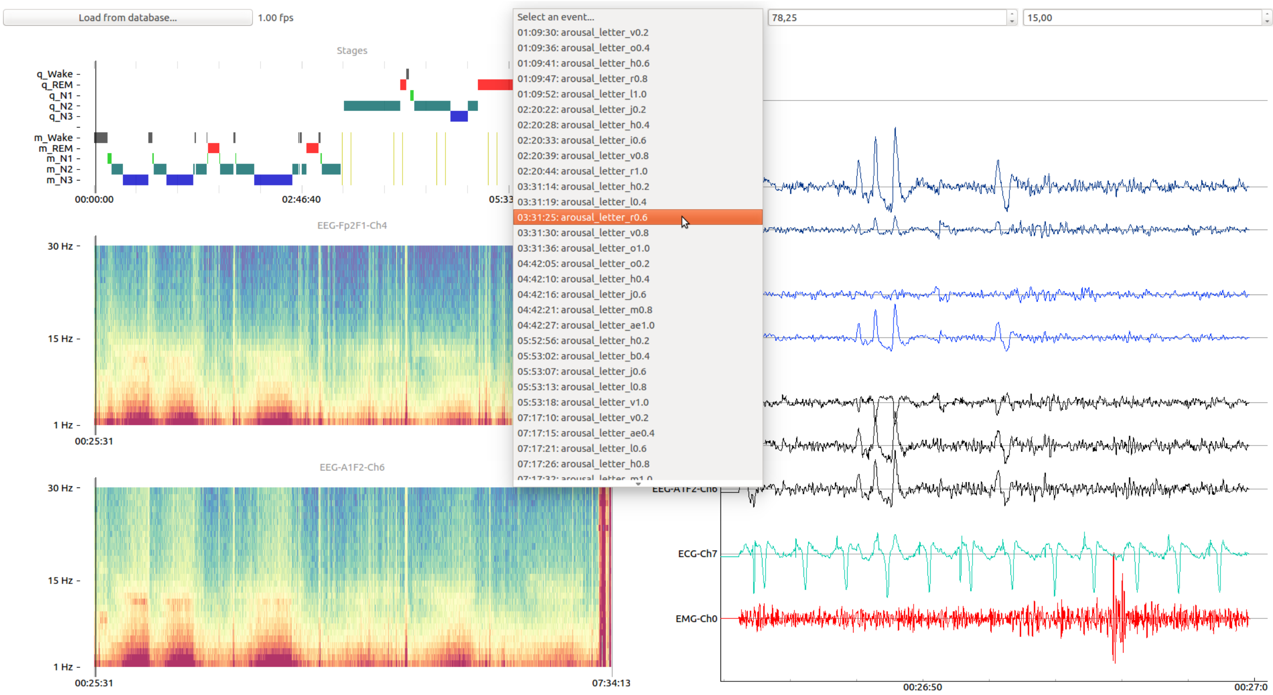

Figure 3.16: When specifying a filter in the config xml file, only certain events are displayed in the dropdown menu and in the detailed view (here: events containing the word “letter”).

The last important feature of the post visualization GUI is, that the sleep scientist can manually sleep stage the recorded data in two different ways. First, it is possible to score the sleep data on a 30 second bases, similar to the procedure in commercial sleep analysis software. The keyboard shortcut A activates the sleep staging. Next, by pressing the keyboard shortcuts W, 1, 2, 3 or R, one can score the currently displayed time window as awake, N1, N2, N3 or REM sleep period, and the focus moves 30 seconds forward, ready for the next scoring. The hypnogram is displayed in the left side plots. It is possible to sleep stage a whole night manually using this standard procedure. However, this time consuming method is not suited for larger datasets consisting of dozens or even hundreds of recorded nights (as might be the case when collecting sleep data with several Traumschreiber systems simultaneously). As a consequence, a second scoring approach has been developed in the Traumschreiber system, named *quick scoring*. By pressing the keyboard shortcut Q, this scoring mode is activated. Next, the sleep scorer presses one of the keyboard shortcuts W, 1, 2, 3 or R, to select the sleep stage to be scored. By pressing and dragging the right mouse button in one of the left plots, the whole selected time period is assigned the according sleep stage (based on one second bins). This way, longer periods of time containing only one sleep stage can be quickly scored at once, e. g. longer periods of slow wave sleep. Questionable time windows can be easily clarified by left-clicking into them and inspecting them the standard way. Especially for creating large training sets for machine learning based sleep staging algorithms, this quick scoring was developed. By pressing the keyboard shortcut S, the manually or quickly scored data are saved into the database.

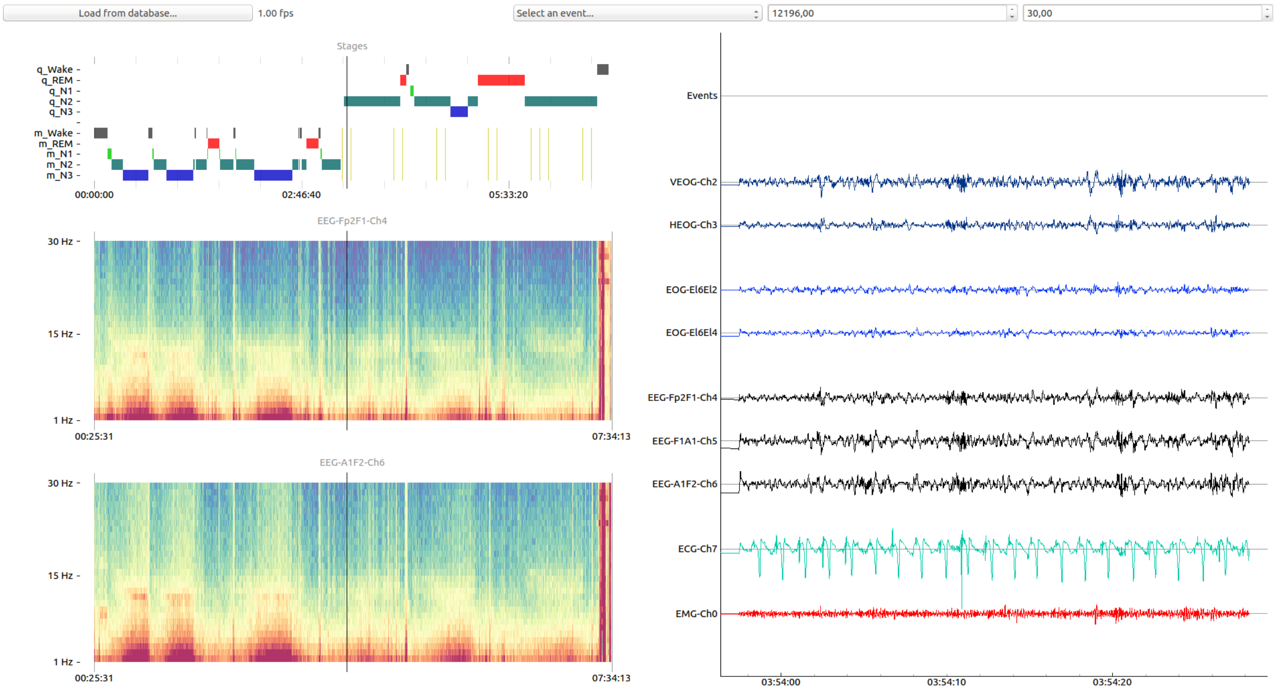

Figure 3.17: The top left plot shows, that the sleep researcher scored the first half of the night in the conventional way using 30-second epochs (sleep stages starting with m_), and the second half of the night with the quick scoring method (sleep stages starting with q_). Both classifications are saved into the database, which contains also the rest of the recording, making them available for training machine learning algorithms such as deep neural networks.

<u>Visualizing the real-time sleep scorings</u>

As described above, the Traumschreiber system is capable of performing real-time classification of the recorded data using a neural network approach based on Keras/tensorflow. The predictions of the AI can be visualized using the script plot_night_predictions.py. The script analyses every database in a given folder, and saves several figures as *.png files.

The first figure plots each prediction timepoint against its POSIX timestamp. There should be one prediction every second, resulting in an (unspectacular) straight line in the plot. If the line is not straight, however, this means that the classification algorithm did not predict a sleep stage every second, i. e. the Raspberry Pi was not able to predict the sleep stage within one second. This was the case at some points during development, and was solved by refactoring the code and minimizing the RAM requirements of sleep stage prediction, in order to make the code faster.

The second figure plots the actual real-time predictions for every second in a greyscale image. Since the neural network outputs the probabilities for every of the five sleep stages in every second, this plot shows all the predictions in one image. This plot enables the researcher to analyze, whether the AI was biased towards one or two sleep stages, e. g. predicting N3 sleep most of the night, as can be seen in figure 3.18.

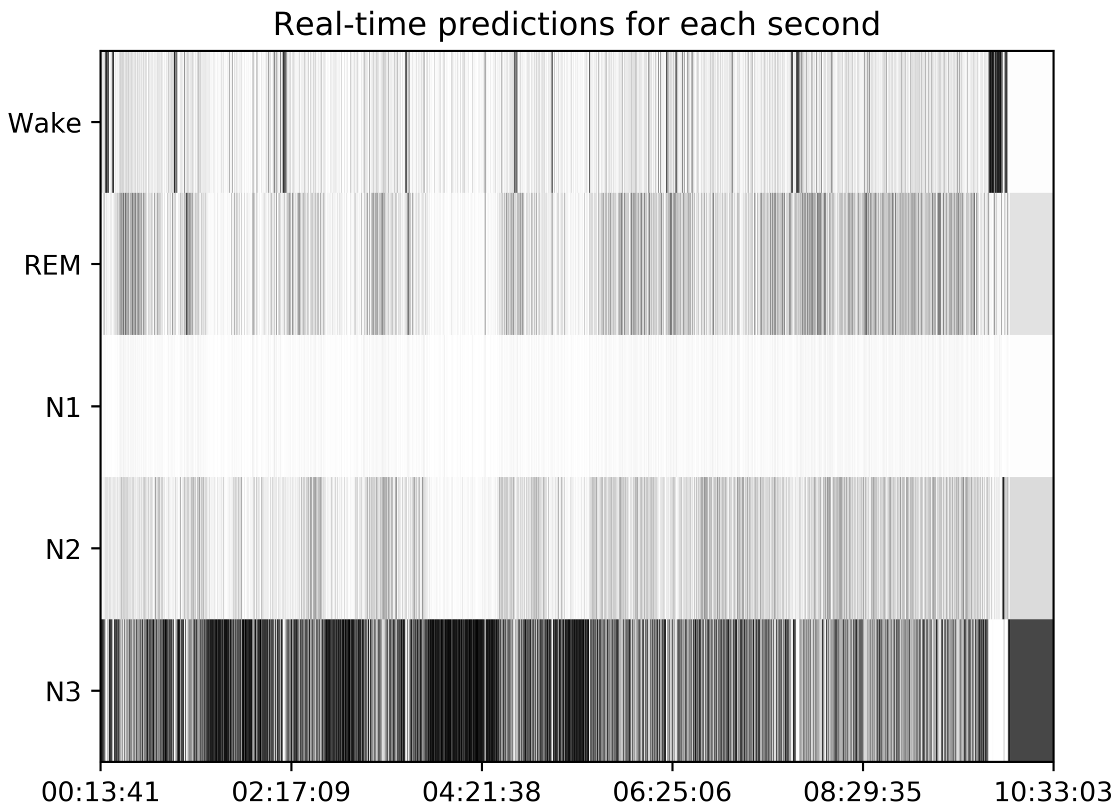

Figure 3.18: This plot shows the real-time sleep stage predictions of the Traumschreiber system. During each second of the recording, the neural network outputs were logged. Black means, that the corresponding sleep stage was very likely at this second, white means the opposite (gray in between). One can see, that the neural network was biased towards predicting N3 sleep in this recording.

The last figure consists of six subplots. In the first column, first plot, the predictions for each sleep stage averaged over 20 minutes (sliding window) are displayed as they were calculated in real-time. Below one can see the resulting hypnogram, depicting which sleep stage was most likely during each second. In the second column, the same is shown, but this time including the additive bias correction term, which takes the subject-individual sleep stage distributions of previous nights into consideration and tries to adjust the real-time predicted sleep stages accordingly. For example, if the neural network is prone to overestimate N3 sleep for an individual subject, in the following nights the bias term tries to correct this. The last column also shows the neural network predictions of the same night, but is post-optimized. This means, that, like in the second column, the original predictions are corrected using an additive bias term. The difference is, that in the third column knowledge is used, which is not available during the time of recording, namely the overall sleep stage distribution of the recorded night (thus post-optimized). An additive bias correction term is estimated based on this distribution, which shifts the sleep stage probabilities up or down. See figure 3.19 for an example.

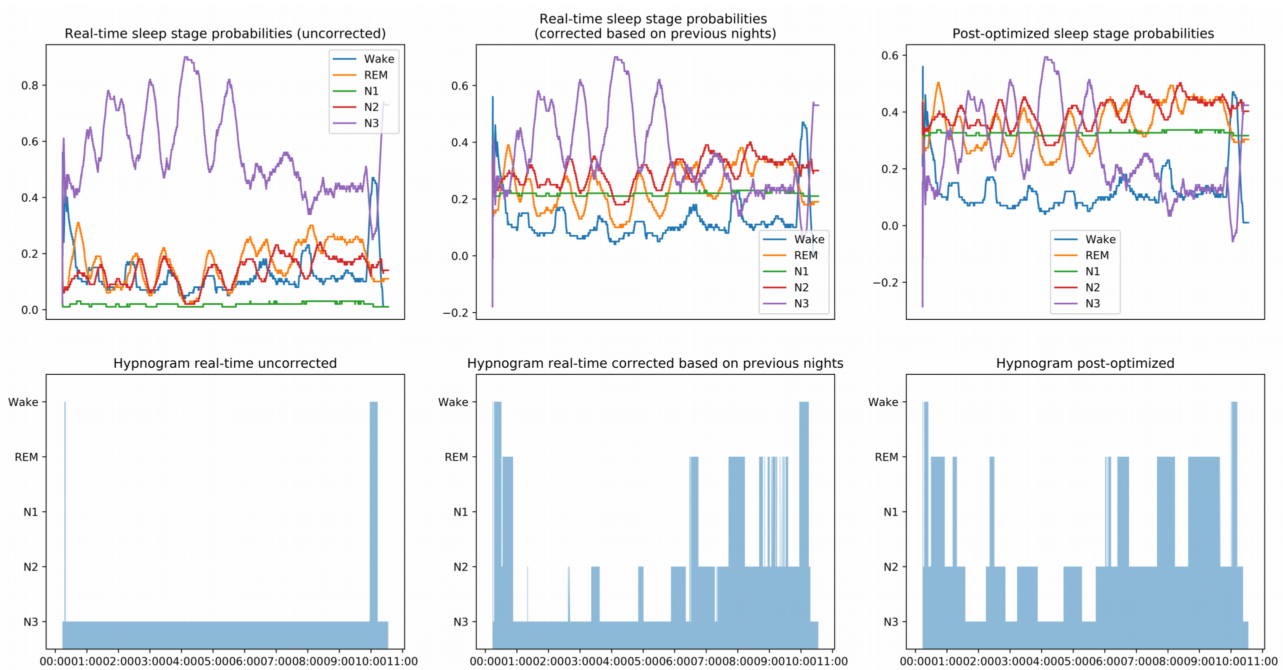

Figure 3.19: The predictions of the same night as depicted in figure 3.18, but averaged using a 20 minute sliding window. The left two plots show the averaged 20 minute probabilities (top: for each sleep stage individually, bottom: displaying only the sleep stage with the highest probability). The two plots in the center show the same predictions, but with an additive bias, which was calculated based on previous recordings of this subject. In the right plots, the nightly predictions were post-optimized, by shifting them vertically such that the distribution of sleep stages comes close to the theoretical average of healthy human sleep, removing most of the real-time prediction bias towards N3 sleep. Typical sleep cycles can be seen in the post-optimized calculation.

3.2 Evaluation

After developing the system, it was evaluated in several studies.

3.2.1 First study: Sleep laboratory validation

This study compared the simultaneous recordings of six subjects with both the Traumschreiber system and the ALICE system, a commercial polysomnographic system, which is used in clinical and research sleep laboratories worldwide. In total, 189 30-second epochs of sleep data were compared to each other, i. e. on average 31.5±0.84 epochs of each subject. The epochs were selected based on their time of recording, with all epochs sampled at 15 minute intervals. Screenshots of all epochs as well as the complete evaluation table can be found in the online appendix. See figures 3.20 and 3.21 for one exemplary comparison.

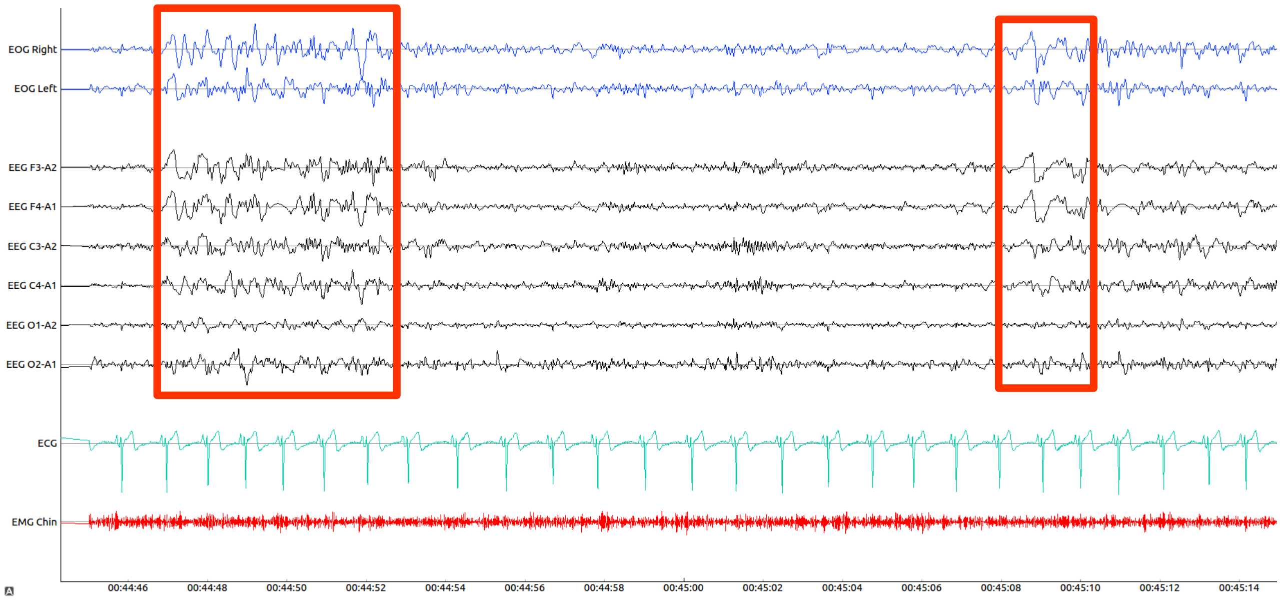

Figure 3.20: This plot shows 30 seconds of polysomnographic data recorded with the commercially available ALICE system, which is used in clinical and research sleep laboratories worldwide.

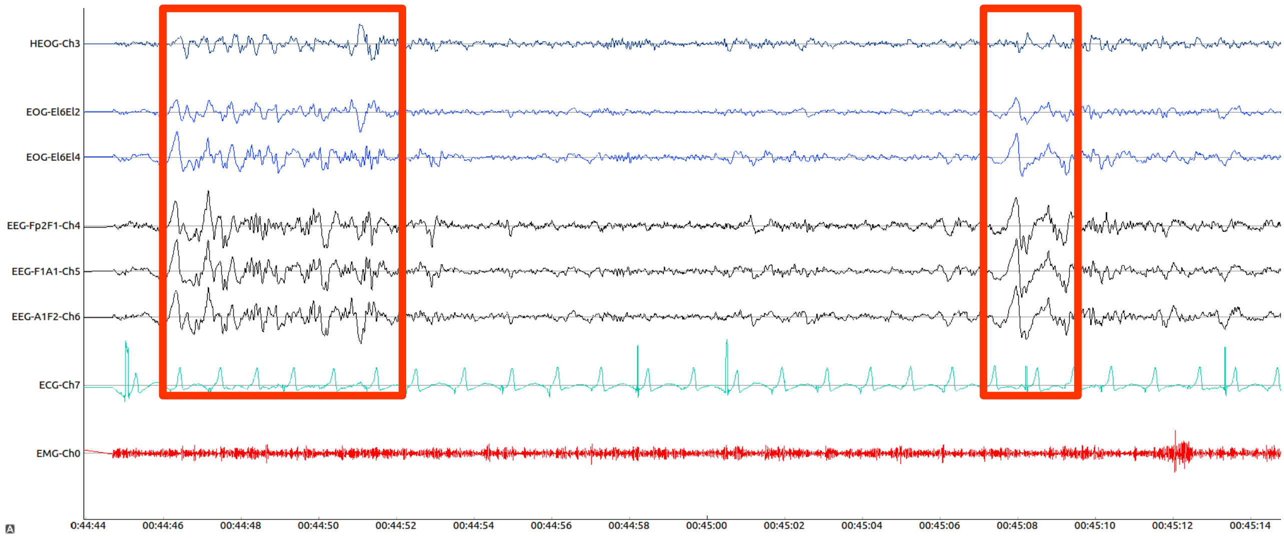

Figure 3.21: This plot shows (approximately) the same 30 seconds of data, recorded with the Traumschreiber system. The red boxes are inserted in order to help the reader to compare both figures.

3.2.1.1 Direct comparison of both systems

In general, both systems recorded very similar data. All sleep graphoelements, except central-occipital sleep spindles and alpha EEG activity, could be detected in both systems in nearly all corresponding epochs, i. e. if one system showed slow waves, the other systems showed slow waves, too.

	Slow waves	Sleep spindles	K-complexes	Low amplitude, mixed frequency EEG	REMs	Heart beats	Arousals	EEG alpha band activity	SEMs	Eye blinks	Vertex waves
	… are visible in __ of the 189 analyzed epochs …										
only in the ALICE system	1	26	3	2	0	0	1	3	0	0	0
in the same epoch in both systems	36	58	53	95	13	189	19	3	1	2	2
only in the Traumschreiber system	0	1	0	0	3	0	0	0	0	0	0

Table 3.3: This comparison shows, which polysomnographic graphoelements could be found in how many corresponding epochs of both systems.

Slow waves could be detected in 36 of the epochs in both systems simultaneously and in one epoch only in the ALICE system. Sleep spindles were clearly visible in 58 corresponding epochs of both systems, 26 times only in the ALICE data, and once only in the Traumschreiber data. In nearly all of the 26 cases, in which spindles were only detectable in the ALICE data, these spindles were measured in the central-occipital region, and were not visible in the ALICE frontal EEG channels, too. K-complexes could be detected in 56 epochs, out of which three were only ALICE recordings. A low amplitude and mixed frequency EEG signal was apparent 95 times in both systems simultaneously, and two times only in the ALICE system. Rapid eye movements could be found in 13 of the epochs in both ALICE and Traumschreiber, and three times only in the Traumschreiber system; slow eye movements only once (both systems). The heart beat was clearly visible in all epochs of both systems. Arousals were found 19 times in both and once only in the ALICE system. Alpha wave activity was detected in three corresponding epochs of both systems, and three times only in the ALICE recordings. Vertex waves were found two times in both systems. The EMG often looked completely different, however, it is unclear whether this was due to a bad signal of the ALICE or the Traumschreiber system, since arousals were detectable in the Traumschreiber system's EMG signal much better than in the ALICE system.

3.2.1.2 Sleep staging comparison

In 175 of the 189 epochs (92.6%), the same sleep stage was scored for both systems based on inspecting the corresponding 30 second windows: 14x wake, 13x REM, 75x N2, 28x N3 and 45x ambivalent, i. e. it remained unclear, whether wake, (tonic) REM, N1 or N2 should be scored, because previous epochs would have been necessary for an exact scoring.

The remaining 14 epochs with different scoring contained 13x ambivalent and 1x REM scoring for the Traumschreiber data, and 11x N2 and 3x wake classifications for the ALICE epochs, i. e. the ALICE system provided some extra clarity regarding the current sleep stage. In most cases, this was due to central-occipital sleep spindle activity.

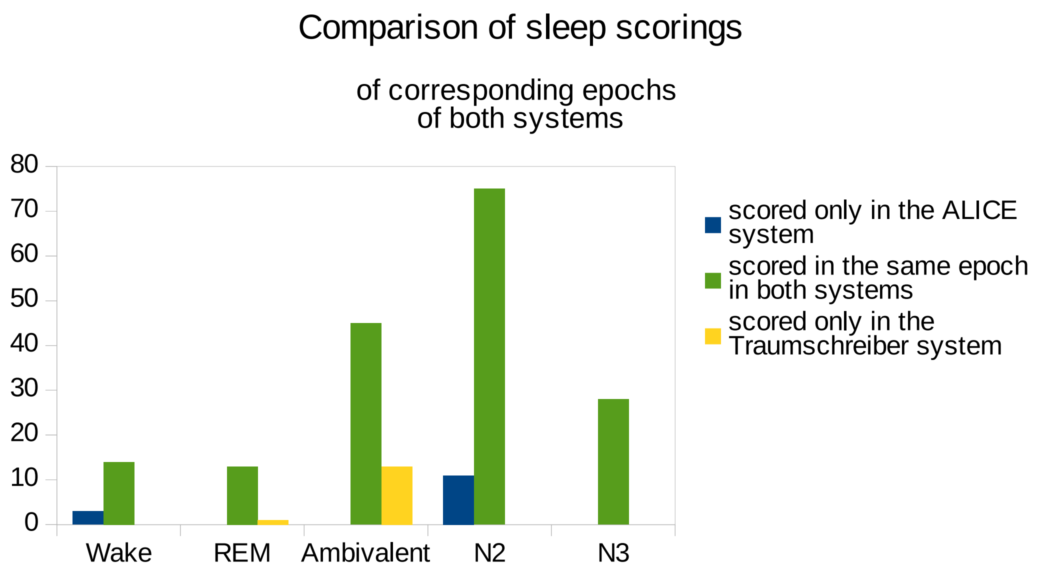

Figure 3.22: The plot shows, how many times the same sleep stage was scored for the 189 corresponding epochs in both systems (green), and in how many cases an epoch was assigned a specific sleep stage in only one of the systems (yellow and blue).

3.2.2 Second study: Home-based prototype study

In this study, a prototype (version 2.2) of the Traumschreiber system was tested at the subjects' homes for the first time, i. e. without a human experimenter at the location of recording. Viewed holistically, the approach to record polysomnographic data during a field study sleep experiment at the subject's home was successful: The Traumschreiber system enabled the naive subjects to carry out the interactive polysomnographic sleep experiment at home, and conducted parts of the experiment on its own. This included playback of acoustic cues at different sound intensities, when the subject was asleep.

3.2.2.1 Data quality

In 14 of the 23 recordings with this prototype version 2.2, data were transmitted from the sleep mask and saved by the minicomputer during the whole night (8 recordings with no signal loss at all, 6 recordings with only a few minutes of signal loss). During the other nights, the data were either not saved or not transmitted throughout the whole night (note that in this (not final) prototype, a lost bluetooth connection was not automatically re-established).

The data quality of the fully recorded nights was analyzed next. The EMG channel showed a good signal in 13 of the 14 nights (93%), with a good signal being defined as 90% or more of the night showing clear data without artifacts. At least one of the two EOG channels (VEOG and HEOG) showed a good signal in 100% of the nights, with both of them having a good signal in 71% of the recordings. In 86% of the nights, at least one of the two EEG channels yielded good signal quality. ECG could be recorded in 86% of the nights in at least one of the two channels. Note that only two EEG channels were recorded instead of three as suggested in the final systems layout, but one ECG channel more.

3.2.2.2 Effect of the system on sleep and dreaming

The total sleep time was nearly the same in both conditions (mean sleep time: 7:56 hours with wearing the sleep mask at night and 8:06 hours without the sleep mask in the control night). The sleep quality was much better in the control night (without the sleep mask) than during the first night of the study. This was the case for both the acoustic stimulation condition ($d=2.9$, $p<0.001$) and the condition without stimulation ($d=1.5$, $p<0.01$), as can also be seen in figure 3.23.

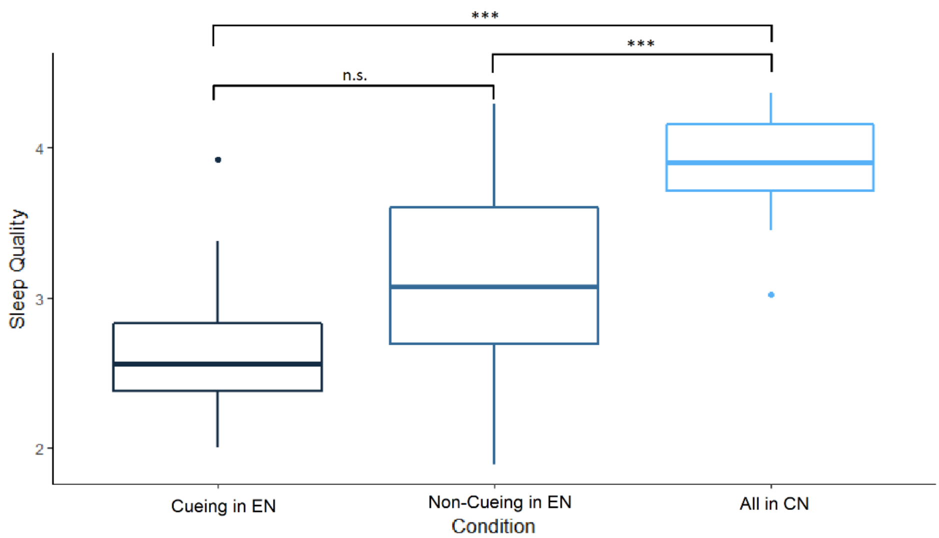

Figure 3.23: This plot depicts the sleep quality in the first night (experimental night, EN), both for the condition with auditory cues throughout the night (left) and without (center), as well as for the control night (CN) without wearing the sleep mask one week later (right). With permission from (Mandt, 2017)

The feeling of recovery was significantly better after the control night, than in the night with the sleep mask (taken both stimulation conditions together; $d=0.82$, $p<0.01$). It was, however, not significantly better, if compared to only the no-stimulation night ($p=0.08$).

Please see figure 3.24 for details. The time to fall asleep was significantly shorter during the control night (d=1.1, p<0.01), which was due to the sleep mask, the electrodes, the unusual circumstances or the acoustic stimuli, as the subjects reported (see table 3.4).

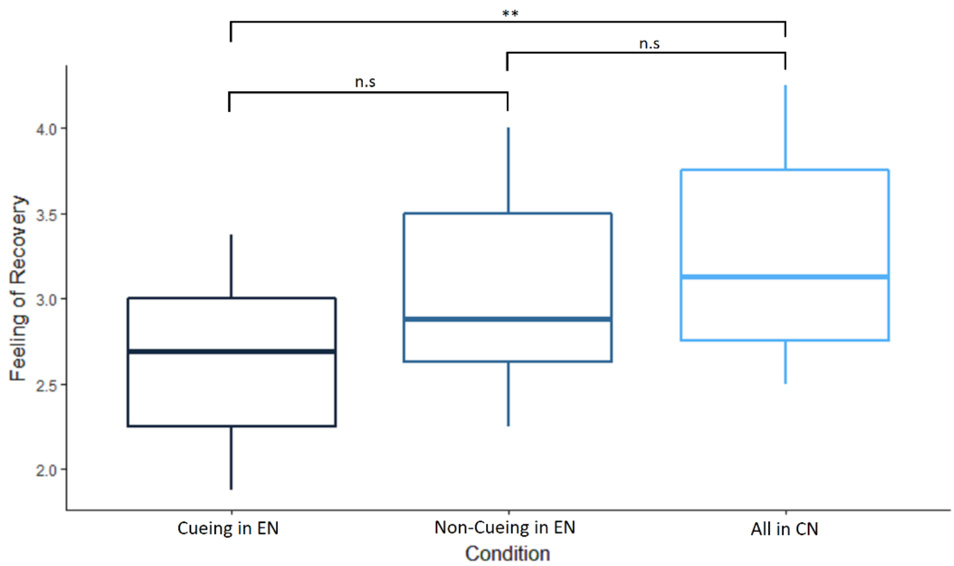

Figure 3.24: This plot shows the feeling of recovery in the morning after the experimental night (EN), for both conditions with cueing (left) and without (center), as well as for the control night (CN) one week later (right). With permission from (Mandt, 2017).

Reasons for not falling asleep	Experimental night		Control night
	Non-Cueing	Cueing	
private reasons/experiences	22.2%	25%	39.1%
sounds	11.1%	33.3%	8.7%
unfamiliar circumstances	22.2%	41.2%	-
sleep mask	44.4%	41.7%	-
exitement	11.1%	8.3%	-
no reason	33.3%	16.7%	60.9%

Table 3.4: The table summarizes the answers of the subjects to the question, what the reasons were for having trouble falling asleep in the beginning of the experimental night (non-cueing and cueing condition) and the control night without wearing the sleep mask. With permission from (Mandt, 2017).

11 of the 14 subjects of the acoustic stimulation condition (78.6%) recalled a dream in the morning, whereas only 4 of the 9 subjects of the condition without stimulation (44.4%) reported a dream. In the control night, 11 of the 23 subjects (47.8%) recalled a dream. The difference between stimulation and no stimulation regarding dream recall was found to be statistically significant with a medium effect size (d=0.766, p=0.034). The experiment was incorporated into six dreams of the stimulation condition, one dream of the condition without stimulation, and no dream of the control night. The stimuli were not incorporated in any reported dreams.

3.2.2.3 Ease of use and comfort of the sleep mask

All except one subject reported, that they could follow the instructions easily (65.2%) or rather easily (30.4%). Attaching the electrodes to the skin took 3 to 30 minutes (average: 15:02 minutes), and removing them in the morning took 2 to 15 minutes (average: 5:38 minutes). Two subjects had difficulties with attaching the electrodes, and four subjects had problems with removing them in the morning (too sticky electrodes). All other subjects did not report any complications.

The majority of the subjects found the sleep mask not at all disturbing for falling asleep (4.3%) or only slightly disturbing (60.9%), while 34.8% rated it as quite disturbing, with no subject stating it to be extremely disturbing. 52.2% of the subjects were not at all disturbed by the cables of the sleep mask, 26.1% slightly, 17.4% were quite disturbed, and 4.3% felt extremely disturbed. The sleep mask was rated as very comfortable or comfortable by 17.4% of the subjects, as okay by 47.8% of the subjects, as uncomfortable by 30.4% of the subjects, and as very uncomfortable by one subject (4.3%). The material was overall perceived as comfortable. 17.4% of the subjects sweated under the sleep mask.

3.2.2.4 Effect of acoustic stimulation on the occurrence of arousal

On average, each subject of the stimulation group was exposed to 45 acoustic tones of different volume throughout the whole night (one tone every ten minutes). Averaged over all subjects, no arousal was detected after 76.1±10.4% of the stimulations, and an arousal was found after 23.9±10.4% of the stimulations. The average stimulus sound volume in case of no arousals was 0.41±0.04, and 0.64±0.08 in case of an arousal. As expected, louder stimuli evoked an arousal significantly more often than quieter stimuli with a large effect size (d=3.2, p<0.001, see figure 3.25).

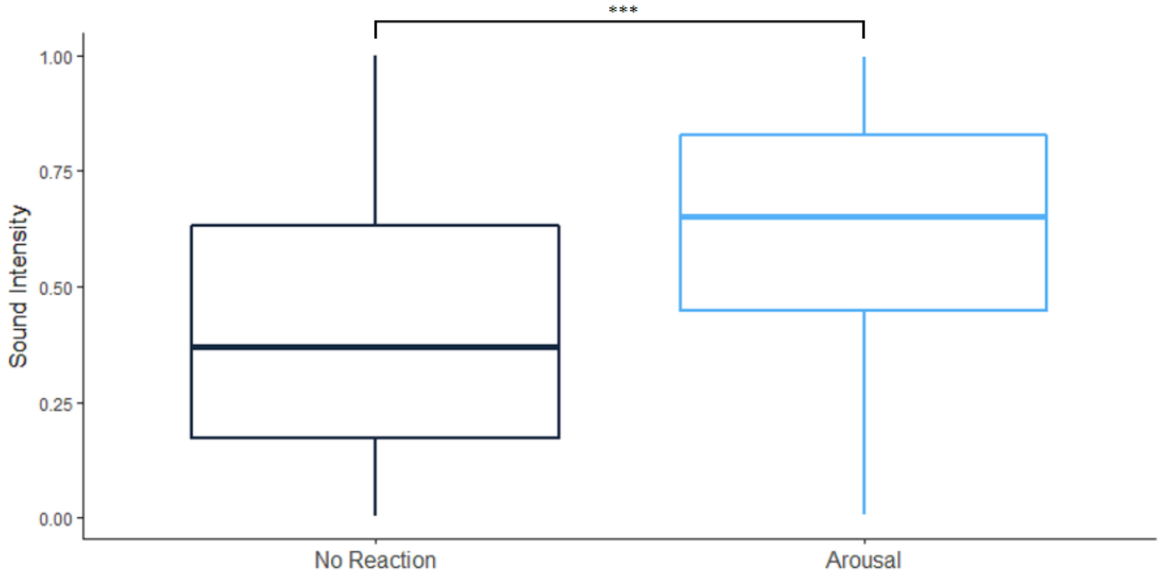

Figure 3.25: The plot shows, that those acoustic stimuli, which lead to arousals, were significantly louder than the cues, which did not provoke an arousal. With permission from (Mandt, 2017).

3.2.2.5 How to further improve the system

The subjects proposed several suggestions, of how the prototype version 2.2 could be improved. Regarding the textile design of the sleep mask, an adjustable elastic head band, a less heavy and smaller battery and a covering cap for the power switch were named.

One of the most important points of how to technically improve the prototype was, that the system should constantly try to reconnect, in case the bluetooth connection gets lost.

Furthermore, the cables should be shortened in order to increase comfort and to minimize the chance of breaking the cable by accident. Several new questions for the self-developed questionnaire about the sleep mask were identified. Moreover, the study showed, that acoustic stimulation should start the earliest 30 minutes after sending the subject to sleep, as the stimuli hindered the subjects to fall asleep. Finally, more practice of the subject in order to ensure good electrode contact was suggested by the experimenter of the study. One way could be to record more nights, and to use the first night as an adaptation and practice night.

All these suggestions were implemented in the final version of the Traumschreiber system.

3.2.3 Third study: Preparing polysomnographic crowd experiments

The goal of this study was to describe all the tasks, which have to be carried out in order to produce one or more entities of the Traumschreiber system for large scale crowd-based experiments. Moreover, a cost analysis was conducted.

3.2.3.1 Description of production work step and cost analysis

Table 3.5 summarizes the work steps based on the experiences from setting up the fourth study of this dissertation. It shows, which tasks have to be conducted and how much time has to be calculated for each work step.

#	**Work step**	**Time**
1	Ordering the components	50 minutes (6 weeks waiting time)
2	Unpacking all the components	4 minutes
3	Cutting the battery holder	3 to 10 minutes
4	Cutting and soldering the electrode cables to the board	14 to 25 minutes
5	Copying the code to the microcontroller and to the BLE chip	2 to 30 minutes
6	Sewing the textile part of the sleep mask and placing the board inside	26 to 90 minutes
7	Copying the Traumschreiber system's code to the micro-SD card of the experiment station	1 minute (1 hour waiting time)
8	Putting the parts of the experiment station together and into a box	6 minutes
9	Initial charging of the coin cell battery	1 minute (0 to 240 minutes waiting time)
10	Functionality test of the system	3 minutes
	Total production time after the components arrived	*60 to 170 minutes*

Table 3.5: This table gives an overview of the work steps, which are necessary for producing a Traumschreiber system, and the time needed for each step. Please see the following text for further details.

1. **Ordering the components**

To start producing one or many Traumschreiber systems, the raw materials and components need to be obtained. These include for each Traumschreiber system (costs as ordered in March, 2017):

For the sleep mask

- A PCB assembled with all the electric components and a battery holder. This is the most costly and most complicated part to order. It can be produced by several Western and Chinese factories. As became clear during development, the Chinese factories offer the same products at much lower prices than the German factories. However, it is hard to know beforehand, how good the quality of the produced goods is. Two Chinese factories have been tried out during the development of the Traumschreiber system. While PCBCART produced boards of excellent quality at two separate orders and offered a very good service, ALLPCB produced boards of which only 10% worked properly. This might have been due to bad luck.

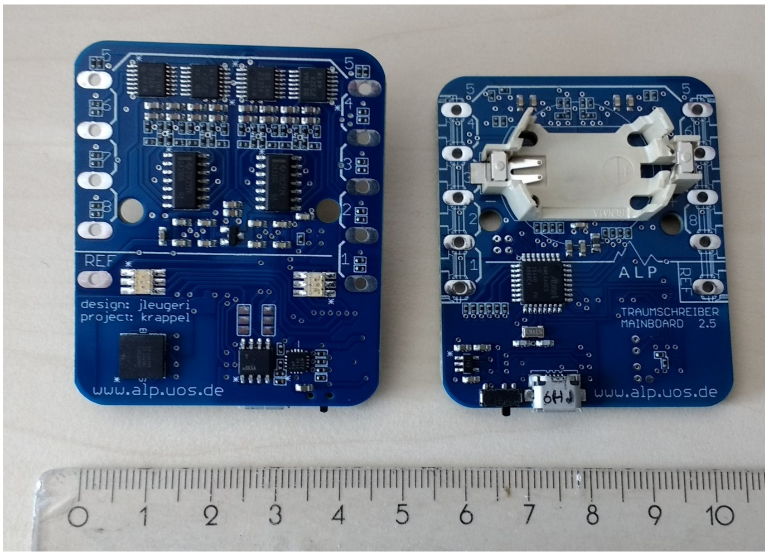

Figure 3.26: Back and front side of the equipped PCB, as it arrives from the factory.

For obtaining a quote and for ordering an assembled PCB, one has to submit a bill of materials (BOM) file and a PCB design file (in optimal case a GERBER RS-274X file) to the factory, e. g. at www.pcbcart.com/assembly, and has to specify several technical details. See the online appendix for the files and details of the last order of the Traumschreiber board.

The costs decrease dramatically the larger the order gets (assembly costs for an order quantity of 10 boards: 56.45 USD per board, for an order quantity of 100 boards: 11.56 USD per board; component costs per board 51.18 USD (order quantity of 10) versus 43.27 USD (order quantity of 100); minimum order quantity costs per board: 14.37 USD (order of 10 boards) v 0.00 USD (order of 100 boards).

The last order during development was placed at PCBCART and contained 20 boards. The total PCB costs were 244 USD, assembly costs (including tooling costs and electric components) 1630 USD, shipping cost from China to Germany 53 USD. Thus, the total costs at this rather small order quantity (20 boards) were 1858 *EUR*, or 93 *EUR* per board.

- 10 electrode cables with 4mm snap-on connectors. These can be ordered in packages of three (red, black, white) at www.olimex.com. This costs 40 EUR for small quantities (12 cables), for large quantities (>49 pcs.) 36 EUR. It is possible to import these cables directly from China at much lower costs, but only in larger quantities. For example, a trader (Lilian Zhang) at www.made-in-china.com offered to produce the same type of cable for 0.92 USD per piece in a quantity of 1000, or 1.2 USD per piece for 500 cables (see invoice in the appendix). A sample order showed, that the Chinese cables were of the same quality as the Bulgarian ones from Olimex.

  Note that in principle any type of EEG/ECG cable can be used – one is not restricted to 4mm snap connectors. Thus, if one would like to record data from occipital regions using reusable cup electrodes, these can be connected to the board as well.

- A 3.6V 180mAh coin cell battery LIR2477, which can be ordered at www.conrad.de for around 5 EUR.

- Molded sleep mask, e. g. model SODIAL, which is imported from China and can be ordered at www.amazon.de for around 2 EUR. As was experienced during development, more expensive sleep masks are not necessarily better, as they are often not molded.
- Piece of cloth (cotton, at least 30x12 cm), hook and loop fastener, and eyelets (all needed for the little pocket containing the electronics). Can be bought at any local textile shop for around 5 EUR.

<u>For the experiment station</u>

- Raspberry Pi 3 Model B including a micro-SD card (class10, with at least 8 GB storage capacity), a case, a power supply (5.1V, 2.5A), and 2 heat sinks. Can be ordered in a bundle, e. g. at www.rasppishop.de for the German market. Costs: around 60 EUR per bundle.
- A pair of USB speakers “Trust Leto 2.0 USB” or similar. Can be ordered at www.amazon.de for around 9 EUR.
- CSL external USB sound card or similar. Can be ordered at www.amazon.de for around 6 EUR.
- Carton box (recommended size appr. 10x17x27 cm) for packing everything. Can be ordered at www.memolife.de for around 2 EUR.

<u>For the recordings</u>

- Covidien Kendall H135SG single use sticky electrodes. 10 electrodes are needed for each recording. Can be ordered at www.ternimed.de for around 7 EUR per package of 50 electrodes, costs reduce slightly for larger quantities.

For the 20 complete Traumschreiber systems, which were produced during the last development iteration in March 2017, the total costs per Traumschreiber system were around 138 EUR for the sleep mask components, 77 EUR for the experiment station, and 7 EUR for recording up to 5 nights with each sleep mask – totaling to 222 EUR for the complete system.

Figure 3.27: All parts of 20 complete Traumschreiber systems.

Note, that if an Android app was used instead of the Raspberry Pi, the costs would decrease by 34% to 147 EUR (assuming that the subjects have an Android smartphone or tablet with BLE). Also note, that the electrode cables make up 26% of the costs of the sleep mask, which is ridiculously high, especially since one half of the cable is thrown away during production anyway (see below). Moreover, note that the production costs depicted here are for a quantity of 20 systems; larger production quantities decrease the costs per item substantially.

Furthermore note, that the depicted costs are the initial fixed costs – after production, for every recording only the single use sticky electrodes have to be bought (variable costs), which is around 1.50 EUR per night (assuming that the sleep masks don't break). Writing of initial fixed costs, the experimenter has to be aware, that some tools are needed for production. These are: eyelet pliers (can be bought for less than 10 EUR), a soldering iron and solder (can be bought for less than 40 EUR), a pair of scissors and a ruler (less than 5 EUR), a scalpel (less than 5 EUR), a programming tool for the microcontroller (e. g. the ATMEL AVR Programmer for less than 40 EUR) and a USB-to-UART adapter for resetting and programming the bluetooth chip (less than 5 EUR). Moreover, for larger sleep mask production quantities, a sewing machine is recommended (around 60 EUR).

The time, which is needed for ordering all the components, is independent of the order quantity. If it takes 5 minutes to order the parts in each of the six online shops plus 20 minutes for ordering the assembled PCB (as this is more complicated), about 50 minutes are needed for ordering.

Based on the experiences of several development iterations, the delivery times can be estimated as follows: The parts of the system, which are bought in European online shops (including Olimex from Bulgaria), usually arrive within a few working days. The textile sleep mask, which is imported from China via Amazon, needs around 3-4 weeks to arrive in Europe. The assembled PCBs are delivered around 6 weeks after the order is placed.

2. **Unpacking the parts**

   Once the orders have arrived from the different online shops, they need to be unpacked. Especially for larger production quantities, the time needed for this step should not be underestimated. Based on the experiences during development, unpacking all the components for one Traumschreiber system takes about four minutes.

3. **Cutting the battery holder**

   Unfortunately, the battery holder, which is assembled to the PCB, does not fit the actually used coin cell battery perfectly. This is due to the unusual height of the coin cell, for which no perfectly matching battery holder could be found so far. This means, that the battery holder has to be cut using a scalpel, so that the coin cell battery fits in it. See figures 3.28 and 3.29 for a comparison of how the battery holder looks like before and after cutting.

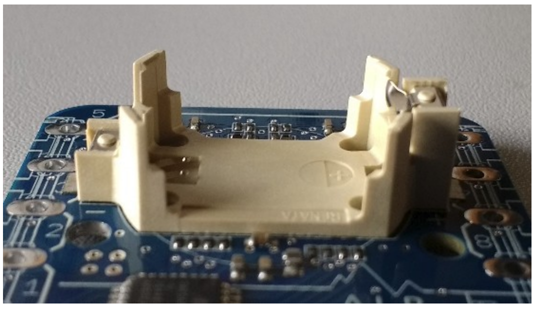

Figure 3.28: The battery holder before cutting.

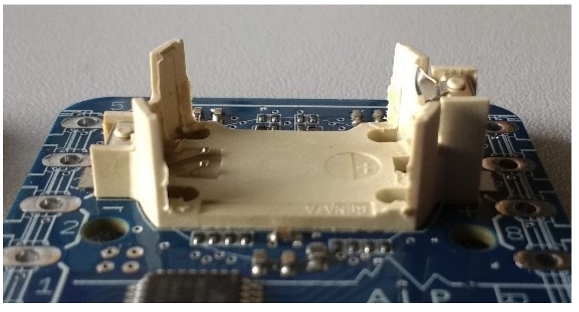

Figure 3.29: The battery holder after cutting.

Cutting the battery holder to a fitting size took on average 5:28 minutes. Noteworthy is that production times speed up due to gaining more practical experience from 9:28 minutes to 2:52, i. e. for larger projects, one can calculate with 3 minutes for this step. The whole step, however, will be unnecessary if a perfectly fitting battery holder is found.

4. **Cutting and soldering the electrode cables to the board**

The ordered cables are 90 cm long and have a 1.5 mm DIN connector at the one end and a 4 mm snap connector at the other end. They need to be shortened, so that no unnecessary long cables hang in the face of the subject. Using a standard pair of scissors, the cables are cut in two pieces of a specified length. The following cable lengths have been found to be useful (measured from the cable end of the 4mm snap connector):

- EMG cables (electrodes 0 and 1): 23 cm and 18.5 cm, preferably use red snap connectors
- EOG cables (electrodes 2, 3 and 4): 10.5 cm, 12.5 cm and 14 cm, preferably use white snap connectors
- EEG cables (electrodes 5, 6 and 7): 8 cm, 19 cm and 20 cm, preferably use black snap connectors
- ECG cable (electrode 8): 62 cm, preferably use red snap connector
- Ground cable (electrode 9): 11.5 cm, preferably use red snap connector.

The second part of the cable (with the 1.5 mm DIN connector) can be thrown away.

Next, the insulation of the cables has to be stripped off at the open end of the cable, and it has to be soldered to the PCB. The cables should be soldered on the side of the battery. With the on-off-switch marking the bottom side of the PCB, the EMG cables are suggested to be soldered clockwise to the bottom left holes, the EOG cables clockwise to the top left, the EEG cables clockwise to the top right, and the other two cables to the bottom right side of the board. See the video in the online appendix (screenshot in figure 3.30) for a detailed illustration of the complete soldering process.

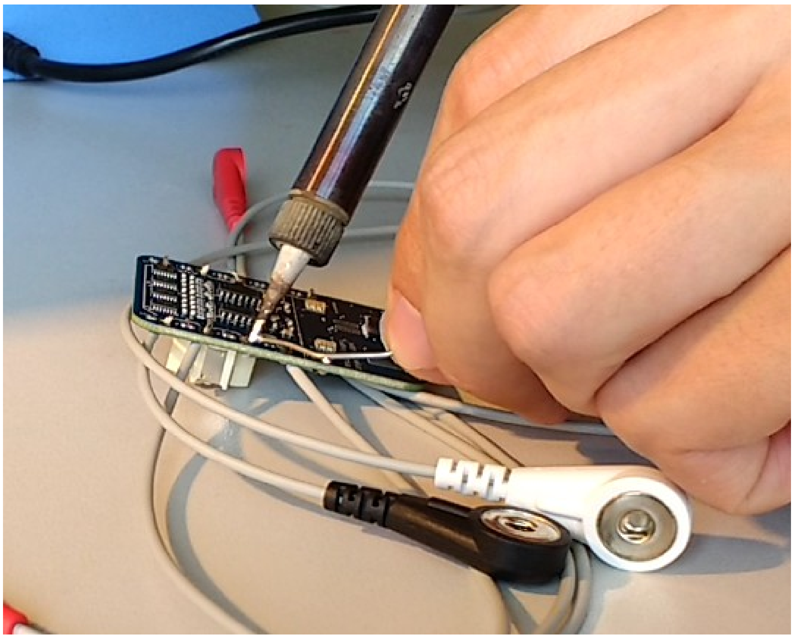

Figure 3.30: Screenshot of the video tutorial, showing how to solder the cables to the Traumschreiber board.

Cutting the cables to the correct sizes takes around 2 minutes per Traumschreiber, removing the isolation 4 minutes (decreasing to 3 minutes after gaining practical experience), and soldering the cables to the board takes a beginner about 19 minutes, decreasing to around 9 minutes after a few soldered boards.

5. **Copying the code to the microcontroller and to the BLE chip**

The microcontroller and the bluetooth chip are delivered without any useful code on them. Thus, they need to be programmed, i. e. the latest development version of the code has to be copied to them.

A programming tool is necessary for this (Atmel AVR programmer for the microcontroller, a USB-to-UART adapter for the bluetooth chip). After connecting the correct pins of the microcontroller or bluetooth chip with the programming tool, the code can be transferred using the software of the programming tool. Further technical details for this step are supplied in the online appendix.

Programming the bluetooth chip took 1:23 minutes on average during the last development iteration. The microcontroller could be programmed in 0:23 minutes on average. Thus, in total about 2 minutes are needed to program both chips. If the procedure is new to the producer, this work step takes considerably longer.

6. **Sewing the textile part of the sleep mask**

It has been found to be useful to enable the subject to look through the sleep mask, e. g. for putting on the sleep mask using a mirror and for filling out questionnaires during the night. For this, a 4x5 cm rectangular hole needs to be cut into the right eye of the sleep mask and is sewn up.

If the length of the elastic headband of molded sleep mask is not adjustable, it is recommended to cut it and to add a hook and loop fastener to it. The same is the case, if the elastic headband is too short.

Most importantly, the electronic parts need to be integrated into the textile of the sleep mask in order to have a comfortable, safe device. Sewing a tiny bag, in which the electronics are stored and which is then fixated on a molded sleep mask, has been identified as the best solution for this.

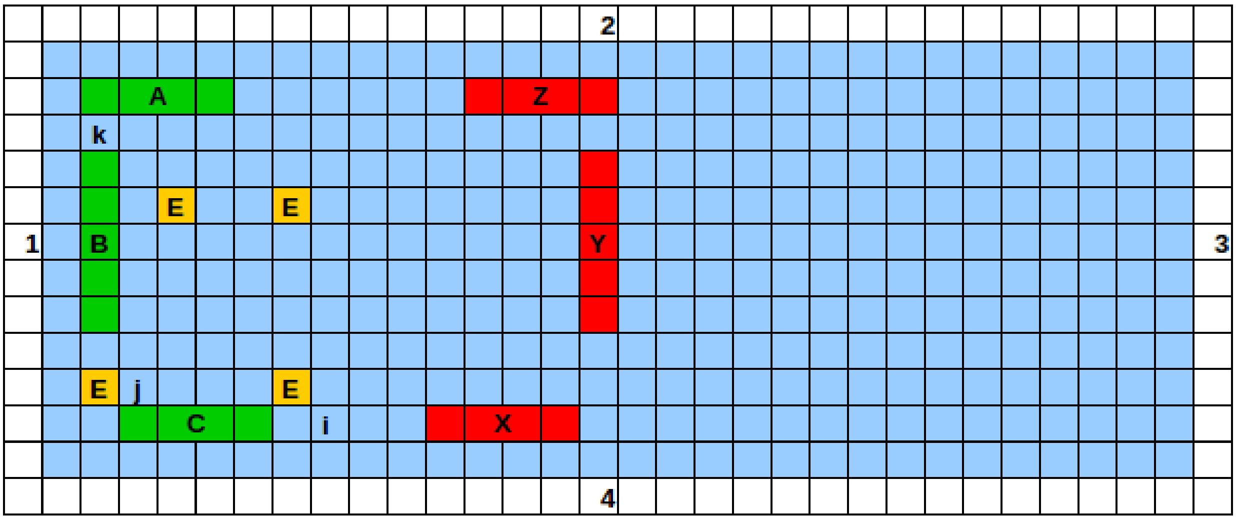

Figure 3.31: Sewing pattern for the sleep mask bag. Each box is 1 cm long. Blue: piece of cotton. Green: hook fastener. Red: loop fastener. Yellow: eyelets.

In order to produce such a tiny bag, a 30x12 cm piece of cloth (cotton, not synthetic, as synthetic material might lead to electrical shorts) has to be equipped with hook and loop fasteners (A, C, X, Y, Z) according to the sewing pattern in figure 3.31. Next, the side 3 is put onto the side 1, with the hook and loop fasteners being inside. The sides 1, 2 and 4 are sewn together, so that only a small (2 cm) hole is left open near the place, where the hook fastener B later is fixated. Next, the bag is turned inside out, and the hook fastener B is sewn onto the cloth, closing the hole. Then the two eyelets near the hook fastener C are used to connect the bag with the molded sleep mask, with both eyelets being fixated in the middle of the top edge of the left eye of the sleep mask. The two other eyelets in the middle are, in a next step, also used connect the bag with the sleep mask. Through these holes, the light of the LEDs will shine into the eyes of the subject. Thus, it is important, that the holes are exactly 3 cm apart from each other. Next, the PCB is placed inside the (open) bag and the cables are used to hold it in position: the electrode cables 4, 7 and 9 are fixated with yarn at fixation point i, the electrode cables 3, 5, and 6 at fixation point j, and the electrode cables 0, 1, 2 and 8 at fixation point k. Finally, the bag is closed. See the video in the online appendix (screenshot in figure 3.32) for a detailed illustration of the complete sewing process.

Figure 3.32: Screenshot of the video tutorial, which shows how to create the textile part of the sleep mask.

The whole work step can be conducted in around 26 minutes. However, when inexperienced with the sewing machine and as long as the single sewing steps are unclear, this procedure may take much longer (up to 1.5 hours).

7. **Copying the Traumschreiber software to the micro-SD card of the experiment station**

   For installing the Traumschreiber software, it is recommended to copy a complete image of the latest development version to the micro-SD card (see online appendix). This is probably the most convenient way, ensuring that no python dependencies are forgotten or have to be installed manually over network.

For copying the content to the micro-SD card, the micro-SD card has to be inserted into the card reader of a computer, and the *dd* command has to be used inside a Linux terminal (equivalent tools exist for Windows and Mac as well). The image file is then transferred to the micro-SD card, after which the software is ready to use.

Inserting a micro-SD card into the card reader and executing the dd command takes less than a minute. However, it might take up to one hour until the content has been copied to the micro-SD card.

8. **Putting all the parts of the system together and into a box**

The parts of the experiment station are delivered separately and maybe even from different online shops. Thus, they need to be put together.

The Raspberry Pi has to be equipped with the two heat sinks, which just need to be stuck onto the two chips (black “squares”) on the top side of the Raspberry Pi. Next, the Raspberry Pi is placed inside the plastic case, and the USB sound card is plugged into any of the four USB ports. The speakers are then connected to both the USB sound card and another USB port, and the power plug is connected to the Raspberry Pi. This ready-to-use experiment station is then placed into the carton box, together with the sleep mask, a package of electrodes, and possibly questionnaires and other paperwork.

Putting the pieces of the Raspberry Pi together takes around 2 minutes. Folding the box and putting everything inside takes another 4 minutes.

9. **Initial charging of the coin cell battery**

Even though the coin cell batteries for the sleep mask should arrive fully charged, this is not always the case. Of the 25 batteries tested, four were completely discharged (0.0 V), one was nearly empty (1.11 V), and the other 20 batteries were completely charged (around 4 V). Thus, time should be calculated for an initial charging of the batteries, which can last up to four hours, if the battery is empty. For charging, the micro-USB power adapter of the Raspberry Pi has to be connected to the sleep mask and a power plug, which takes less than a minute.

10. **Functionality test of the system**

Once everything is set up, the system can be tested by switching on the Raspberry Pi minicomputer and waiting for the instruction from the USB speakers to switch on the sleep mask. If everything is in order, the Traumschreiber system will detect the sleep mask after a few seconds and it will start saving the data to the micro-SD card every 30 seconds (folder: data/databases). This step takes about 3 minutes in total.

Summed up, any interested scientist should be able to produce a complete Traumschreiber system following these 10 steps. In the beginning it will take longer, but once the procedure is clear, and especially if several systems are produced in bulk, a single person should be able to produce one system in an hour of time – as was the case for the author of this dissertation.

3.2.3.2 Programming the experiment

Once sufficiently many experiment boxes have been produced, the next step is to program the experiment. In order to adjust the experimental protocol to the exact research question in mind, in simple cases, only some parameters have to be changed. In more complex experimental paradigms, the actual Python scripts have to be adapted.

As was described in chapter *3.1.2.2.1 Autonomous, easy to program experiments*, an xml template exists, which can be modified to reflect the experiment design. It is possible to create several kinds of experiments using this standard procedure. Most likely, the beginning of each experiment will consist of welcoming the subjects, asking them to fill out some questionnaires, to prepare for going to bed, to put on the sleep mask according to the instructions in the tutorial video, and to finally go to bed and switch on the sleep mask. Afterwards, a bio signal calibration might be conducted. What happens afterwards, highly depends on the experimental question being investigated. One could just record a night of undisturbed sleep, present stimuli to the subject in regular time intervals or during specific sleep stages, or ask the subject to fill out further questionnaires during the night or in the morning. Moreover, if the study's design is more complicated, one can modify the python code by programming new xml elements or by training and applying advanced EEG pattern detectors, e. g. for closed-loop slow wave sleep stimulation.

Afterwards, the updated experiment xml files (and eventually any other updated files of the Traumschreiber system) need to be copied to the experiment stations.

Finally, the experiment boxes can be handed out to the subjects or can be sent by post.

3.2.4 Fourth study: A crowd-based polysomnographic experiment

This study was carried out in order to investigate, whether the Traumschreiber system enables inexperienced crowd subjects to perform a polysomnographic sleep and dream experiment at home. Moreover, a parallel study design was tested, i. e. more than 10 subjects recorded data in parallel, decreasing the duration of the data acquisition substantially.

3.2.4.1 General results

13 of the 14 subject, who each collected a Traumschreiber system, recorded three full nights. The 14^{th} subject dropped out due to a technical defect (on-off switch broke). The further analysis will be based on the 13 subjects, who participated in the whole experiment.

In all 39 nights, the Traumschreiber system enabled the naive crowd subjects to conduct the sleep and dream experiment at home. More specifically, it carried out the following tasks:

- It welcomed and instructed the subject in the evening about what to do when.
- It conducted the bio signal calibration procedure.
- It wished good night.
- It woke up the subject multiple times during the night according to the procedure specified in the experiment xml file.
- It carried out real-time sleep staging in every second of each night using a neural network based machine learning approach.
- It requested the subject during the night to fill out the nightly questionnaires.
- It told the subject to continue sleeping.
- It protocoled everything (times, actions, stimuli).

During the short time frame of the experiment – exactly one week –, 39 polysomnographic measurements were conducted, and 207 questionnaires were filled out by the subjects during the night, after they were acoustically stimulated by the Traumschreiber system.

Figure 3.33: Example of the bio signal calibration procedure, which the Traumschreiber system carried out at the beginning of each night. One can clearly see the eye movements, which the Traumschreiber system asked the subject to perform, in the VEOG and HEOG channels.

The subjects were asleep prior to the nightly stimulation in 85.2% of the cases, according to their own self-rating, and overslept 15.6% of the acoustic stimulations. Even though no human experimenter was at the place of recording, the subjects' reliability concerning the nightly questionnaires was high: 98.2% of the nightly questionnaires were filled out at the time of nightly stimulation, as was revealed by the coding number, which the subjects could obtain only during the night.

3.2.4.2 Data quality

While the transmission quality was good in only two of the 13 first nights, this changed to 10 out of 13 nights for the second and third recording of each subject (statistically significant, d=1.569, p=0.001, comparing first and second night).

What were the reasons for bad transmission quality? Two subjects reported in the first night, that the on-off switch of their sleep mask was loose. This fits the transmission plots, which indicate fragmentary data transmission for all three nights of these two subjects (see online appendix). Six of the remaining first night recordings with bad transmission quality show an abrupt loose of signal after a few hours, three times directly following the acoustic stimulation. Two reasons might explain this: either the subject (intentionally or

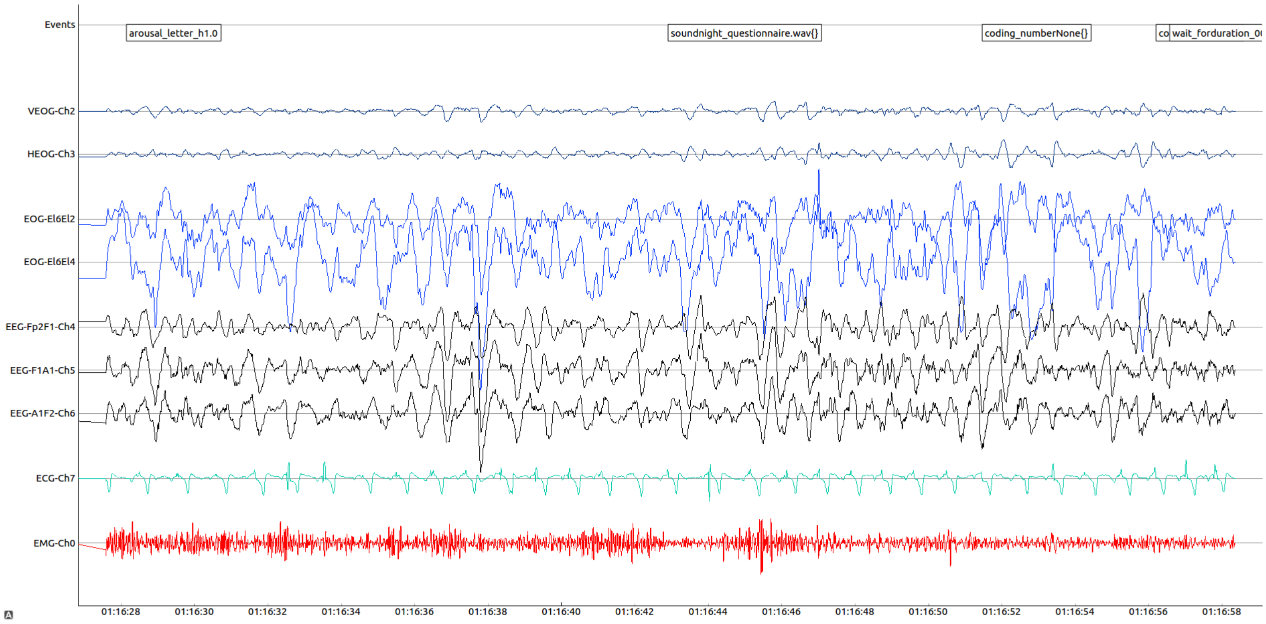

Figure 3.34: Example of a nightly arousal procedure, during which the subject overslept (N3 sleep continues). This matches the nightly questionnaire, which was not filled out by the subject.

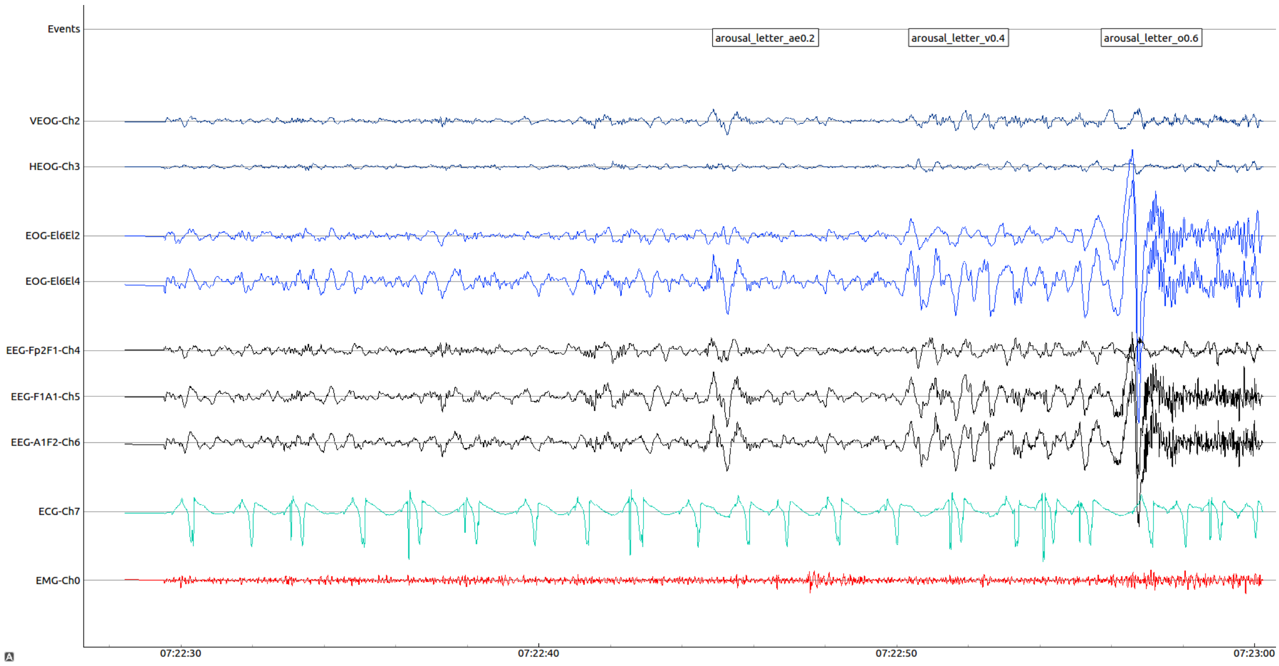

Figure 3.35: Example of a nightly arousal procedure, during which the subject woke up. In the nightly questionnaire, the subject reported to have heard the letter "o" first after waking up, i. e. the subject missed the first two stimuli "ä" and "v".

unintentionally, consciously or subconsciously) switched off the sleep mask, or the batteries were not fully charged before conducting the experiment the first time (even though all the batteries were checked before handing them out to the subjects – they might have discharged before the first experimental night). In one of the remaining three recordings with bad transmission quality in the first night, no data was received at all, which might be due to the subject having forgotten to switch the sleep mask on, or a completely empty battery. For the two other cases of the first night, it remains unclear, why the data transmission was bad. In the third recording during the second experimental night, which showed poor transmission quality, the data transmission was stopped after about half an hour, suggesting that the battery was not charged. The data of the last recording with bad transmission quality (third night) indicate, that the sleep mask was switched on briefly in the evening for a few seconds, but switched off again. In the morning, shortly before the Raspberry Pi was switched off, again some seconds of data were transmitted, suggesting that the subject accidentally moved the on-off switch in the wrong direction.

Looking at the data quality during the 22 nights with good signal transmission, overall, the quality of the transmitted data was very good. If the first night is considered a training and practice night, and also the two successfully recorded datasets of the first night are excluded, the second and third experimental night (N=20) show a good EEG signal in 19 of the 20 recordings in at least one channel for at least 90% of the night, and in many cases also the other channels showed a good data quality (at least two good EEG channels: 16 recordings, all three EEG channels: 9 recordings). The same is the case for the EMG channel, which had a good data quality in 19 of the 20 recordings. The EOG yielded good data in 18 nights in at least one channel (two channels: 11 recordings), whereas the ECG channel only recorded data of good quality during 15 of the 20 nights. In the two first night recordings with good signal transmission, both the ECG and EMG channel recorded data of good quality in both subjects, whereas only in one of the two recordings a good EEG and EOG signal could be obtained.

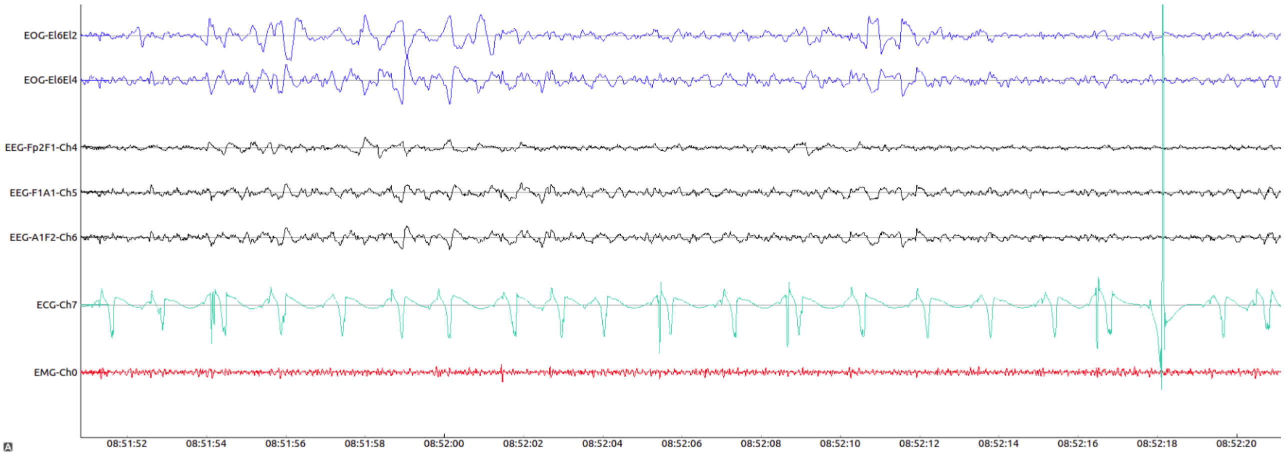

Figure 3.36: Example of REM sleep, recorded autonomously by the Traumschreiber system at the subject's home.

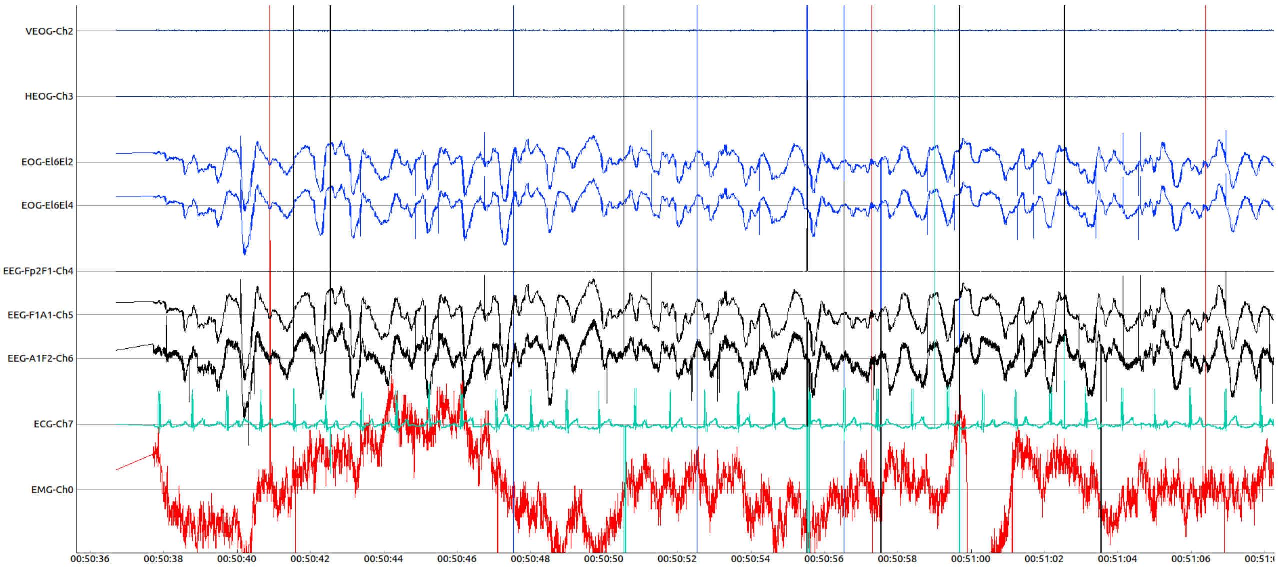

Figure 3.37: Unfiltered, raw data example of a recording with bad quality. The channels 2, 3 and 4 are flat (most likely due to static charges on the electrodes). The EMG (channel 0) shows large drifts, however, these can be filtered out in software using a bandpass filter. Channel 5 and 6 show clearly visible slow waves, with 50 Hz power line noise on channel 6 (can be filtered out in software, too). The ECG shows a clear heart beat. On all channels, spikes are visible, which is unfortunately the case for all recordings of the here used version of the Traumschreiber system, and most likely due to a programming error of the microcontroller and its internal ADC. However, these spikes can be removed using a median filter or a threshold. This bug is removed in the in the latest firmware version, which is attached in the online appendix.

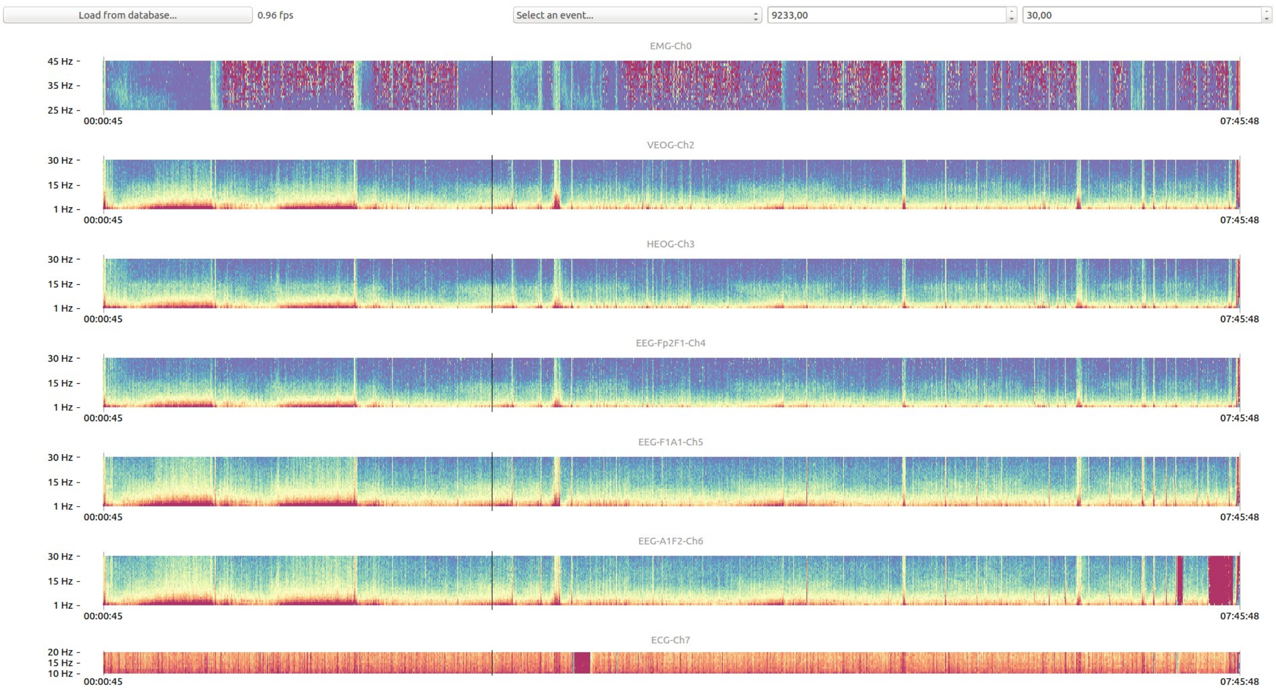

Figure 3.38: Example of a Traumschreiber system recording (time frequency plots of seven channels) with good data quality on all EMG, EEG, EOG and ECG channels in at least 90% of the night. Only one EEG channel (6th row) has a bad data quality at the end of the night (dark red color), as well as the ECG for a few minutes during the night.

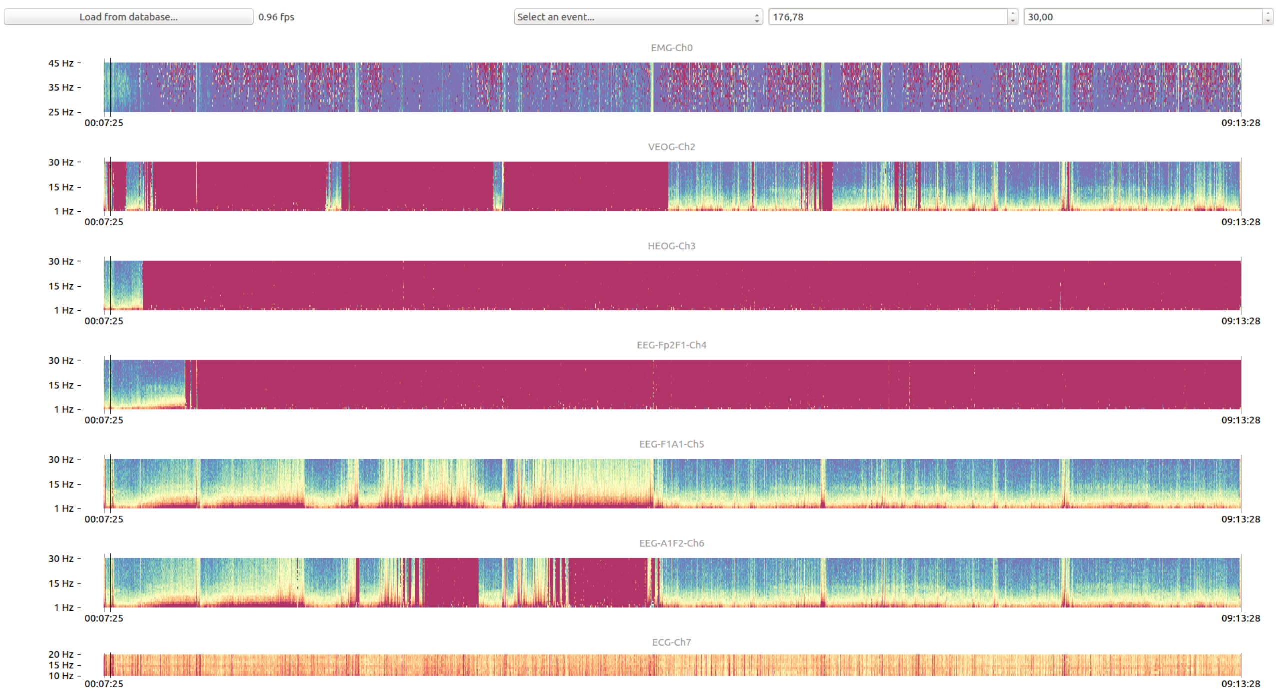

Figure 3.39: Example of a Traumschreiber system recording (time frequency plots of seven channels) with bad data quality in several channels (both EOG channels, two EEG channels).

Taking the transmission success and the data quality together, and excluding the two subjects with loose on-off switches in their sleep masks, 86% of the recordings of the second and third night showed a good EEG signal, 82% a good EOG signal, 86% a good EMG signal and 68% a good ECG signal. Ten of the eleven subjects with intact sleep masks delivered at least one full night of polysomnographic recording during night two or three (EEG, EOG and EMG), six of which recorded both nights two and three successfully. Eight of the eleven subjects recorded whole nights with EEG, EOG, EMG and ECG.

11 subjects, second and third night (N=22)			
Recordings with good EEG signal	Recordings with good EMG signal	Recordings with good EOG signal	Recordings with good ECG signal
86%	**86%**	**82%**	**68%**

Table 3.6: This table shows, how many of the recordings of the eleven subjects with intact sleep masks yielded a good EEG, EMG, EOG, and ECG signal, respectively.

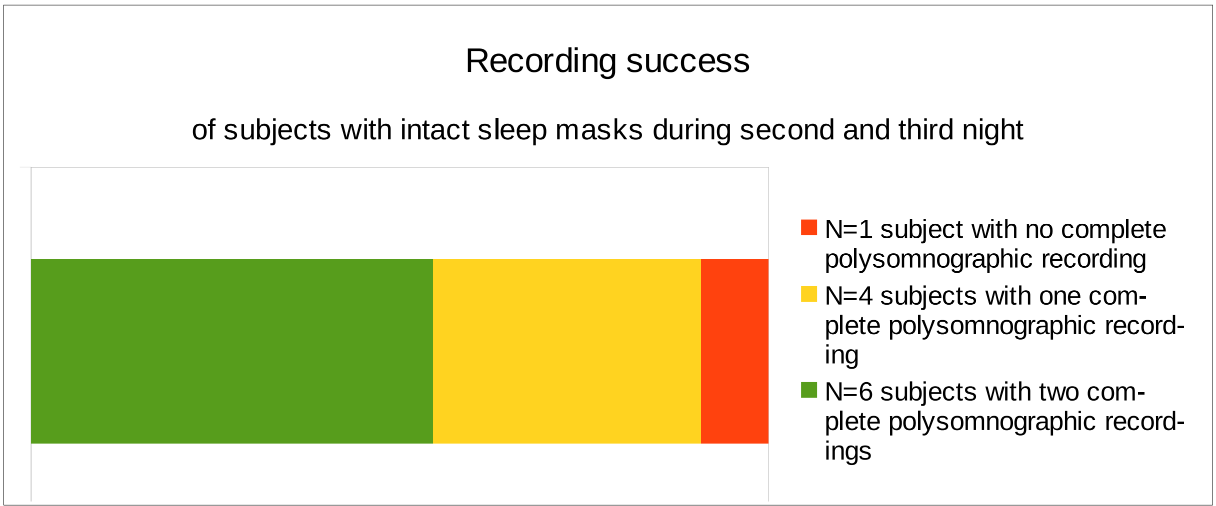

Figure 3.40: This figure shows the recording success during the second and third night of the eleven subjects with intact sleep masks.

There was no significant difference between the second and third night regarding the data quality, except for the ECG channel, which was better during the second night (nine versus six out of ten whole night recordings, d=0.739, p=0.032).

3.2.4.3 Sleep quality

The sleep quality (SQ) was not significantly different between the three experimental nights (SQ night 1: 3.03±0.74, night 2: 3.06±0.51, night 3: 3.1±0.7. d(nights 1 and 2)= 0.04, d(nights 1 and 3)= 0.1, d(nights 2 and 3)= 0.08). The feeling of recovery in the morning (FoR) was also not significantly different between the three nights (FoR night 1: 2.89±0.89, night 2: 2.75±0.44, night 3: 2.69±0.84. d(nights 1 and 2)= 0.20, p(nights 1 and 2)=0.661, d(nights 1 and 3)= 0.24, p(nights 1 and 3)=0.618, d(nights 2 and 3)= 0.10).

The sleep quality and the feeling of recovery was worse during this experiment than in the reference groups provided by the questionnaire makers, which is not a surprise as the subjects were woken up on purpose several times during the night (SQ of both reference groups: 3.86±0.81 and 4.05±0.83, FoR: 3.48±0.78, 3.38±0.74).

3.2.4.4 Ease of use, comfort and durability of the Traumschreiber system

The subjects found it easy to use the system (putting on electrodes and sleep mask, following the written, auditory and video instructions) – indicated by an average answer to the regarding questions in the sleep mask questionnaire of 1.61±0.60 (scale: 1-easy, 5-difficult). The video instructions were helpful (3.26±0.59, 1-not at all helpful, 4-very helpful). In nearly all nights, the subjects reported that they experienced no technical problems with using the system. In four nights, the subjects reported having switched on the sleep mask too early, so that they had to restart the minicomputer in order to be ready for the bio signal calibration in time. One subject had trouble finding the on-off switch during the first night. Even though the sticky electrodes did not fall off in a single case (as reported by the subjects), it was rather easy to remove them (2.62±1.16, 1-easy, 5-difficult).

The sleep mask and the cables were perceived as slightly disturbing for falling asleep (1.79±0.47, 1-not at all, 4-very disturbing). Overall, the subjects reported, that sleeping with the sleep mask and the sleep mask material was neither comfortable nor uncomfortable (2.92±0.45, 1-very comfortable, 5-very uncomfortable). When asked after the second and third night, whether they slept better or worse than in the previous experiment night, the subjects said that they slept slightly better in the later nights (2.46±0.90, 1-much better, 5-much worse).

No signs of wear were visible after using the sleep mask three nights for each subject, except one ECG cable, which broke during the third night of one subject.

3.2.4.5 Feedback of the subjects to the sleep mask and the experiment

Overall, the feedback was mixed. Some subjects praised the design or reported the sleep mask to be comfortable or at least more comfortable than expected. Other subjects complained about parts of the experiment or made suggestions, how to improve it: Eight of the 13 subjects found the volume of the acoustic stimuli inappropriate (six times too loud, two times too quiet). Four subjects wanted more padding at the ear or the nose part of the sleep mask. Three subjects found it difficult to wash the glue residues off the skin after the sticky electrodes were removed. Two subjects suggested to label the cables better.

3.2.4.6 Automatic sleep scoring algorithm and subject-specific adjustment

All Traumschreiber systems predicted the current sleep stage using the Keras/tensorflow neural network approach during every second of the experiments, in which data was transferred from the sleep mask. Furthermore, the predicted sleep stages were used for steering the experiment and determining the stimulation times. This happened in real-time autonomously, and followed the exact rules given in the experiment xml file.

The quality of the real-time sleep scoring algorithm, i. e. the sleep stages predicted, however, was not sufficient in most recordings, including the ones with very good polysomnographic data quality. Most automatically scored hypnograms were heavily biased towards the N3 sleep stage. Even though the subject-based real-time adjustment of the predictions changed the actually predicted sleep stages in 18 of the 20 second and third nights, this helped improving the prediction quality only in eight nights, and even with the adjustments, the sleep staging quality remained very poor. Figure 3.41 illustrates this exemplarily (see online appendix for further plots).

In the left two plots, one can see that N3 sleep was predicted for basically the whole night, as its probability among all five sleep stages was highest. However, one can also see, that cyclic patterns exist within the N3 sleep predictions, as well as in the other sleep stage predictions. This suggests, that the neural network detected these overall sleep cycle-like patterns, but had a too high prior for the N3 sleep stage.

The plots in the middle column demonstrate, that the predictions were adjusted, since an additive prior was added to the other sleep stages based on the sleep stage distribution of the previous night, and the N3 predictions were shifted downwards. Even though this improved the prediction results slightly, this was not enough in order to deliver a good real-time sleep stage prediction.

In the plots on the right, the priors were calculated automatically retrospectively, knowing the predictions of the actual night and shifting them up or down. Here, one can see a plot, which looks pretty much like a human-scored hypnogram. Classical sleep macro structure elements are visible, e. g. alternating patterns of REM and non-REM sleep, and more deep sleep in the first half of the night than in the second (even though the first and last REM period should probably rather be classified as awake). The slight deviation from the normal 90 minute sleep cycle length is probably because of the six awakenings of the subject due to the auditory stimulation.

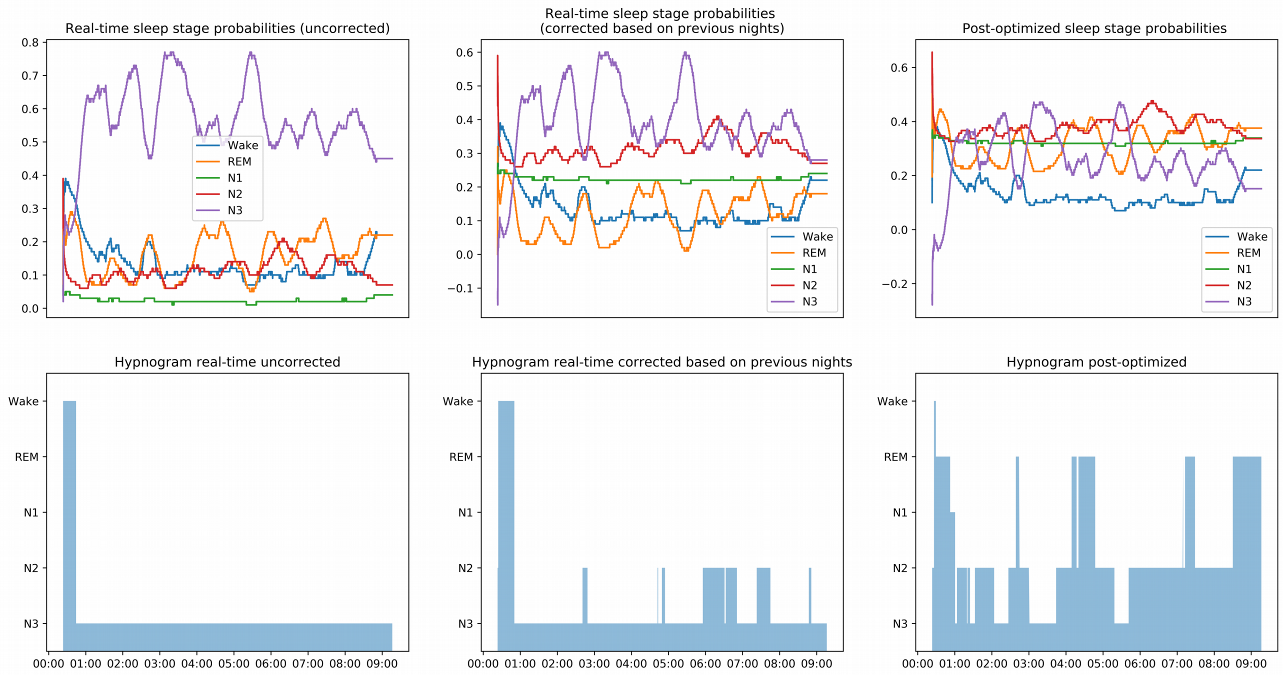

Figure 3.41: Real-time prediction, real-time adjustment, and the automatically post-optimized version.

Summarizing, the Traumschreiber system performed a real-time sleep stage classification using a deep neural network approach. It also adjusted the experiment timings accordingly, and took subject-individual differences into consideration. However, the prediction quality of the simplistic sleep staging algorithm was by far not sufficient and needs further improvement. It has to be kept in mind, though, that only a simplistic sleep staging algorithm was used due to the limited availability of training data, and that, thus, the poor sleep staging performance was to be expected.

3.2.4.7 N3 and REM sleep differences

Ten subjects recalled and rated 18 REM sleep dreams and 14 N3 deep sleep dreams, after they were woken up by the Traumschreiber system during the second or third night (sleep stages scored by a human rater). N3 sleep dreams were attributed significantly stronger by the subjects as being “rather static thoughts, no story” than REM sleep dreams (N3=2.50±1.72, REM=0.67±0.88, d=1.396, p=0.001), and far less “lively or with an action-packed plot” (N3=2.07±2.15, REM=5.78±1.47, d=2.059, p<0.001). REM sleep dreams were described as being much more “entertaining, would like to continue dreaming about it” than N3 sleep dreams (REM=3.89±1.73, N3=1.93±1.94, d=1.074, p=0.006). Even though the REM sleep dreams were rated as being more “bizarre” than the N3 sleep dreams by the subjects, this effect was not statistically significant (REM=2.28±2.08, N3=1.36±1.59, d=0.49, p=0.199). The same is true for the time needed to wake the subject up: There might be a difference between the two sleep stages, but this was not found to be statistically significant (REM=2.74±1.62, N3=3.77±2.07, d=0.558, p=0.064).

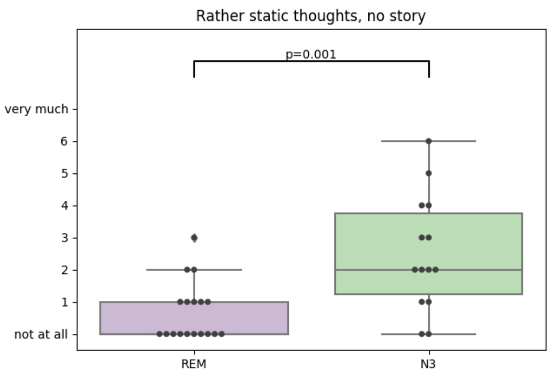

Figure 3.42: Difference between REM and N3 sleep dreams, regarding in how far they were perceived as rather static thoughts with no story.

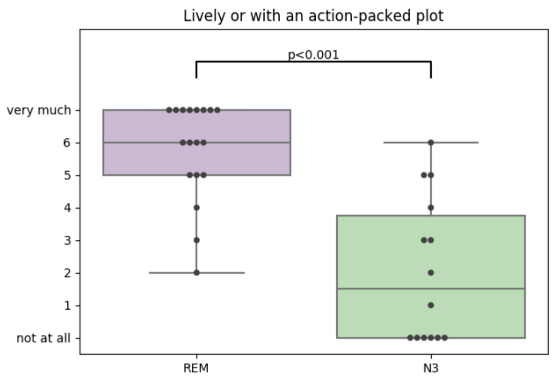

Figure 3.43: Difference between REM and N3 sleep dreams, regarding in how far they were lively or with an action-packed plot.

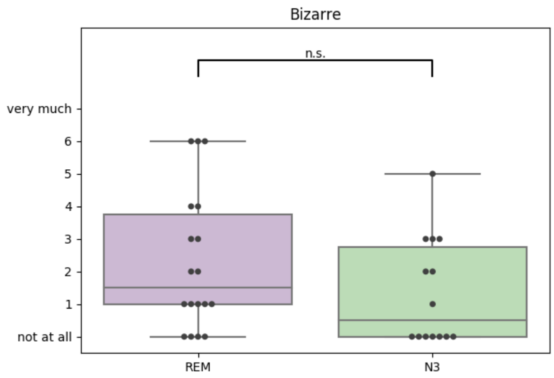

Figure 3.44: Difference between REM and N3 sleep dreams, regarding in how far they were bizarre.

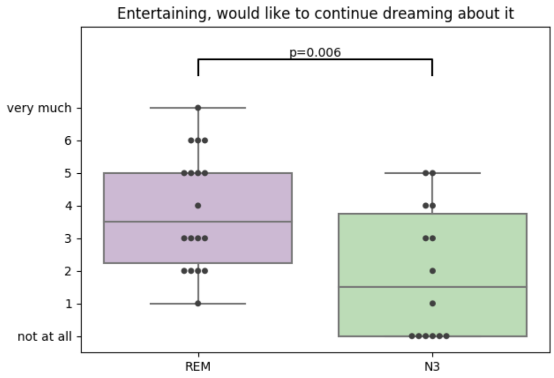

Figure 3.45: Difference between REM and N3 sleep dreams, regarding in how far they were entertaining and whether the subject wanted to continue dreaming about it.

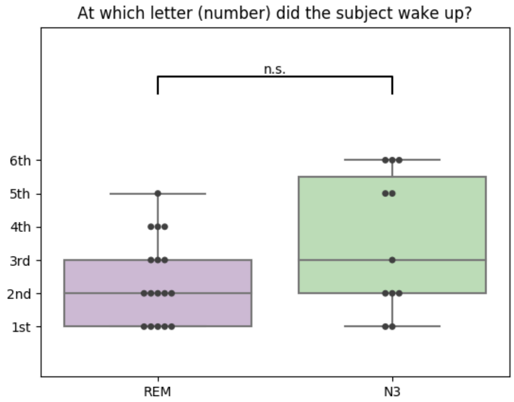

Figure 3.46: Difference between REM and N3 sleep, regarding which of the letters the subject heard first during the arousal procedure.

3.2.4.8 Sleep depth

The correlation analysis, which set the night number (1^{st}, 2^{nd}, 3^{rd}) in relation to the time it took the subject to wake up, revealed that subjects slept significantly deeper during the later nights of the experiment, even though only a weak correlation could be found (r=0.21, p=0.025). Furthermore, the same type of analysis showed that acoustic stimuli presented later during a night (i. e. more towards the morning) woke up the subjects significantly faster (again only weak correlation, r=-0.19, p=0.041).

3.2.4.9 Workload of the experimenter and costs of the experiment

Before handing out the experiment boxes to the subjects, the experimenter had to extend the Traumschreiber system software slightly by adding the experiment-specific auditory arousal procedure (letters with increasing volume), which also included recording the acoustic instructions to fill out the nightly questionnaire.

When the experiment boxes were handed out to the subjects, the experimenter had to answer only some smaller organizational questions of the subjects. These were mostly about how, where and when to return the materials, and how to receive the signature for the subject hours.

During the experiment week, only one subject contacted the experimenter (via email). This was the subject with the on-off switch, which fell off before the first experimental night. A spare experiment box was offered to the subject, but she declined and chose to not continue the experiment.

All subjects returned their experiment box in time. The boxes were checked for completeness (all complete), and the sleep masks were inspected, whether any signs of wear could be detected (see above). Finally, the questionnaires and the micro-SD cards of the minicomputers were taken from each box for the data analyses.

Thus, the workload of the experimenter for actually conducting the experiment was extremely low compared to laboratory polysomnographic studies with acoustic stimulation of the subjects and sleep staging in real-time during the night.

The variable costs per night consisted of the costs of the single use sticky electrodes and the printing costs of the subject information leaflet, the consent form and the questionnaires. No money was paid to the subjects. Thus, in total less than two EUR had to be invested for each experimental night, resulting in total costs of less than 100 EUR for the whole experiment of 39 recorded nights.

4 Discussion

4.1 General discussion

The here developed Traumschreiber system offers a new methodological approach to sleep and dream research. It enables naive crowd subjects to conduct complex polysomnographic experiments at home, i. e. in their natural sleep environment. No professional human experimenter is necessary at the place of recording, which allows the researcher to focus on creating experiment ideas and on analyzing experiment results instead of spending time with repetitive tasks during the night. The Traumschreiber system instructs the subject, what to do how and when, and carries out experiment tasks, when the subject is asleep. The technology used inside the Traumschreiber system records data of good quality on eight electrophysiological channels, including EEG, EOG, EMG and ECG. Furthermore, the raw data is accessible in real-time, and real-time stimulation of the sleeping subject is possible (acoustically, visually). The Traumschreiber system is a completely open source and non-commercial technology and can be extended as needed. A detailed description, of how to create own entities of it, is supplied in this dissertation. Due to the very low costs of the system (less than 230 EUR for the complete system including a Raspberry Pi 3 Model B minicomputer, or less than 140 EUR for just the sleep mask), many Traumschreiber systems can be used even on a low budget in parallel. As a result, far more nights can be recorded by using a crowd-based approach in a much shorter time at much lower costs and with far less efforts for the researcher and the subject, than would be possible with polysomnographic sleep laboratory recordings – and at the same time going far beyond the possibilities of previous portable devices for field studies, because also complex experimental paradigms can be carried out. This enables new, large-scale and data-driven scientific explorations in the field of sleep and dream research.

The Traumschreiber system is not only far less expensive, but compares well to the previously existing sleep and dream research methods in many aspects (for further details regarding the existing technologies, please see chapter *1.3 Assessment of sleep and dreaming in the sleep laboratory* and chapter *1.4.2 Field studies using electronic tools*):

- Compared to polysomnographic in-laboratory recordings, the main advantages of the Traumschreiber system are that no laboratory is necessary, resulting in drastically reduced resource needs and workload of the experimenter. Moreover, the sleep of the subject can be studied in the natural sleep environment, avoiding potential influences of the unfamiliar setting on sleep or dreams. The visual stimulation capabilities of the high-tech sleep mask and the easy to program experiments are further advantages of the system over standard in-laboratory sleep recordings. It has to be noted, however, that the data quality (even though is it good) is worse than what can be achieved using polysomnographic sleep laboratory recordings.
- Compared to medical portable sleep recording devices, the Traumschreiber system has a lot of advantages and only a few disadvantages. Actigraphy is not able to measure EEG or EOG and thus is not able to differentiate between sleep stages, which is possible with the Traumschreiber system. Portable polysomnographic medical devices are far more expensive than the Traumschreiber system and need a trained sleep technician to apply them in the evening, in contrast to the here developed system. Moreover, to the author’s knowledge, no portable sleep experiment system exists, which allows to conduct as complex sleep experiments as is possible with the Traumschreiber system (e. g. acoustic stimulation of the sleep based on the real-time data, real-time sleep evaluation using machine learning algorithms such as deep neural networks, easy-to-program sleep experiment framework). Furthermore, the available medical portable sleep recording devices are proprietary, commercial products, limiting their extendability and, in most cases, the access to the raw data in real-time. The Traumschreiber system, on the other hand, is open-source and can be extended and modified by any interested researcher. It has to be noted, however, that the Traumschreiber system is not intended to be used for medical purposes but only designed to be used for research purposes. Moreover, there is no commercial, profit-oriented producer behind it, no salesmen and, thus, only limited technical support.
- Compared to the variety of consumer sleep recording devices, and in contrast to most of them, the Traumschreiber is validated against a polysomnographic in-laboratory device, it records more electrophysiological channels, it is cheaper and requires no licensing fees, is open-source and allows real-time data access, is

tailored to scientific sleep experiments and supports the researcher with an easy way to create automated sleep experiments, and it is ready-to-use and not only promised to be sold sometime in the nearer future. No other consumer product sleep recording device offers the combination of advantages of the Traumschreiber system. It has to be noted, however, that there is no profit-oriented company behind the Traumschreiber system offering professional user support, but only the developing researchers.

As described in chapter *1.6 Sleep and dream research and artificial intelligence*, various approach to use methods from the field of artificial intelligence for sleep research purposes exist, e. g. for using deep neural networks for sleep stage classification. For the first time, the Traumschreiber system offers an open-source hardware and software combination, into which these existing tools can be integrated – the Keras/tensorflow deep neural network framework of the Traumschreiber system can be easily filled with state-of-the-art or future neural network architectures.

Summarized, the Traumschreiber system is a new tool for sleep and dream researchers, offering a unique combination of features, which make possible new types of experiments.

4.2 Discussion of the development process and evaluation studies

4.2.1 Discussion of the development process

Starting from scratch, first the requirements were defined - based on the experiences of the author from work in two scientific sleep laboratories as well as from sleep research field studies. Furthermore, the requirements were continuously updated based on the feedback of other researchers from collaborations, conferences and workshops. It is still likely, that the features of the here presented Traumschreiber system are not optimal for every use case. This means, that other researchers would have set different priorities for development, e. g. to implement less or more recording channels, to use a better but more expensive microcontroller, to build in other types of stimulation into the sleep mask, or to set a stronger focus on developing a smartphone app. The here developed Traumschreiber system tries to optimize a complex network of interdependences between costs, quality, features, comfort, development and production time, and many more. But since the Traumschreiber system is completely open regarding both hardware and software, any researcher with enough technological background (or colleagues) can modify it according to his or her special needs.

Choosing an iteration-based approach for developing the Traumschreiber system is quite standard for high-tech devices, as everbody knows from other technical devices such as smartphones or even polysomnographic recording equipment, which have new, additional features in every new version. Overall, this approach worked fine and lead to constant improvement of the latest prototype, resulting in the final system as presented here. However, only a handful of researchers were involved in the actual development work of this complex technology, and all of them worked only part-time or as a hobby on this project. No professional electrical engineer, no professional sleep researcher with decade-long experience in the field and no professional product designer was part of the development team. Moreover, the project's budget was low, and acquiring money from independent charity organizations was a time consuming and bureaucratic act. Thus, the speed of development was rather low, and some decisions were made, which experienced industrial developers might not have made. One example for this is the decision to construct a self-designed differential EEG with operational amplifiers, instead of using ("pre-built") instrumentation amplifiers, which was neither cheaper nor better regarding the data quality in the end. Another example was to choose a cheaper factory with shorter lead times for the second PCB, which was produced and equipped in China. In the end, 9 out of 10 boards did not function properly, and the expected shorter lead time was much longer than promised. Summed up, a lot of time-consuming learning was necessary throughout the whole development process, due to starting as greenhorns. On the other hand, this probably eased innovative development research, as no "this is not possible" or "we never worked this way" stopped producing new solutions to occurring problems.

4.2.2 Evaluation studies

The Traumschreiber system was evaluated in several studies. In the first study, simultaneous sleep recordings of the Traumschreiber system and a commercial medical polysomnographic system were carried out in a sleep laboratory, and the data of both systems was compared. It was found out, that the Traumschreiber system can record data of high quality, in which the most important types of sleep graphoelements can be identified, and which lead to the classification of the same sleep stages in more than 90% of the compared epochs of both systems. In the second study, a rather simple type of sleep experiment was conducted by naive crowd subjects using a prototype of the system, demonstrating that this approach is in principle feasible. In the third study, it was measured, what resources are necessary for producing the Traumschreiber system, and the work steps were described in detail, so that any interested researcher can produce an arbitrary number of Traumschreiber systems. This description also functions as a tutorial. The last evaluation study showed, that many Traumschreiber systems can be used in parallel by multiple naive crowd subjects with very low organizing demands for the scientist. Moreover, it was shown that the built-in machine learning based algorithms are able to steer complex experimental paradigms, which also require real-time analysis of the subject's sleep (even though improvements of the internal sleep staging algorithm are needed).

Some limitations of the general evaluation process need to be addressed, before each of the four studies is discussed. First, the evaluation studies were conducted by the developers of the Traumschreiber system and their students. Even though all studies were carried out in a highly objective way and following good scientific practices, independent evaluations of the Traumschreiber system should be conducted.

Second, another weakness of these studies is the selection of the subjects. Only healthy young adults participated in the three studies, which evaluated the Traumschreiber system in independent subjects. Thus, it remains unclear, how well the Traumschreiber system is suited for measuring patients with sleep disorders or other illnesses, for who sleep staging might be harder, or older subjects, who might be more insecure with using this new technology.

Another limitation regarding the evaluation studies is the usage of different versions of the Traumschreiber system. Of course it would have been a better idea to conduct these studies all with the exact same device after finishing development, instead of using a prototype for two studies. However, due to practical reasons this was not possible (the project's time frame and the iterative development process). And since very far developed prototypes were used, which differed not significantly regarding the relevant technical specifications, this procedure was viewed as an acceptable solution.

4.2.2.1 First study: Sleep laboratory validation

This study simultaneously measured sleep of six subjects with both the Traumschreiber system and the ALICE system, a commercial polysomnographic system, which is used in clinical and research sleep laboratories worldwide. The comparison of 189 epochs (30 second data bins) of both systems demonstrated, that both systems record very similar data, and that the Traumschreiber system can, in principle, thus be used for sleep experiments. All sleep graphoelements (e. g. slow waves, sleep spindles, K-complexes, REMs, heart beat) could be detected in both systems in nearly all corresponding epochs, e. g. if one system showed slow waves, the other systems showed slow waves, too. The only exceptions to this were central-occipital sleep spindles and alpha EEG activity, which were mostly not detectable in the Traumschreiber system due to the frontal placement of the electrodes. However, if one changes the suggested recording layout and collects EEG data with occipital electrodes (e. g. cup electrodes), these graphoelements should be measurable as well. The downside of this idea is, that inexperienced subjects will find it very hard to impossible to fixate the cup electrodes on the back of their head.

Manually sleep staging the 189 epochs showed, that in 92.6% of the cases, the same sleep stage would be assigned. This demonstrates, that the data of the Traumschreiber system is well suited for professional sleep experiments, which want to analyze or compare only selected sleep stages. However, viewing only single 30-second epochs for classifying sleep stages, instead of scoring the complete nights, led to the effect that sometimes it was impossible two differentiate between N1, N2, REM sleep or wakefulness, since knowledge about the sleep stage of the previous epoch would have been necessary. Thus, an ambivalent sleep category had to be introduced for these cases. This does not necessarily mean, that sleep staging these epochs is not possible, however, it remains unclear, how well the Traumschreiber system can be used in these complicated cases.

Another limitation of this experiment is, that only seven subjects were recorded, with one of the recordings being excluded afterwards. Thus, sleep characteristics, which are rare to find in many subjects, might have been missed (e. g. sawtooth waves in the sleep EEG of REM sleep).

The placement of the electrodes in this experiment has to be discussed as well. As can be seen in figure 2.14, the electrodes of both systems were placed as close to each other as possible. However, because of the size of the single use sticky electrodes, about two to three centimeters of space remained between the electrodes of the two systems, which might be an explanation for the slight differences in the recordings of both systems. Another reason for the slight differences in the shape of both signals might be special hardware or software filters of the ALICE system, which are not known since the system is proprietary (not open).

4.2.2.2 Second study: Home-based prototype study

In this study, the Traumschreiber system was used for the first time by naive crowd subjects. The results of this experiment show, that home-based autonomous sleep experiment including acoustic stimulation of the sleep of subjects, who are instructed by the system how to set up the polysomnographic measurements, are feasible, and that the subjects find it rather easy to use the Traumschreiber system. Moreover, this experiment identified several points, how the system needed to be improved. Most importantly, an automatically re-establishing bluetooth connection was necessary. The experiment shows further, that the data quality of the recordings measured by the Traumschreiber system was good, if the bluetooth connection did not disconnect during the night.

The sleep quality was significantly better during the control night, in which the sleep mask was not worn, than in the experimental night with the Traumschreiber system. This was the case for the experimental subgroup, which received acoustic stimuli every ten minutes throughout the whole night, as well as for the subgroup, which was not stimulated acoustically. The feeling of recovery in the morning, however, was not significantly different between the control night and the night with wearing the Traumschreiber sleep mask for the subgroup without acoustic stimulation (but for the subgroup, which was stimulated, it was). Moreover, the majority of the subjects reported, that the sleep mask was not or only slightly disturbing and was at least okay to wear, if not even comfortable. Taken together, these results suggest, that the Traumschreiber system leads to slightly impaired sleep, even though wearing it was comfortable or at least okay for the subjects.

Not surprisingly, acoustic stimuli, which lead to arousals, were significantly louder than the cues, which did not provoke an arousal. Even though this outcome was to be expected, this can be viewed as a further sanity check, that the Traumschreiber system conducted its task successfully. Another insight of finding such an effect is, that even though differences between the subjects and their sleeping environment existed and a direct comparison between them was not sensible, on a group level significant effects could be found. Especially for much larger crowd experiments with many more subjects, this effect is a strength of the Traumschreiber system, as it is inexpensive and can be recorded simultaneously. This means, that for example differences regarding the exact distance between the speakers and the bed, the direction of the speakers, the individual preferred body positions, and other circumstances such as the type of pillow or the general loudness of the room, can be neglected, if enough subjects are recorded.

A limitation of this study is, that only one night was recorded for each subject with the prototype of the Traumschreiber system, and one control night without the system. No adaptation or practice night was conducted. As described in the results (how to improve the system), this limits the study's validity regarding sleep quality, ease of use, and also data quality, since the subjects might have got used to wearing the sleep mask. Note, however, that in the fourth study, these questions were analyzed in greater detail.

4.2.2.3 Third study: Preparing polysomnographic crowd experiments

This study analyzed, how quickly and at which costs a Traumschreiber system can be produced, and described each individual work step. The description of the work steps can be viewed as a tutorial for other researchers, who want to use this new, open technology themselves. Overall, the production time for one Traumschreiber system was found to vary strongly depending on the experience of the manufacturer, and can be assumed to lie between 170 minutes for inexperienced workers to 60 minutes for people experienced in producing the system, especially if larger quantities are produced and several Traumschreiber systems can be produced in parallel. Additionally, several weeks of time have to be kept in mind for waiting time, until the ordered components arrive. One limitation of this study is that the experimenter, who conducted the work steps, was part of the Traumschreiber system development team (the author of this dissertation). Thus, it can only be estimated, how long each work step takes for completely inexperienced experimenters. On the other hand, having a tutorial at hand like the one presented in this dissertation probably increases work speed substantially, as best practices are available. Moreover, it can be criticized, that the fixed number of Traumschreiber systems, which were produced during this study (20 pieces), and the total number of producers (one person) limits the generalizability of this study further.

The production costs of the Traumschreiber system are very low, compared to commercial devices, which, moreover, do not even offer the same functionality (e. g. open hardware/software, raw data access in real-time, artificial intelligence controlled experiment conduction). 20 of these low-budget systems cost 222 EUR each (as of March 2017). If the Raspberry Pi experiment station is replaced by a smartphone app and mobile phones of the subjects are used, the production costs drop by further 34%. However, the existing Android app protoype needs substantial further development, before it can be used in a similar way as the Raspberry Pi experiment station. Another big cost factor are the electrode cables, which cost around 40 EUR, and which could be imported from China for around a third of the price, as a sample order showed. One has to keep in mind, however, that all these costs depend on several factors, ranging from the total order quantity to the currency exchange rate, and can thus only serve as estimators. Furthermore, the production costs include only those costs for the materials. Depending on the situation of the researcher producing one or more Traumschreiber systems for own experiments, additional costs for paying production assistants, premises and so on might occur.

Taken together, this study gives a detailed description of the work steps necessary to produce arbitrarily many Traumschreiber systems. The production times and costs should be seen as an estimate, giving the researcher a first impression of the resources needed. They also enable the researcher to compare the production time for a Traumschreiber system to the time usually spent for recording a single night in the sleep laboratory: During the time needed for recording one subject in the laboratory, about eight Traumschreiber systems can be produced.

4.2.2.4 Fourth study: A crowd-based polysomnographic experiment

The most complicated experimental paradigm was used in the last of the four evaluation studies. More than ten subjects received one Traumschreiber system each and recorded three nights each, demonstrating the system’s suitability for parallel recording. Despite obtaining 39 polysomnographic datasets within one week, the efforts and the costs for the experimenter stayed very low, demonstrating the scalability aspect of crowd-based sleep experiments. Moreover, several other evaluations were conducted.

First, in general, the data quality was found to be very good in nearly all nights, if the data transmission worked well and the sleep masks’ power supply was stable. However, this was not the case in most of the first nights of each subject. Loose on-off switches in three of the fourteen handed out sleep masks as well as not fully charged batteries (in the first night) were major sources for nights with unusable data. It might also be the case, that some subjects intentionally or accidentally switched off the sleep mask throughout the first night. In general, the recording quality of the second and third nights were much better than during the first night. This shows, that an adaptation and practice night is helpful.

Ten of the eleven subjects with intact sleep masks could deliver a fully functional polysomnographic recording for at least one of the second or third night (N=22). Averaged over all subjects with intact sleep masks for the second and third night, 86% of the recordings showed a good EEG signal, 86% a good EMG signal, 82% a good EOG signal, and 68% a good ECG signal. Nevertheless, a quite high fraction of recordings with not complete polysomnography (i. e. EEG, EOG and EMG) after the practice and adaptation night remains (6 of 22 nights), despite the number of backup channels. As a result, researchers need to be aware in future studies, that such autonomous recordings conducted by inexperienced subjects lead to a quite substantial amount of dropout nights. This is might not be very problematic for most experiments, as recording a few further nights is inexpensive and results only in a limited amount of extra work and costs for the experimenter, but might be a disadvantage, if a specific night of a specific subject is of importance.

The sleep quality and the feeling of recovery in the morning as measured using the Schlaffragebogen A questionnaire were found to be similar in all three experimental nights. However, when the subjects were asked directly during the later nights, whether they slept better or worse than in previous experiment nights, the average answer was “slightly better”. Moreover, the subjects were significantly harder to wake up during later nights of the experiment by the Traumschreiber system’s acoustic stimulations. Cautiously interpreting these contradicting results, it can be concluded that the subjects’ sleep was either equally good or slightly better during the later nights, but definitely not worse. The mixed findings regarding the sleep quality differences between the three experimental nights should be investigated further in future studies, which might also analyze this effect for a longer time period than three nights. Furthermore, it was found out that the sleep quality was significantly worse during the here recorded nights than in the questionnaire control group, data of which was provided by the questionnaire authors. This is not surprising, though, because they subjects were woken up several times during each night by the Traumschreiber system on purpose.

The crowd subjects reported, that the Traumschreiber system is easy to use. The instructions video, which showed how to put on the electrodes and the sleep mask, was very helpful. In all nights, no major technical problems (apart from the loose on-off switches in three sleep masks) were reported. The subjects found the sleep mask neither comfortable nor uncomfortable, but slightly disturbing for falling asleep. Except one broken ECG cable, no signs of wear could be detected. This demonstrates, together with the overall good data quality, that even sleep recording inexperienced subjects can successfully measure their sleep on their own, if they are instructed as done by the Traumschreiber system, and return these data a few days later to the experimenter.

The next evaluation showed, that the Traumschreiber system performed a real-time sleep stage classification in all recorded nights using a deep neural network approach. The system also adjusted the experiment timings accordingly, and took subject-individual differences into consideration. However, the prediction quality of the simplistic sleep staging algorithm was by far not sufficient and needs further improvement. The bad sleep stage prediction quality was to be expected, since the machine learning algorithm was trained on only a few nights of data and was constructed in a very simple form. Nevertheless, the underlying technology (deep neural networks using Keras/tensorflow) has been shown to be able to solve very complicated tasks (see chapter *1.5.2 Machine learning and deep neural networks*), including image and video classification, and including tasks, for which several temporal timescales have to be considered. If such an advanced deep neural network is trained, it can be run on the Traumschreiber system without any modifications, promising excellent sleep staging quality at least for healthy human sleep.

An exemplary dream research experiment was conducted in this study as well, and showed, that one can come to similar results by using the Traumschreiber system as with in-laboratory sleep research. In this experiment, differences between 18 REM and 14 N3 dreams were analyzed. REM dreams were found to be significantly less static, but more action-packed and entertaining, fitting results from previous dream research (Nir & Tononi, 2010). Even though REM dreams were rated as being more bizarre, this effect was not statistically significant, probably due to the low number of dreams being analyzed. The same is true for the time needed to wake the subject up: There might be a difference between the two sleep stages, but this was not found to be statistically significant.

Finally, taking all the before mentioned points together, the experiment showed, that the Traumschreiber system

- enables naive crowd subjects to conduct complex, sleep-stage dependent polysomnographic recordings including stimulation in a home-setting, and
- that is can take over the experiment lead during the time the subject is asleep.

The general strength of this crowd-based, large-scale, data and machine learning driven approach is, that despite a possibly higher dropout rate and more nights with bad data quality, the sheer amount of nights, which can be recorded without much effort, leads to a high number of successful recordings, and possibly new scientific insights about sleep and dreaming.

4.3 Future research directions and prospects

4.3.1 Future research directions

4.3.1.1 Further developing the Traumschreiber system

The main goal of this dissertation could be reached: The Traumschreiber system enables naive crowd subjects to conduct complex interactive polysomnographic sleep experiments at home, without the need for a professional researcher to be at the place of recording. Furthermore, it serves as a basis for further open source developments and even more elaborated experiments. Nevertheless, the system can be improved in nearly every aspect. This is due to the complexity of this project, limiting the available time for all the different subtasks – which ranged from identifying modern sleep and dream research's limitations, to electrical engineering of a whole polysomnographic system including EEG, to costs optimization including outsourcing to Chinese factories, to increasing the usability of the system and comfort of the subject, to data quality analyses, to public relation management, to obtaining finances for the project, to conducting the actual sleep studies with the new system, to training and supervising research assistants, to actually managing all this, setting the right priorities and keeping an eye on the overall timely constraints. Despite the great support of several co-workers with the subtask for this project, quite a number of tasks and improvements remain open. These are:

- Better sleep staging and pattern recognition algorithms: Even though simplistic sleep staging and pattern recognition algorithms based on machine learning are implemented into the Traumschreiber system, the goal of this dissertation was not to optimize their performance. Thus, the existing underlying technology based on Keras/tensorflow deep neural networks can be used much more effectively. As was described in chapter *1.6 Sleep and dream research and artificial intelligence*, numerous approaches for automatic sleep staging and pattern recognition exist. A promising idea might be to combine the excellent pattern detection abilities of convolutional neural networks (LeCun, Bottou, Bengio, & Haffner, 1998) with the multi timescale properties of long-short-term-memory cells (LSTMs, (Hochreiter & Schmidhuber, 1997)). Also, the preprocessing and feature extraction of the data can be improved, for example in a similar way as described in (Popovic, Khoo, & Westbrook, 2014). This way, both long term patterns in the data like sleep cycles as well as short term pattern such as the current spindle activity would be used.

- Conducting crowd experiments: The way, how the crowd experiments are conducted, could be elaborated on further. For example, by implementing a better subject interaction (adjusting volume, repeating instructions) or by showing the instruction video directly on a screen of the experiment station instead of sending the subject an internet link to the video. Moreover, the questionnaires could be conducted in a digital form, and the experiment station could control, that the subject fills them out at the correct time point (e. g. by keeping the subject awake until the questionnaire is completed during the night). Furthermore, the Traumschreiber system could check, that the battery of the sleep mask is charged before the recording starts and that the data quality is sufficient (good electrode contact).
- Hardware improvements: Regarding the hardware, several further developments should be thought of. More data could be transferred over the BLE connection by using compression methods, leading to a higher sampling rate. Furthermore, an impedance measurement could be implemented. Lastly, a different battery holder as well as a more stable on-off switch could be used.
- Data encryption: A dedicated encryption chip is already placed on the PCB, but has not been used so far. The idea is to encrypt the recorded data directly in the sleep mask, send it to any real-time data analysis station (possibly even over the internet, as shown in (Kayyali et al., 2008)), and to decrypt the data there. A similar approach

for encrypting sensor data in general was already proposed by (Bruyneel, Van den Broecke, Libert, & Ninane, 2013; Healy, Newe, & Lewis, 2008).

- An Android smartphone app to be used instead of a Raspberry Pi: A demo app was programmed and receives BLE data from a dummy device (see chapter *3.1.2.1.2 Experiment station*). The BLE service can be run in background without stopping data transmission. Furthermore, some introductory slides are available to the user and can be modified. The next steps are: modifying the code so that it receives BLE data from the Traumschreiber sleep mask, implementing a basic experiment station functionality like storing the data on microSD card and plotting the real-time data, and eventually adding real-time data analysis features (the tensorflow neural networks are in principle usable on Android as well (Abadi, Agarwal, et al., 2016)). For future versions, one could think of using the Android app for forwarding the (encrypted) data over the internet to a server and conducting the data storage and real-time data analyses there, sending back only the results and commands to the smartphone, similar to approaches in telemedicine (Craig & Patterson, 2005).
- Reusable electrodes: During the textile development of the Traumschreiber sleep mask, several ideas how to replace the single use sticky electrodes by electrically conductive fabric or yarn have been tried out, as they have been successfully used for example by the Zeo consumer product (Griessenberger et al., 2013; Shambroom et al., 2012). This included stitching reusable electrodes into the sleep mask, using conductive fabric as electrodes, and replacing the electrode cables by conductive yarn. It became clear, however, that the signal quality of the self-stitched electrodes was not good enough yet. Further research should investigate this idea in more detail, as this could make the system easier to use and more comfortable.
- Safety certificates: Depending on the actual usage, specific safety measurements and certificates might be necessary, for example regarding electromagnetic compliance. Using the Traumschreiber system for medical purposes requires additional safety checks and certificates.
- The look and feel of both the Traumschreiber sleep mask as well as the Traumschreiber experiment station could be improved further.

4.3.1.2 Suggestions for further studies with the Traumschreiber system

On the one hand, studies should be conducted, which evaluate the Traumschreiber further:

- A study, which compares the sleep quality of nights with the Traumschreiber system, with in-laboratory sleep and with undisturbed sleep, all in the same subjects, should be conducted. This way, it could be assessed, how large the effect of the Traumschreiber system is on the sleep of the subjects. Such an extended validation of the Traumschreiber system should be conducted in independent sleep laboratories. Besides comparing the sleep graphoelements and manually scored sleep stages, the comparison could also include an evaluation of the (at that time possibly more advanced) automatic sleep staging capabilities of the system, and include other sleep characteristics like the total sleep time, sleep efficacy, or sleep latency (compare (Popovic et al., 2014)).
- Moreover, a large-scale study with at least 100 subjects, which runs over a longer period of time (at least ten nights per subject), should be conducted. In a pessimistic view, if only half of the recorded nights produce polysomnographic data of good quality, this would result in 500 successfully recorded nights. These could be scored using the quick scoring method of the Traumschreiber system, and then be used as training data for improving the automatic sleep scoring capabilities of the Traumschreiber system – for sleep staging, but also for other pattern detection methods. Moreover, the durability of the material could be evaluated in such a long-term study. Assuming that the subjects can be recruited without any difficulties and 20 Traumschreiber systems are at hand, these 1000 nights could be recorded (in theory) in less than two months, with 3 to 6 months being a more realistic estimate.

On the other hand, the Traumschreiber system makes possible several new experiments. A few of these ideas are listed here in order to demonstrate their variety:

- First, in the field of memory consolidation, complex sleep laboratory studies could be replicated by a subject crowd in the field, building a bridge from the theoretical in-laboratory research into the practice. For example, a study (Ngo, Martinetz, Born, & Mölle, 2013) showed, that a specific type of auditory stimulation during slow wave sleep increases the memory performance (vocabulary) by around 70%. The Traumschreiber system could be used to replicate this finding in the field, by implementing this type of real-time pattern detection and real-time stimulation into it. Moreover, by using the built-in LEDs of the Traumschreiber sleep mask, the same experiment could be conducted with a different modality and the results could be compared. Furthermore, it could be investigated, how easily this technology can be transferred to the masses and to a crowd outside of science.

- Second, the role, which sleep plays for gaining insights into current problems, could be investigated further using the Traumschreiber system. A study (Wagner, Gais, Haider, Verleger, & Born, 2004) suggests, that sleep plays an important role for restructuring new memory representations and facilitates the extraction of explicit knowledge. However, this study could not be replicated so far. Recording a larger amount of subjects with the Traumschreiber system and conducting this type of experiment in an automated way could lead to new insights about insights inspired by sleep. Moreover, the experiment could be extended by investigating a possible effect of auditory or visual cueing, as suggested in (Appel et al., 2016).
- Third, the effect of auditory or visual stimulation on the dream content could be investigated. A number of studies in this direction has already been carried out, e. g. (Dement & Wolpert, 1958). Since the costs of such studies using the Traumschreiber system are very low, extending these experiments and including far more types of acoustic or visual stimulation in far more subjects might lead to new insights about dreaming in general, but also about how dreams can be altered from the waking world, possibly opening new research perspectives for nightmare therapy.
- Fourth, if the Traumschreiber system is used for medical purposes, several medical assessments and therapies could be further developed and conducted by naive subjects or patients in the field. For example, the multiple sleep latency test (MSLT, (Carskadon, 1986)) could be conducted in such a way (even though it would need adjustment to the recording environment), or new depression therapies could be developed by inhibiting sleep or specific sleep stages in a specific way (Dallaspezia & Benedetti, 2015). Moreover, if sleep physicians are provided with many nights of a patient’s sleep in the natural environment, instead of just one or two in-laboratory nights, better diagnoses could become possible.

- Fifth, lucid dreaming experiments could benefit greatly from the Traumschreiber device, since lucid dreams are very hard to record in the sleep laboratory (compare chapter *1.3 Assessment of sleep and dreaming in the sleep laboratory*). Thus, by using the Traumschreiber system, elaborated lucid dreaming techniques such as the communication between the lucid dreamer and the waking world, in which eye movements and acoustic or visual stimuli are used (Appel, 2013), could be practiced by the subject at home for several nights, before recording them in the laboratory.
- Lots of further research ideas can be thought of, e. g. in the field of chronobiology and jet-lag (e. g. applying light stimuli (Geerdink, Walbeek, Beersma, Hommes, & Gordijn, 2016)). More ideas are described in (Braumann, 2016).

4.3.2 Future prospects

Even though the Traumschreiber system is designed for scientific sleep and dream experiments, it might also be used for non-research purposes. One could imagine, that one day many people would have their own personal sleep assistant (Daskalova et al., 2016), who knows the individual sleep characteristics, knows how to stimulate the sleep best in order to increase the sleep quality, and maybe even knows how to enrich the dreams of the user. Devices based on the Traumschreiber system could be used for this.

Due to its very low costs, the Traumschreiber system is an ideal candidate for using it for educational purposes. This could benefit students in disciplines such as electric engineering, neuroscience, medical science or computer science. The great advantage of the Traumschreiber system is, that the students would have a direct connection to the recorded data (their own EEG / ECG / EOG / EMG activity), making the topic to be learned more interesting to them.

Also, using the Traumschreiber system for EEG, ECG or eye tracking studies during wakefulness might be an interesting option. Moreover, the Traumschreiber system could become an inexpensive and easy to use tool also for researchers from other disciplines, who are unfamiliar with the sleep laboratory environment, but who would like to analyze the subjects' sleep as a side note.

As the Traumschreiber system is open source, a community of researchers, developers, and consumer users might grow, and the ideas, creativity and work force of these people could be bundled.

Many more use cases can be thought of. The most important point regarding the future of the Traumschreiber system is, however, that it is actually used. It does not matter, for which purpose: for sleep and dream studies, for the personal fun of single developers and users, for education, or for completely different purposes.

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Appendix

1. “Erklärung über die Eigenständigkeit der erbrachten wissenschaftlichen Leistung”
2. Peer-reviewed articles
    1. Appel, K. (2017). Kurzvorstellung der Studentischen Initiative Sleep & Dream Osnabrueck. *Somnologie*, 21(3), 252-254.
    2. Appel, K., Pipa, G. (2017). Auditory evoked potentials in lucid dreams: a dissertation summary. *International Journal of Dream Research*, 10(1), 98-100.
    3. Appel, K., Pipa, G., & Dresler, M. (2017). Investigating consciousness in the sleep laboratory - an interdisciplinary perspective on lucid dreaming. *Interdisciplinary Science Reviews,* 1-16.
    4. Kern, S., Appel, K., Schredl, M., & Pipa, G. (2017). No effect of alpha-GPC on lucid dream induction or dream content. *Somnologie*, 21(3), 180-186.
    5. Appel, K., Kern, S. (2015). Phänomenologie luzider Träume und Induktionstechniken. Schulz, Geisler, Rodenbeck (Hrsg.) *DGSM Kompendium Schlafmedizin.* Ecomed Verlag, Landsberg, XVIII-3.9.1, 1-5.
3. Examples of media coverage about the Traumschreiber system and other research of the author of this dissertation
    1. Screenshots of the Traumschreiber and other own research on television
    2. Article in “The New Scientist” reporting (among other things) about sleep and dream experiments of the author of this dissertation
    3. Article in the online magazine “Netzpiloten” with the author of this dissertation as domain expert
4. Filter responses of the analog filters in the Traumschreiber sleep mask
5. Technical specifications of the artificial neural networks used in this dissertation
6. Example preforma invoice of cables imported from China
7. CV of the author of this dissertation

Erklärung über die Eigenständigkeit der erbrachten wissenschaftlichen Leistung

Ich erkläre hiermit, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet.

Bei der Auswahl und Auswertung folgenden Materials haben mir die nachstehend aufgeführten Personen in der jeweils beschriebenen Weise entgeltlich / unentgeltlich geholfen.

1. Herr Leugering: Maßgebliche elektrotechnische Entwicklung der PCB, anfangs gemeinsam mit Prof. Dr. Pipa, Programmierung des Bluetoothchips und des Microcontrollers sowie eines rudimentären Demo-Skriptes, um die Bluetoothverbindung herzustellen, technischer Teil der Bestellung der PCB.

2. Studierende, die ihre Bachelorarbeit im Themenkomplex Traumschreiber-System geschrieben haben und deren Ergebnisse in dieser Dissertation verwendet wurden (Bachelorarbeiten im Online-Appendix). Alle wurden von mir betreut, die Aufgabenteilung war wie folgt:

- Erste Evaluierungsstudie
    - Kristoffer Appel: Studienidee, Ethikantrag inkl. Studiendesign, Herstellung der Schlafmaske und Programmierung des Experimentes, Wiederholung der Datenanalyse, Einarbeitung und Betreuung des Studenten,
    - Frederik Nienhaus: Versuchspersonenrekrutierung, operative Durchführung der Studie (d. h. Datensammlung im Schlaflabor), Datenanalyse (Ergebnisse nicht verwendet in dieser Dissertation).
- Zweite Evaluierungsstudie
    - Kristoffer Appel: Studienidee, Ethikantrag inkl. Studiendesign, Herstellung der Schlafmaske und Programmierung des Experimentes, Einarbeitung und Betreuung der Studentin,
    - Laura Mandt: Versuchspersonenrekrutierung, Erstellung des “Fragebogen zum Gebrauch des Traumschreibers” in Rücksprache mit mir, Aufnahme des ersten Instruktionsvideos, operative Durchführung der Studie (d. h. Aushändigen und Einsammeln des Traumschreiber-Systems, statistische Datenanalyse in Rücksprache mit mir).
- Explorative Android-App-Programmierung
    - Kristoffer Appel: Betreuung des Studenten,
    - Martin Jäkel: Programmierung der App.
- Literaturrecherche zur Stimulation des Schlafes
    - Kristoffer Appel: Studienidee, Betreuung der Studierenden,
    - Sophia Braumann: Literaturrecherche, Einbringen eigener Experimentideen.

Weitere Personen waren an der inhaltlichen materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder andere Personen) in Anspruch genommen. Niemand hat von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

(Ort, Datum) (Unterschrift)

Allgemeine Informationen

Termin & Ort
2.–4. März 2018, Potsdam

Tagungshomepage

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Veranstalter
Arbeitsgruppe Pädiatrie der Deutschen Gesellschaft für Schlafforschung und Schlafmedizin (DGSM) e. V.

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Chefarzt und Ärztlicher Direktor
Schwerpunktbezeichnung Neonatologie
Zusatzweiterbildungen Pädiatrische Intensivmedizin, Schlafmedizin

Tagungsthema
Zeit – Alter – Schlaf

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Sie sind herzlich eingeladen, die Tagung mit wissenschaftlichen und klinischen Beiträgen zur Kinderschlafmedizin mitzugestalten. Senden Sie Ihren Abstract bis **1. November 2017** an:
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Kurzvorstellung der Studentischen Initiative Sleep & Dream Osnabrück

Kristoffer Appel, Studentische Initiative Sleep & Dream Osnabrück, Universität Osnabrück

Abstract

Die studentische Initiative Sleep & Dream Osnabrück ist eine rein studentische Forschungsgruppe, die ein kleines jährliches Budget des AStA erhält und sich auf vielfältige Weise mit der Schlaf- und Traumforschung beschäftigt – unabhängig von Professoren und PostDocs, externen Drittmittelgebern und Industrie. Im Jahr 2012 als Selbstlern-Gruppe für Themen im Bereich des Schlafes und des Träumens gestartet, haben die Studierenden mittlerweile ein eigenes professionell ausgestattetes Schlaflabor, führen selbstständig eigene wissenschaftliche Experimente durch, kooperieren dabei mit Schlafforschern im In- und Ausland, organisieren eigene Workshops und Events, und fahren regelmäßig auf Exkursionen, z. B. letztes Jahr zu zwei finnischen Schlafforschungsgruppen oder zu den DGSM-Nachwuchsworkshops. In diesem Artikel werde ich als Gründer der Initiative die letzten fünf Jahre kurz Revue passieren lassen – auch mit der Absicht, so möglicherweise ähnliche Entwicklungen in anderen Teilen Deutschlands anstoßen zu können.

Die Anfänge

Etwa 10 Studierende folgten Ende 2012 der Email-Einladung des Autors, eine studentische Interessengruppe im Themenbereich Schlaf und Träumen zu gründen. Ein Grund für die Etablierung einer solchen Gruppe war, dass dieses Gebiet in der unviersitären Lehre nur am Rande behandelt wurde. Ein weiterer Grund war der Wunsch der Studierenden, sich mit Gleichgesinnten über eigene persönliche Schlaf-/Traumerfahrungen auszutauschen und gemeinsam luzides Träumen, polyphasisches Schlafen o. Ä. auszuprobieren. Schnell wurden erste regelmäßige Treffen einberaumt, z. B. gemeinsame Frühstücke, bei denen sich die Studierenden u. a. gegenseitig die Grundlagen des Schlafs (Schlafstadien etc.) beibrachten.

Obwohl mittlerweile fast alle ursprünglichen Gründungsmitglieder die studentische Initiative wegen Studienabschluss und Wohnortwechsel verlassen haben, hat sich doch ein regelmäßiger Nachwuchsstrom aus jüngeren Semestern gebildet, sodass die Initiative bis heute konstant etwa 10 bis 20 regelmäßige Mitglieder von Bachelor- bis PhD-Level zählt, sowie mehrere Dutzend weitere Mitglieder, die immer mal wieder bei den Treffen dabei sind. Die meisten Mitglieder studieren Cognitive Science, es sind aber auch einige Studierende anderer Fächer dabei.

Eigenes Schlaflabor

Nach langer Suche bedingt durch die Raumknappheit an der Universität wurden der studentischen Initiative im Jahr 2015 zwei eigene Räume zugewiesen. Schnell war klar, dass darin ein eigenes Schlaflabor eingerichtet werden sollte. Doch woher sollte das Equipment kommen? Der AStA der Universität Osnabrück fördert zwar studentische Gruppen auf Antrag finanziell. Doch die Förderung der Sleep & Dream Initiative lag für das Haushaltsjahr 2015 bei nur 400 Euro (mittlerweile bei etwa 1800 Euro) – eine professionelle Schlaflaborausstattung lässt sich davon nicht erwerben. Eine erste kleine experimentelle Grundausstattung konnte vom Institut für Kognitionswissenschaft geliehen werden. Eine Email an den DGSM-Vorstand führte schließlich zu einer großen Sachspende: Dank der Vermittlung von Prof. Young aus Münster trafen ein paar Monate später drei große Kisten bei der Studentengruppe ein. Darin enthalten war eine komplette professionelle Schlaflaborausrüstung, teilweise gebraucht, die ein namhafter Medizingerätehersteller an die Studierenden spendete. Selbst Verbrauchsmaterialien wie Einwegelektroden und Grass-Paste waren dabei.

Nachdem Räumlichkeiten und Equipment bereit standen, tauchten neue Fragen auf: Wie und wo werden die Elektroden korrekt befestigt, um EEG, EKG, EMG und EOG aufzunehmen? Wie funktioniert die Software, welche Parameter müssen wie eingestellt werden? Wie werden all die anderen Geräte und Sensoren, etwa Pulsoximeter, Schnarchmikrofon, Lagesensor, Thermistor, Brustgurte, Infrarotkamera, CPAP usw., bedient? Welches Kabel gehört zu welchem Gerät, wie werden die einzelnen Bestandteile verbunden und angeschlossen?

Da es an der Universität keinen Somnologen oder Wissenschaftler mit Hauptfokus auf Schlafforschung gab, fanden die Studierenden die Antworten hierauf durch Versuch und Irrtum heraus. Das bedeutete, zunächst einmal alles auszupacken und zu sichten sowie aus den Kabelbeschriftungen und Steckertypen zu schließen, welche Systeme wie verbunden werden müssen – ein Nutzerhandbuch konnte auf die Schnelle leider weder offline noch online gefunden werden. Nach dem Start des Systems und dem vorsichtigen Umherklicken in der vorinstallierten Software konnten die Studierenden dann ohne nennenswerte Änderung der voreingestellten Software-Parameter bereits erste Sensordaten wie Herzschlag oder Atmung (Brustgurte) live betrachten. Glücklicherweise hatten einige von ihnen zuvor schon praktische Erfahrungen als Assistenten in einem lokalen Schlaflabor gesammelt, und manche auch schon Praktika in wissenschaftlichen Schlaflaboren z. B. bei Prof. Schredl am Zentralinstitut für Seelische Gesundheit in Mannheim und Prof. Steiger am Max-Planck-Institut für Psychiatrie in München absolviert. Basiswissen über die korrekte Elektrodenplatzierung oder elementare Softwarenutzung war also bei einigen schon vorhanden und konnte direkt weitergegeben werden. Nach und nach wurden so die meisten Geräte in Betrieb genommen und noch in der folgenden Nacht getestet.

Am nächsten Morgen war die Freude groß, als typische Graphoelemente des Schlaf-EEGs wie Slow Waves, Schlafspindeln oder K-Komplexe in den Aufzeichnungen der Nacht identifiziert werden konnten, und auch die übrigen Systeme brauchbare Daten erzeugt hatten. Der Techniker des Herstellers, der einige Tage später anrief und seine Hilfe beim Aufbau anbot, musste also gar nicht mehr vorbei kommen.

Eigene wissenschaftliche Experimente

Die erste eigene Schlaflaborstudie konnte also beginnen. Da das Luzide Träumen (synonym: Klarträumen) eines der Hauptinteressen der Studierenden war, beschlossen sie, als erstes eine Klartraumstudie durchzuführen, bzw. eine solche Studie zu replizieren und um eigene Ideen zu ergänzen. Dabei durchliefen sie das „volle Programm“: Von der Ideenfindung und dem Studiendesign, bei dem Prof. Erlacher aus Bern (Schweiz) dankenswerterweise beratend zur Seite stand, über den Ethikantrag bis zur Versuchspersonenrekrutierung, von der Experiment-Organisation und Schichtplanung bis zur tatsächlichen Durchführung, von der Datenanalyse bis zur Publikation der Ergebnisse auf Konferenzen und in einem wissenschaftlichen Journal (in prep.). Dabei führten die Studierenden polysomnografische Messungen bei 20 Versuchspersonen für jeweils ein oder zwei Nächte durch

▲ Initiativenmitglieder im Schlafraum des studentischen Schlaflabores

– wohlgemerkt alles in ihrer Freizeit. Mittels eines komplexen Versuchsprotokolls, das u. a. eine nächtliche Echtzeit-Klassifizierung der Schlafstadien erforderte, wollten die Nachwuchsexperimentatoren Luzide Träume bei klartraum-ungeübten Versuchspersonen auslösen, was auch tatsächlich mit einer ähnlich hohen Erfolgsrate wie im Originalexperiment gelang.

Mittlerweile gibt es eine zweistellige Anzahl an kleinen und mittelgroßen wissenschaftlichen Studien und Abschlussarbeiten, die von den Studierenden zum Teil im eigenen Schlaflabor, zum Teil gemeinsam mit Forschern anderer Institute durchgeführt wurden – z. B. in Kooperation mit den Gruppen von Prof. Danker-Hopfe vom Schlafkompetenzzentrum der Charité in Berlin, von Prof. Young vom Uniklinikum Münster, von Prof. Schredl vom Zentralinstitut für Seelische Gesundheit in Mannheim, oder von Prof. Dresler vom Donders Institute in Nijmegen (Niederlande). Beispielhaft seien hier der Beitrag „Phänomenologie luzider Träume und Induktionstechniken“ im DGSM-Kompendium Schlafmedizin, der von zwei Initiativen-Mitgliedern geschrieben wurde, oder der Artikel „No effect of α-GPC on lucid dream induction or dream content“ in dieser Somnologie-Ausgabe genannt. Weitere Kooperationen, Praktika und Abschlussarbeiten sind auch für die Zukunft geplant – die Arbeitsgruppe „Klinisch-wissenschaftlicher Nachwuchs“ der DGSM kann hierfür sicher eine gute Grundlage bieten.

Exkursionen und andere Events

Natürlich geht es den Studierenden nicht nur darum, viel über Schlaf und Träume zu lernen und eigene Experimente im eigenen Schlaflabor durchzuführen, sondern zuallererst auch einfach um den Spaß in der Gruppe. Deshalb fanden neben zahlreichen weiteren Aktionen u. a. schon mehrere Filmabende statt (in denen natürlich Schlaf/Traumbezogene Filme wie z. B. Inception gezeigt wurden), die Studierenden organisierten einen Klartraumworkshop mit Übernachtung im Schlaflabor, und kürzlich wurde ein universitätsweiter Traumwettbewerb ausgerufen mit Prämierung der besten eingereichten Träume in einem feierlichen Rahmen.

Außerdem fährt ein Teil der Gruppe hin und wieder auf Exkursion: zuletzt mit acht Studierenden im Nachtzug zur DGSM-Jahrestagung nach Dresden, und zuvor bereits zu anderen, internationalen Konferenzen. Am DGSM-Nachwuchsworkshop in Hofgeismar nahmen letztes Jahr einige Teilnehmer aus Osnabrück teil, und 2015 gab es eine eintägige Exkursion zum Schlafkompetenzzentrum der Charité in Berlin. Das Highlight war bislang wohl die einwöchige Exkursion von zehn Osnabrücker Studierenden zu den Arbeitsgruppen von Prof. Stenkamp aus Helsinki und Prof. Revonsuo aus Turku (beide Finnland) und der anschließende Kurzbesuch der Jahrestagung der finnischen Schlafforschungsgesellschaft. Für diesen Sommer ist bereits die nächste Exkursion geplant, dieses Mal nach Südwestdeutschland.

Im Namen der Studentischen Initiative Sleep & Dream Osnabrück möchte ich mich bei dieser Gelegenheit gerne bei allen Unterstützern sehr herzlich bedanken! Und wer weiß, vielleicht entstehen ja bald auch an anderen Universitäten ähnliche studentische Gruppen?

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Auditory evoked potentials in lucid dreams: A dissertation summary

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Summary. Are lucidly dreaming subjects able to discriminate between two different auditory stimuli using an oddball paradigm? How does the evoked potential (P300) in the EEG during this task look during lucidity, as compared to wakefulness and to non-lucid REM sleep? These are the central questions in Dr. Johannes Oliver Strelen's dissertation, which is summarized in English language in this article. Six experienced lucid dreamers underwent polysomnographic recordings in the sleep laboratory for a total of 21 nights. Their task was to move their eyes from left to right, whenever they heard the target stimulus of an oddball paradigm, which was presented throughout the whole night. Three of the six subjects experienced a verified lucid dream and conducted the given task within it. The performance (correct responses) in the oddball task during lucid dreaming was worse than during wakefulness, but significantly better than what could be explained by chance. Thus, Strelen showed,that it is possible to react to simple auditory stimuli with a pre-defined eye movement, while dreaming lucidly, without waking up in between. Moreover, for two of his subjects, Strelen analyzed the auditory evoked potential (P300) of the EEG signal during the oddball paradigm. In one case, he found a clear, in the other case a unclear P300 peak. The morphology of the P300 EEG pattern for the correctly answered target stimuli during lucid dreaming was similar to the P300 EEG pattern during wakefulness, suggesting that information processing during lucid dreams is closer to wakefulness than to non-lucid REM sleep.

Keywords: Lucid dreaming, auditory evoked potentials, P300, dissertation summary

1. Introduction

This review summarizes the most important results from the dissertation of Dr. Johannes Oliver Strelen, which was handed in at the Johannes Gutenberg University, Mainz, Germany, in 2006 under the title “Akustisch evozierte Potenziale bei luziden Träumen - eine Untersuchung über diskriminierendes Wahrnehmen und selektives Beantworten von Tönen in REM-Schlaf” (Auditory evoked potentials in lucid dreams – an investigation of discriminative perception and selective answering of tones during REM sleep). The goal of this review is to make the study's main findings available to the scientific community by translating them into English, as they might be of great interest to other lucid dream researchers, and possibly to researchers from other fields, as well.

2. Summary of Strelen's dissertation

2.1. Motivation of the study and study goals

Even though evoked potentials can deliver information about the consciousness state, they have not yet been used for lucidly dreaming subjects – other than, for example, for the sleep stage N1, for which it was demonstrated that they describe the subjective and objective state of consciousness better than the spontaneous EEG (Campbell and Colrain, 2002).

Investigating evoked potentials during lucid dreams could thus lead to new insights about the phenomenon of lucid dreams. Besides this, Strelen sees it as an exciting challenge to let experienced lucid dreamers conduct the paradox task of reacting to waking world stimuli during sleep with eye signals.

Thus, the aim of Strelen's study was to present auditory stimuli using an oddball paradigm during lucid dreams and to analyze both the performance of the subjects during the oddball task, as well as the evoked potentials in the EEG signal.

2.2. Methods

2.2.1 *Participants*

Six healthy volunteers (three male, three female, aged 21-50) were recorded at the Stanford Psychophysiology Laboratory in the year 2001. The subjects were experienced lucid dreamers (based on self-assessment), and underwent polysomnographic recordings for 6, 7, 5, 1, 1, and 1 nights. No adaptation night was recorded. The subjects went to bed at their preferred time and slept ad libitum. Written informed consent was obtained for the study.

2.2.2 *Materials*

Stimuli were presented using in-ear speakers in the left ear throughout the whole night at 30 dB above the individual perceptional threshold. The stimuli consisted of 70 ms long sine wave tones in random order at either 1000 Hz (80% probability, non-target stimuli) or 2000 Hz (20 % probability, target stimuli), according to the oddball paradigm.

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Table 1. Definitions

Definitions
- lucid dream: a dream in which the dreamer knows that he or she is dreaming
- evoked potential: event-related brain activity pattern following a (e. g. auditory) stimulus, measured using EEG
- oddball paradigm: a series of stimuli of two types, one with high probability (non-target items) and one with low probability (target items)
- P300: evoked potential measured around 300 ms after stimulus onset, which is thought to reflect processes involved in stimulus evaluation, e. g. in an oddball paradigm (Sutton et al., 1965)

The single stimuli were each followed by 2.0 ± 0.1 seconds of silence.

A Neuroscan SynAmps system was used for recording physiological (EOG, EMG, ECG) and EEG data (28 channels, using the 10-20 system). Impedances were kept below 5 kOhm. The data were sampled at 1000 Hz. Baseline correction was applied to the EEG data, as well as filtering (0.3 – 30 Hz) and artifact rejection.

2.2.3 The task of the subjects

The task, which the subjects were supposed to conduct in case they experienced a lucid dream during the nights in the sleep laboratory consisted of:

- moving the eyes left-right-left-right (LRLR) when reaching lucidity,
- listening to the auditory stimuli and moving the eyes another time LRLR when incorporating them into the lucid dream,
- moving the eyes LR immediately after each of the target (higher pitched) auditory stimuli, but not after the non-target (lower pitched) stimuli,
- moving the eyes LRLRLRLR directly after waking up,
- writing down a dream report after each waking up from a lucid dream, as well as filling out a questionnaire about the tones.

The subjects were asked to practice their task for at least 10 minutes a day during wakefulness during the days before the sleep laboratory nights. The task was also conducted at the sleep laboratory during wakefulness for 10 minutes (wakefulness condition).

2.2.4 Data analyses

Sleep stages were scored according to the criteria of Rechtschaffen and Kales (1968).

Only those lucid dreams were used for further analysis, which took place during REM sleep, were marked clearly by a LRLR eye signal in the beginning of the lucid dream, and had a written dream report indicating subjective lucidity.

For the evaluation of the oddball task, the LR eye movements were identified without knowing the timing or the category of the tones. For each LR eye movement, the tone was assigned, which was played during the 2000 ms before the eye movement. The oddball task was counted, if the subject tried to conduct the task (even if he or she did not succeed in hearing the tones), and if there was at least one target tone during the try.

The auditory evoked potentials were calculated for four conditions: wakefulness (based on the training periods before going to sleep and after waking up in the morning), non-lucid REM sleep, lucid REM sleep with signals to the oddball tones, and lucid REM sleep without signals to the oddball tones (if the task was not conducted during lucidity). If sufficient data was available, the EEG data was averaged for each condition, both for the target and the non-target tones, and the P300 EEG pattern was identified. Furthermore, the latency and amplitude were determined.

2.3. Results

2.3.1 General lucid dreaming results

Five of the six subjects subjectively experienced a lucid dream. In total, there were 23 subjective lucid dreams. Eighteen of these lucid dreams could be verified in four subjects, i.e. they took place during REM sleep and were clearly marked with a LRLR eye signal.

2.3.2 Oddball task

The oddball task was correctly conducted in 10 of the 18 verified lucid dreams, by three subjects. Reasons for not correctly conducting the task were lack of time (too short lucidity phase), forgetting the task or remembering it in a false way, giving unclear eye signals, or being distracted by the dream content (e. g. distractions by other dream characters, or the dream was too loud, i. e. louder than the stimuli).

The 10 lucid dreams, in which the subjects tried to conduct the oddball task, were on average 143 seconds long and contained on average 54 non-target tones and 14 target tones. In eight lucid dreams, the subjects managed to respond to the target tones with eye signals. The hit rates (correctly responded target tones divided by the total number of target tones) lay between 27% and 100% for the individual lucid dreams. In five of the 10 lucid dreams, the subjects responded also to the non-target tones (hit rates between 1% and 8%). Viewing the average performance over all lucid dreams for each subject separately, the hit rates for the target tones were 71%, 35%, 27%, and for the non-target tones 0.5%, 3%, 3%. The task was never conducted by the subjects subconsciously during non-lucid REM sleep. During wakefulness, the oddball task was conducted by all subjects nearly perfectly (hit rates > 98 % for the target stimuli and < 0.5 % for the non-target stimuli).

The subjects were further asked whether they heard the tones only after concentrating on the task or already before. In seven of the 10 lucid dreams, the subjects noticed the tones only when concentrating on them, in two lucid dreams already before, and in one lucid dream the memory was unclear.

2.3.3 Evoked potentials

For calculating the evoked potentials, only two subjects supplied enough data of sufficient quality (in the one case with 42 target tone EEG epochs, and in the other case with 56 epochs).

During wakefulness, as to be expected, a clear P300 signal could be detected in both subjects. The latencies were 319 ± 28 ms and 339 ± 39 ms. During non-lucid REM sleep, only less clear P300 patterns were visible (especially in one of the two subjects), with latencies of 350 ± 32 ms and

391 ± 22 ms. During lucid REM sleep, the P300 EEG pattern of the correctly signaled target stimuli showed a similar morphology as the ones during wakefulness, and were clearly visible for one of the two subjects, and less clear for the second subject (it must be noted that this subject also showed a less clear P300 signal during wakefulness and REM sleep). During lucid REM sleep, the latencies were 323 ms and 297 ms (as only a grand average was computed for this condition, no standard deviation is reported). The amplitudes of the lucid REM sleep P300 patterns were in both subjects much smaller than during wakefulness, comparable to the P300 during non-lucid REM sleep. For one subject, enough data was available to analyze the lucid dreaming EEG signal of those target stimuli which were missed and not reacted to via eye movement during the lucid dream. For these stimuli, no P300 peak could be found.

2.4. Discussion

In this study, Strelen showed that it is possible for a lucidly dreaming subject to consciously discriminate between two auditory stimuli of an oddball paradigm, which were presented in a random order during sleep. For this, six lucid dreaming experienced subjects underwent polysomnographic recordings in the sleep laboratory, and were instructed to react to the target stimulus (a short 2000 Hz sine wave tone) with a simple pre-defined eye movement to the left and right. Three of the six subjects were able to conduct the given task during their lucid dreams. All of them were able to send eye signals to the target stimuli with worse performance than during wakefulness, but significantly better performance than what would be expected by chance.

The analysis of the P300 EEG patterns suggests that the cognitive information processing capabilities of lucid dreamers tend to be more similar to awake subjects than to non-lucid REM sleep subjects. For two subjects, sufficient data was available to compare the P300 evoked potentials for the lucid dreaming state, non-lucid REM sleep and wakefulness. The morphology of the P300 EEG pattern for the correctly answered target stimuli during lucid dreaming was similar to the P300 EEG pattern during wakefulness. A clear P300 peak was visible in one of the two subjects, in the other one, a less clear P300 peak was visible. The latency of the clear P300 EEG pattern was similar to the one during wakefulness, for the other case, it was slightly shorter. The amplitudes of the P300 peaks were in both cases much smaller than during wakefulness, and comparable to the ones during non-lucid REM sleep of the same subjects. For one subject, enough data was available to analyze the lucid dreaming EEG signal of those target stimuli which were missed and not reacted to via eye movements during the lucid dream. For these stimuli, no P300 peak could be found.

3. Remarks on Strelen's study

Strelen's experiment extends the knowledge of lucid dreaming regarding the interaction with the waking world, as well as the knowledge of the underlying neuroscientific processes of this phenomenon. As Strelen points out himself, his study builds on previous research: It was already known that external stimuli are sometimes incorporated into dreams (Schredl, 1999); that sleeping subjects can react subconsciously to external stimuli (Harsh and Badia, 1990); that a similar discriminative information processing takes place during REM sleep as during wakefulness, as suggested by the analysis of auditory evoked potentials (Niiyama et al., 1994, Bastuji et al., 1995); and that lucid dreamers are able to conduct given tasks within their lucid dreams (e. g. Hearne, 1978, LaBerge, 1980). In a case study, a lucidly dreaming subject was able to react to external stimuli (electric shocks) with muscle contractions, however, by initiating the stimuli himself (Fenwick et al., 1984).

As is unfortunately the case for many lucid dreaming studies, Strelen's experiment also suffers from a very low subject count. Only three subjects had verified lucid dreams during the experiment, and only two subjects delivered sufficient data for an evoked potential analysis of the EEG data. As a result, this experiment can only be regarded as a case study. Thus, the results must be treated cautiously, as Strelen himself also suggests in his dissertation.

Since 2006, when this dissertation was handed in at the Johannes Gutenberg University, Mainz, Germany, other lucid dreaming research has extended Strelen's experiments. For example, in an experiment by the author of this summary, it could be shown that even transferring a meaningful message (a random math problem) using Morse code into the dream, and answering to it using Morse-coded eye movements, is possible (Appel, 2013).

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Investigating consciousness in the sleep laboratory – an interdisciplinary perspective on lucid dreaming

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ABSTRACT

During dreaming, we experience a wake-like hallucinatory reality, however with restricted reflective abilities: in the face of a bizarre dream environment, we do not realize that we are actually dreaming. In contrast, during the rare phenomenon of lucid dreaming, the dreamer gains insight into the current state of mind while staying asleep. This metacognitive insight often enables the dreamer to control own dream actions and the course of the dream narrative. Lucid dreaming allows for radically new methodological and theoretical approaches and has led to new insights in diverse scientific disciplines beyond classical sleep and dream research, including neuroscience, psychotherapy, philosophy, art, and sports sciences. Here, we review past research and the current knowledge on lucid dreaming. We present insights into the scientific work in a sleep laboratory and describe how lucid dreams can be induced through methodologies from diverse academic backgrounds including psychology, electrical engineering and pharmacology.

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Sleep; EEG; lucid dreaming; cognition; metacognition; consciousness

1. Dreaming – a brief introduction

Our conscious experience during sleep markedly differs from that of wakefulness: We hallucinate, engage in loose associations and confabulations, we are convinced that bizarre situations are real – or at least are not uncomfortable with their bizarreness –, we are disoriented regarding time, place and persons, we lack concentration, insight and willpower, we experience strong and varying emotions, and afterwards we quickly forget most of these highly unusual experiences (Hobson, Stickgold, and Pace-Schott 1998).

On the physiological level, each night we cycle through different *sleep stages*. Distinct features such as rapid eye movements (REMs), specific brain activation patterns such as sleep spindles and k-complexes, or muscle atonia allow the sleep researcher to classify periods of sleep into these stages. The two main categories REM sleep and Non-REM (NREM) sleep are labelled according to sleep periods with and without REMs, and can further be subdivided.

For many years, dreaming was considered to be phenomenon occurring during REM sleep only. Shortly after the discovery of different sleep stages in the 1950s (Aserinsky

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and Kleitman 1953), sleep laboratory experiments showed that 74–80% of REM sleep awakenings resulted in vivid dream recall, compared to only 7–9% of NREM sleep awakenings (Dement and Kleitman 1957a, 1957b). A strong hint for the connection of REM sleep and dreaming was found in the 1960s, when experiments with cats revealed brain stem regions that control REM sleep atonia, i.e. the nearly complete paralysis of the skeletal muscles during this sleep stage, which is thought to be a protective mechanism preventing the dreamer from acting out dream movements. Cats with brain stem lesions showed a surprising behaviour when falling into REM sleep, apparently hunting non-existing mice or fighting non-existing enemies while being nearly unaffected by external stimuli (Jouvet and Delorme 1965). Naturally, this behaviour was interpreted as REM sleeping cats acting out their dreams. In the 1980s, a similar phenomenon was observed in humans as well: Patients suffering from the so-called *REM sleep behaviour disorder* (RBD) showed excessive movements during REM sleep, closely related to their dream contents (Schenck et al. 1986). This parasomnia bears apparent risks, as RBD patients acting out their dream have been reported in several cases to try diving from the bed into furniture or walls, choking or headlocking their bed partner or caregiver, or jumping out of a window (Schenck et al. 2009).

Already in the 1960s and 1970s, it became increasingly clear that dreaming is not a REM sleep exclusive phenomenon, but occurs in other sleep stages as well. The way how subjects are asked about their mental sleep experiences played an important role in this regard: Changing the question from 'tell me if you had a dream' to 'tell me anything that was going through your mind just before you woke up' resulted in much more frequent reports (up to 74%) of mental activity during NREM sleep (Foulkes 1962; Rechtschaffen 1973). However, NREM dreams are – especially in the first half of the night, when deep sleep is prevalent –, more thought-like, shorter, less visual, less motorically animated, less emotional and less vivid (Fosse, Stickgold, and Hobson 2001).

Even though the existence of NREM dreams is largely undisputed today, REM sleep dreams can be particularly well explained by their neurobiological basis. While some modern neurobiological dream theories support the traditional Freudian view of dreams as being the royal road to the unconscious, revealing unconscious desires related to egoistic and often infantile sexual impulses (Freud [1900] 1965; Solms 2000, 2004), other theories strictly doubt this. The highly influential activation-synthesis model (Hobson and McCarley 1977) and its revised form, the activation-input-modulation model (Hobson, Pace-Schott, and Stickgold 2000), consider dreaming not as a goal-directed messenger from the unconscious, but rather as the result of basic neurobiological activations devoid of deeper meaning: during REM sleep, the cerebral cortex is chaotically stimulated by brain stem regions via so-called Ponto Geniculate Occipital waves, which randomly activate cortically stored perceptions, memories, and motor sequences. The cerebral cortex as a self-organizing system then tries to make sense out of these random activations of cognitive elements, and synthesizes them into a relatively coherent narrative in the best possible way. Due to the chaotic input, the result is a surrealistic storyline full of bizarre elements and transitions.

Since the 1990s, neuroimaging techniques enabled new insights into the neurobiology of dreams and the conscious experiences therein (Nir and Tononi 2010; Dresler et al. 2014). For example, it was found, that visual association cortices and limbic regions including the amygdala are strongly activated during REM sleep, nicely explaining the visual hallucinations and the strong emotions during dreaming. In contrast, cognitive deficits experienced in typical dreams such as impaired reflective thought and logical reasoning can be mapped to deactivations of the dorsolateral prefrontal and frontopolar cortices, which are involved in these functions during wakefulness (Hobson and Pace-Schott 2002).

2. Lucid dreaming

A special kind of dreaming differs from the impaired reflective capacity that characterizes normal dreams: During the so-called *lucid dreaming*, the dreamer realizes that he or she is dreaming while staying asleep (Van Eeden 1913). More sophisticated definitions of lucid dreaming demand that further criteria are fulfilled, such as full access to intellectual capabilities including waking life memories or the ability to exert control over the dream plot (Barrett 1992; Metzinger 2003; Windt and Metzinger 2007). Different questionnaires have been developed to assess such subtle degrees of dream lucidity (e.g. Kahan and Sullivan 2012; Voss et al. 2013). Lucid dreams thus frequently provide intentional influence over an internal virtual reality (Dresler et al. 2014), enabling the skilled lucid dreamer to freely pursue arbitrary actions in arbitrary environments with arbitrary people in arbitrary times. Accordingly, lucid dreams are used for a variety of aims. A survey among 301 lucid dreamers revealed that the most frequent application of lucid dreaming is just *having fun*: More than 80% of the lucid dreamers reported to have used their lucid dreams at least once for purposes such as flying, having sex, or other hedonistic activities: 'One of the nicest things was that lemon cake which I enlarged to the size of a house. The best thing was that it really tasted like lemon cake!' (Schädlich and Erlacher 2012). Besides *having fun*, lucid dreamers reported to use their lucid dreams for *changing a bad dream or nightmare into a pleasant one* (64%), *solving problems* (30%), *getting creative ideas or insights* (28%) and *practicing skills* (21%).

Generally, lucid dreaming is a rare phenomenon: Only about 23% of individuals experience them once or more per month, and only about every second person can remember at least one lucid dream at all from his or her own experience (Saunders et al. 2016). For comparison, non-lucid dreams are recalled about once a week (Schredl 2008). Lucid dreams are common amongst children and young adolescents, but seem to become less frequent after puberty, which has been associated with the maturation of prefrontal brain regions (Voss et al. 2012). There are no significant differences between sexes regarding the lucid dreaming frequency (Watson 2001). However, the general dream recall ability is correlated with lucid dream frequency (Schredl and Erlacher 2004), as well as with the occurrence of nightmares (Spadafora and Hunt 1990). Moreover, regular practice of meditation was also found to promote lucid dreaming (Gackenbach, Cranson, and Alexander 1986; Hunt 1991). Lastly, greater lucidity in dreams or more frequent lucid dreaming is linked to personality traits such as a higher internal locus of control, but not higher creativity (Blagrove and Tucker 1994), openness to experience (Schredl and Erlacher 2004), to well-being and vividness of visual imagery (Wolpin et al. 1992), to need for cognition (Blagrove and Hartnell 2000), to field-independence (Gackenbach et al. 1985), and to dissociation, daydreaming, sleep paralysis, and multi-sensory imagery (Denis and Poerio 2017).

From a physiological perspective, lucid dreaming has been associated with a higher activation of the autonomic nervous system – e. g. breathing frequency, heart rate, and skin conductance – in contrast to non-lucid REM dreams (LaBerge, Levitan, and Dement 1986). Brain activity of lucid REM sleep as measured by electroencephalography (EEG) appears to differ from non-lucid REM sleep in the alpha (Tyson, Ogilvie, and Hunt 1984), beta (Holzinger, LaBerge, and Levitan 2006), and gamma bands (Voss et al. 2009). In particular the latter finding suggests a plausible neurophysiological explanation for the phenomenal characteristics of lucid dreams: The EEG of lucid REM sleep shows similarities to the EEG of the waking brain in the 40 Hz gamma band over the dorsolateral prefrontal cortex (DLPFC), which is typically deactivated during normal REM sleep. This type of brain activity can also be observed in the waking brain during tasks that require higher cognitive functions and conscious awareness (Uhlhaas et al. 2009). Increased dorsolateral prefrontal activations during lucid REM sleep have been confirmed by a combination of sleep EEG measurements and functional magnetic resonance imaging (fMRI, Dresler et al. 2012). In addition to the higher activation of the DLPFC, the fMRI recordings also revealed a higher activation of the so-called precuneus during lucid REM sleep. This region in the medial parietal cortex has been associated with self-directed cognition during wakefulness (Cavanna and Trimble 2006), which appears plausible given the definition of lucid dreaming as a state characterized by conscious reflection on one's current state of mind. Further insights into the neurobiological correlates of lucid dreaming might be gathered by network analyses of brain activity, as Spoormaker et al. suggest (2010a, 2010b).

Given the elusive character of dreams in general and the rarity of lucid dreams in particular, how can we be sure that lucid dreaming is a real phenomenon, and not based e.g. on false memories of entirely normal dream experiences? In the following, we will answer this question by describing the procedures in a typical night of lucid dreaming research in the sleep laboratory.

3. A night in the sleep laboratory

Lucid dreams are difficult to study due to their rarity – sleep researchers can hardly record weeks of sleep just to catch a single lucid dream. Consequently, in most lucid dreaming sleep laboratory studies participants are selected based on their lucid dream frequency, thereby increasing the chance to record a lucid dream in a given night. Subjects with frequent lucid dreams, which in addition have to be long enough to conduct scientific experiments within them, are hard to find. It is thus not uncommon to invite participants from the whole country or even from abroad for a lucid dreaming study, requiring effort for advertisement, recruitment, payment, and travelling.

Preparation and performance of actual lucid dreaming experiments in the sleep laboratory are complex as well – besides the usual extensive procedures necessary to conduct sleep laboratory studies, including as a minimum polysomnographic measurements of the brain activity by EEG, of eye movements by electrooculography, and of muscle activity by electromyography. For these measurements, electrodes are fixed on the scalp and in the face of the subject. The polysomnographic recording is necessary to determine whether a subject is awake or asleep, and also in which of the different sleep stages the subject is in, with standardized scoring rules being applied for sleep stage classification. Further, the research question in lucid dreaming projects often requires more detailed measurements of brain activity than is measured in normal sleep experiment settings, e.g. for elucidating specific neurobiological correlates of a certain lucid dreaming task. As a result, preparation for the experiment can take several hours before the subject is sent to bed. In lucid dreaming studies with high-density EEG for topographical analyses or source localization of brain activity, for example, it takes two experimenters about three hours to instruct and prepare the subject, including fitting of the 128 EEG electrodes and measuring their positions and orientations.

Then the actual sleep recordings begin: In contrast to daytime EEG studies, where the subject usually sits still in front of a computer screen, sleeping subjects are turning around frequently, moving their heads, rubbing them into the pillow, pulling cables, and so on. Thus, lucid dreaming experimenters usually need to stay awake for the whole night in order to continuously supervise the quality of the recordings and to intervene in case of bad signal quality. There is nothing more frustrating for a lucid dream researcher than a bad EEG signal during the critical few minutes of a lucid dream. However, given that the preparation was successful and the subject finally experiences a lucid dream: How can this subjective experience be validated with objective scientific methods?

Even though the phenomenon of lucid dreaming has been described in the scientific literature already more than one century ago (Van Eeden 1913), it took more than 50 years until Green (1968) proposed a method for objective measurement of lucid dreams, which was ten years later put into practice by Hearne (1978) and LaBerge (1980a). According to the so-called scanning hypothesis (Ladd 1892), eye movements during REM sleep largely correspond to the subjectively experienced dream eye movements. Hearne and LaBerge asked their subjects to move their eyes in a predefined left-right-left-right (LRLR) manner as soon as they would become aware of their dreaming state, i.e. lucid. After awakening, a dream report was collected – and the previously agreed eye movements were consistently observed in both the dream report and the electrooculogram, clearly distinguishable from normal eye movements of REM sleep (LaBerge et al. 1981). These findings have been replicated in numerous studies since then, and allow for objective and exactly timed measurements of lucid dreams (Erlacher 2007; Dresler et al. 2011).

Having quickly developed into the gold standard in lucid dream research, also in our studies we use these LRLR eye signals to objectively verify that the subject actually achieved a lucid dream: eye movements are recorded and displayed on a computer screen in real-time, allowing for the experimenter to immediately identify a lucid dream whilst the subject is still asleep. After a predetermined time (or signs that the subject lost dream lucidity again), the successful lucid dreamer wakes up on his or her own, or is awakened by the experimenter in order to prompt a dream report and prevent forgetting of the dream. Besides writing down the dream report, also questionnaires about degrees of lucidity are filled out, and specific questions about the experiments conducted within the lucid dream are answered, before the subject goes back to sleep again for another lucid dreaming attempt.

The necessity to wake up subjects in case of a lucid dream without self-initiated awakening requires the experimenter to continuously monitor the eye recordings on the computer monitor throughout the whole night. While unfortunately still no automatized solutions for lucid dreaming LRLR eye signal detection in the sleep laboratory exist, some researchers have recently started developing such tools by applying methods from the field of machine learning and pattern recognition to automatically detect lucidity-indicating eye movements or bad EEG signals in real-time (e.g. Appel 2013).

In the morning, when the subject declares that he or she cannot sleep any more, recordings are stopped, and it usually takes another one or two hours to let the subject fill out more questionnaires, to tidy up and clean the equipment, or to take a few other measures depending on the experiment. For example, a classical study protocol for motor skill training during lucid dreaming needs performance measurements of the chosen skill both in the evening and in the morning. All in all, the whole experimental procedure of recording one night including preparations and follow-up usually takes from 8 pm until 11 am the next day – for a few recording minutes of data of interest in the best case scenario, i.e. the subject experiencing an actual lucid dream. In many cases, two or three consecutive nights are recorded in a row in order to reduce travelling demands on the subject, resulting in an extensive workload for the lucid dream researcher. Given all these efforts and constraints, it is not surprising that lucid dreaming studies often suffer from a limited number of participants – if exceeding the character of case-studies of single subjects at all.

4. The variety of lucid dreaming induction methodologies

As our illustration of a typical night in the sleep laboratory demonstrates, recording a lucid dream is an effortful procedure – if succeeding at all, as an entirely non-lucid night is even in experienced lucid dreamers the more usual case. Development of a reliable method allowing to induce lucid dreaming on demand would thus imply strong progress for the field of lucid dreaming research. However, even though during the past 40 years numerous studies tested methods from different disciplines such as psychology, electrical engineering or pharmacology in search for this 'Holy Grail' of lucid dreaming research, no reliable method has been found yet (for an extensive overview see Stumbrys et al. 2012). Lucid dreaming is considered to be a learnable skill, even though it can take from days to months until the first lucid dream is experienced by the novice (LaBerge 1980b; Tholey 1983). Most lucid dream induction methods can be used stand-alone or in combination with each other. In the following we will discuss exemplary methods in order to demonstrate their variability, different methodological approaches and multidisciplinary backgrounds.

Psychological methods

Psychological methods for inducing lucid dreaming have been investigated most frequently (Stumbrys et al. 2012). These methods include all cognitive and behavioural activities that are carried out to increase the likelihood of lucid insight into the dream state. *Tholey's combined technique* (Tholey 1983), for example, makes use of intention (imagining being in a dream and recognizing this), autosuggestion (repeatedly suggesting oneself to become lucid when falling asleep), and reflection, i.e. the development of a critical-reflective frame of mind concerning one's state of consciousness: by repeatedly asking oneself throughout the day whether one is dreaming, a habit of critical self-awareness is developed. After some time, this self-reflexive habit will be transferred to the dream state and might thus prompt lucid insight into this state. However, on a generally uncritical background cognition that prevails during most dreams, such reflection on the current state of mind does not necessarily lead to actual dream lucidity. In order to systematically test whether one is currently in a dream or awake, therefore a number of so-called *reality checks* have been developed. One classic example is to read a short text within a dream, look away from the text and back again – the text often changes its content during this procedure (LaBerge and DeGracia 2000). A further reality check would be to hold one's nose and try to breath through it nevertheless, which obviously does not work while being awake, but is possible surprisingly often during a dream (this might be the case because the sleeping body is in fact breathing through the nose). *Tholey's combined technique* has been found to successfully increase the probability of lucid dreams: A field study by Paulsson and Parker (2006) with 20 participants compared a baseline week with no application of the technique to two weeks of using *Tholey's combined technique*. During the baseline week, on average only about 2% of the nights included a lucid dream. During the first week of applying the induction technique, 11 participants had lucid dreams (5 of which never had a lucid dream before), summing up almost one lucid dream per week. The number of lucid dreams further increased during the second week, resulting in also statistically significant increase in lucid dreaming frequency compared to the start of the study.

Numerous other cognitive techniques exist, for example the mnemonic-induced lucid dream (MILD) technique (LaBerge 1980b), which was tested most often empirically so far in scientific experiments. MILD requires the dreamer to rehearse a dream before falling asleep and to visualize achieving lucidity, combined with autosuggestion. A different cognitive approach is chosen in the so-called wake-induced lucid dreaming techniques, in which – in contrast to the previous described methods – the dreamer does not try to gain insight into the dreaming state during the dream, but tries to maintain this awareness already when falling asleep, e.g. by concentrating on the hypnagogic imagery at sleep onset (LaBerge and Rheingold 1990).

Pharmacological methods

Besides psychological induction methods such as *Tholey's combined technique*, also pharmacological approaches have been developed to directly alter the brain's chemistry such that lucid dreams become more probable. In one of the very few studies until now, LaBerge (2004) administered Donepezil, i.e. a drug from the class of acetylcholine esterase inhibitors usually indicated for patients suffering from Alzheimer's disease. This drug increases the level of the neurotransmitter acetylcholine in the body and in the brain, and thereby also affects lucid dreaming, as demonstrated in a double-blind placebo controlled experiment: In the Donepezil conditions (5 mg or 10 mg), nine out of ten subjects reported one or more lucid dreams during two nights, whereas only one out of ten subjects reported a lucid dream in the placebo night. As with most prescription drugs, however, Donepezil comes with side effects – for example more than one out of ten patients will experience nausea, other side effects include heart rate changes, cramps, hallucinations, or insomnia. Thus, despite its promising lucid dream induction capabilities, Donepezil is not well suited for lucid dreaming studies or private use for lucid dreaming purposes at home due to its side effects. Alpha-Glycerolphosphorylcholine, a non-prescription alternative to Donepezil that is thought to act on the acetylcholine system with less side effects, was recently tested with no significant results (Kern et al. 2017).

This shows that even though pharmacological strategies are promising, more research is needed in order to find a both reliable and safe drug for lucid dream induction.

Technical devices

During the past 40 years of lucid dream research also technical approaches for lucid dream induction have been tested, frequently leading to the development of commercially available consumer products. Most prominent in this regard are sleep masks that emit light effects or auditory cues during REM sleep. The idea behind this strategy is that these signals get incorporated into the dream and remind the dreamer of his or her plan to become lucid. The main difficulty thereby lies in the correct adjustment of the stimulus intensity: if the stimulus is too bright or loud, the subject wakes up, if it is not intense enough, it does not affect the dream. Studies focusing on light stimulation during REM sleep alone without combining it with e.g. cognitive methods showed only poor results of around 5% success rate per night (LaBerge 1988; Paul, Schädlich, and Erlacher 2014). Other stimulation types such as vibro-tactile (Reis 1989), electro-tactile (Hearne 1983), vestibular (Leslie and Ogilvie 1996) or water splashes in the face (Hearne 1978) have been investigated as well, however did not lead to reliable solutions for lucid dream induction on demand.

Electrical brain stimulation

Instead of using lights or sounds to indirectly alter dreaming, recent studies used transcranial direct current stimulation (tDCS, Stumbrys, Erlacher, and Schredl 2013) or transcranial alternating current stimulation (tACS, Voss et al. 2014) for lucid dream induction. For such electrical brain stimulation methods, electrodes are attached to the scalp and a small electrical current below the perception threshold is applied. The aim is to evoke neuronal activity in cortical areas which are associated with lucid dreaming, e.g. the DLPFC (see above). Since the subject is asleep and side effects can occur, this technique is not (yet) suited for home use. The results of the two studies conducted about this new lucid dream induction method look promising: compared to sham (placebo) stimulation, both tACS and tDCS slightly increased dream lucidity as measured with a dream questionnaire or via the eye signalling technique. However, the effect sizes especially in non-frequent lucid dreamers were rather low, and further improvements of this methodology are needed.

Unfortunately, none of the psychological, pharmacological or technical induction techniques developed so far induces lucid dreams both reliably and safely on demand, rendering lucid dreaming experiments in the sleep laboratory an effortful and time-consuming endeavour.

5. Lucid dreaming – an interdisciplinary field of research

Lucid dreaming is not restricted to private use, but has been studied as both a scientific tool and topic in different academic disciplines. In the following we will briefly overview how lucid dreaming research has been conducted in different fields such as neuroscience and psychology, sport science, arts, therapy, and philosophy.

Neuroscience and lucid dreaming

One example of a neuroscientific research problem, which was solved using lucid dreaming experiments, is the question whether the neuronal activity of the brain during waking experiences is similar to that of analogous, but merely dreamed experiences. The main obstacle to answer this question lies in the elusiveness of dreams: every dream is different, sleeping subjects normally cannot be asked to dream a specific content, and researchers do not know when exactly which element of the dream report happened in the respective sleep recording. With lucid dreaming, these problems can be solved: experienced lucid dreamers were asked to perform particular hand movements during their lucid dreams, and again later during wakefulness. Lucid eye signals were used as exact temporal markers of the tasks executed during dreaming. Subsequent analysis of the recorded brain activity could thus be performed exactly time-logged to the dreamed task performance, demonstrating that brain processes are indeed very similar between dreaming and wakefulness (Erlacher, Schredl, and LaBerge 2003; Dresler et al. 2011). Another neuroscientific experiment aimed to answer the old question whether the flow of time experienced during dreaming corresponds to objective time during wakefulness. To test this question, again lucid dreamers were instructed to use intentional eye movements during the dream as markers for the start and end of dream actions. By doing so, it could be demonstrated that the time needed for counting in a lucid dream is comparable to the time needed for counting in the waking state (LaBerge 1985). Interestingly, motor activities such as performing squats, walking, or a gymnastics routine appear to require slightly more time during dreaming compared to wakefulness, which might be due to the absence of muscular feedback or slower neural processing during REM sleep (Erlacher & Schredl, 2004; Erlacher et al. 2013).

Therapy and lucid dreaming

Viewed from a medical perspective, the *prima facie* potential of lucid dreaming as a therapeutic approach for nightmares is apparent: if the dreamer realizes during a nightmare, that the experienced threats are merely dreamed and thus not real, the nightmare becomes much less frightening. Moreover, the lucid dreamer can try to alter the dream story, letting the threats disappear, or change into something more pleasant. Various studies have examined this psychotherapeutic potential of lucid dreaming for nightmares, and also for post-traumatic stress, and supported its efficacy (Spoormaker, van den Bout, and Meijer 2003; Spoormaker and Van Den Bout 2006; Soffer-Dudek, Wertheim, and Shahar 2011; Holzinger, Klösch, and Saletu 2015). Besides using lucid dreaming for nightmare therapy, it might also help by serving as a new treatment approach for patients with schizophrenia. Dreaming has already been discussed as a natural model for psychosis for several centuries (Hobson 2004), and recent empirical work supports this idea (D'Agostino, Limosani, and Scarone 2012). One major symptom of psychotic patients is that they are not able to recognize their pathologic state as such – just as healthy subjects during dreaming typically do not recognize their current state of mind. In the dreaming-as-psychosis model, lucid dreaming thus represents the successful insight of the patient into his or her state. And in fact, psychotic patients with impaired insight into their pathologic state show anatomical and functional changes in exactly those brain regions that are more active in lucid compared to non-lucid dreams (Dresler et al. 2015). On this background, lucid dreaming training might serve as a therapeutic approach to increase state insight also in patients with schizophrenia, and new schizophrenia drugs might be tested in healthy subjects with lucid dreaming frequency as a new outcome measure of interest.

Philosophy and lucid dreaming

Lucid dreaming has gained increasing interest from philosophers in recent years due to its implications for philosophical theories on consciousness. Common distinctions of this term differentiate between basal (primary) and higher (secondary) consciousness: Primary consciousness includes mostly sensations and perceptions, whilst secondary consciousness constitutes by reflecting about these basal contents (Edelman 2003). Insofar, gaining lucid insight into the dream state represents a very pure form of secondary consciousness, as the transition from primary to secondary consciousness happens within a comparable physiological milieu (Dresler et al. 2009; Hobson 2009; Hobson and Voss 2010). Further, the phenomenon of lucid dreaming is seen as of great value particularly for philosophical theories on subjectivity and the self, as lucid dreams represent a unique class of phenomenal states, namely the full experience of the current subjective state as being a merely simulated model of the world (Metzinger 2003, 2009; Windt and Metzinger 2007).

Sports science and lucid dreaming

Dreams in general can be seen as a perfectly simulated virtual reality (Revonsuo 1995). This makes lucid dreams, in turn, highly interesting for sport sciences, since they offer exceptional training opportunities (Erlacher and Chapin 2010). In particular extreme sports with high risks of injury benefit from the safe training environments that allows a risk-free rehearsal of complex movements. Few studies have tested the potential of lucid dreams for sports training, however with promising results. For example, it could be shown that it is possible to practice movements during a lucid dream and thereby improve also the waking performance of this task (Erlacher and Chapin 2010; Erlacher and Schredl 2010; Erlacher 2012; Schädlich, Erlacher, and Schredl 2017; Stumbrys, Erlacher, and Schredl 2016). Moreover, a survey among 840 German athletes revealed that 25% of them experience lucid dreams regularly, and that around 10% of the athletes use lucid dreaming for training purposes and to improve their performance during wakefulness (Erlacher, Stumbrys, and Schredl 2012). It thus appears that the promising sports training options of lucid dreaming are already used by a significant number of athletes.

Arts, music and lucid dreaming

Lucid dreaming is valued by artists because of its potential for incubating or boosting creative processes (Barrett 2001). Dreams in general are reported to have been the source of many artistic works or musical pieces – not only in surrealism, which explicitly uses dreams as a theoretical basis, but also in many other artistic directions (for an overview see Dresler 2008). Systematic studies about incubative processes of creativity confirm these anecdotal evidences (Marisch et al. 2016). One reason for this lies in the neurophysiological milieu that harbours dreaming, and that provides many prerequisites considered to be important by psychological and neurocognitive theories of creativity: a variable cortical arousal, unusual connections between distant brain regions, flat associative hierarchies and a state of defocused attention (Dresler 2012; Marisch et al. 2016). Lucid dreaming offers a particularly creativity-enabling state: like in non-lucid dreams, the dreamer experiences a hyper-associative state with unusual combinations of ideas and sensations, however in contrast to a non-lucid dream he or she is capable of deliberately evaluating these new impressions with respect to their artistic value. And in fact, a number of painters and musicians use their lucid dreaming abilities for inspirational purposes – e.g. an artist looking for new scenes in a virtual dream gallery (Barrett 2001) or a musician looking for new melodies in lucidly dreamed radio programmes (Dobe 2012).

6. Conclusions and future directions

Lucid dreaming is both topic and tool in various scientific disciplines, from neuroscience to philosophy to sports science to arts to therapy. However, further research on the induction of lucid dreams, in the sleep laboratory and at home, is necessary. Despite numerous tested approaches from various academic backgrounds including psychology, electrical engineering or pharmacology, until now no method has been found to induce lucid dreams reliably and safely on demand for everybody and in every desired night. Besides the development of completely new ideas for lucid dream induction, work in this direction should also focus on further developing existing approaches. Combining and integrating approaches from different scientific disciplines might be the key to finding a reliable method for lucid dream induction – for example, by using supplements, technical devices and cognitive induction techniques simultaneously and by studying, which combinations of which methods increase the probability of lucid dreams best. It might be the case, however, that some induction techniques even reduce the effectiveness of other techniques, when used at the same time. From these interactions it might be possible to understand better, in which way each induction technique influences the lucid dream probability, why some methods work better for some people than for others, and whether a smart combination of techniques exists that induces lucid dreams in everybody.

Furthermore, more research should be conducted to investigate, how lucid dreams can be used most effectively for the various purposes described in this paper. This also includes research on 'best practices' of how lucid dreamers can influence their dreams best and how to transfer these best practices from one discipline to another. For example, if artists develop a good and reliable method for boosting and using creativity in lucid dreams, the same practice might be used for finding solutions to challenging problems in other applications.

Finally, a more advanced information transfer than simple LRLR eye signals from the lucid dream to the waking world is a promising aim for future research. With a bidirectional message exchange system (Appel 2013), ideas like a direct interaction between lucid dreams and the waking world for creating art, direct psychotherapeutic coaching during nightmares, or advanced neuroscientific sleep studies seem realizable in the nearer future.

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Original contribution

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No effect of α-GPC on lucid dream induction or dream content

Electronic supplementary material
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Introduction

Lucid dreaming

Lucid dreaming describes a phenomenon in which a dreaming person becomes aware of the fact that he is dreaming [18]. In the second half of the 20th century, researcher LaBerge [10] proved the existence of lucid dreams using objective sleep laboratory measurements. A recent representative survey in Germany [19] found out that around half of the population has experienced at least one lucid dream, with around 20% having a lucid dream at least once per month.

It is assumed that, in principle, everybody is able to develop the ability to dream lucidly [8]. Nevertheless, frequent lucid dreaming is considered a rare skill, and a reliable method of lucid dream induction remains to be discovered [27]. However, some personality traits (such as thin boundaries, imagination and absorption) and activities correlate with the occurrence of lucid dreams, such as dream recall frequency and meditation [18]. Most often, lucid dreamers use their skill for having fun, practicing motor skills, treating their nightmares and solving other problems [26].

Neurobiological background

Most lucid dreams appear during rapid eye movement (REM) sleep [10], although rare non-REM (NREM) lucid dreams have been reported as well [25]. The underlying neural mechanisms and neurochemical basis of lucid dreaming are a topic of ongoing research [3, 5]. One possible mediating variable influencing the occurrence of lucid dreams could be the cholinergic system, as lucid dreaming occurs almost exclusively during REM sleep. According to the Activation Input–Output gating Modulation (AIM) model [5], REM sleep is cholinergically potentiated and aminergically suppressed. Acetylcholine seems to initiate REM sleep via cholinergic REM-on neurons in the pedunculopontine nucleus. Moreover, during REM sleep there is an increase in cholinergically triggered ponto-geniculo-occipital (PGO) waves [13]. It is further speculated that PGO waves themselves are used in the construction of hallucinoid visual imagery of dreams and therefore account for dream bizarreness [6, 12]. In experimental studies, cholinergic activation with agonist substances tends to extend the duration of REM sleep [7, 21, 24]. One study by Hohagen et al. [7] also found a co-occurring decrease in REM density, while another study [14] did not.

Induction of lucid dreams

A variety of techniques have been proposed to induce lucid dreaming. Most methods focus on cognitive techniques such as awareness training, autosuggestion or hypnosis; or on external sensory stimulation using technical devices [27]. In addition, Yuschak [29] suggests that several substances can aid lucid dream induction. Many of these substances act on the cholinergic system, which seems plausible given the cholinergic nature of REM sleep. A study by LaBerge [9] extends this pharmacological approach to lucid dream induction: In a double-blind placebo-controlled experiment, lucid dreams could successfully be induced using the acetylcholinesterase inhibitor class drug donepezil. Despite the limited sample size of only ten subjects, results from this study seem promising: Nine of the ten participants experienced at least one lucid dream during the two donepezil nights, whilst only one of the ten did during the placebo night. A questionnaire-based study [23] regarding the use of donepezil for lucid dream induction showed that people report differences in lucid dream quality after intake of the substance.

Aims of this study

In this randomized double-blind placebo-controlled field study, we examine another drug that acts on the cholinergic system: L-alpha glycerylphosphorylcholine (α-GPC). α-GPC is an acetylcholine precursor which, in contrast to acetylcholine itself, is able to cross the blood–brain barrier. Compared to donepezil, α-GPC is prescription free and has fewer side effects. Here, we test the hypothesis that α-GPC induces lucid dreams. While a small-scale study [11] found a positive correlation between REM density and lucid dreaming, we do not know what effect α-GPC has on the various REM sleep parameters.

Furthermore, since other studies [9, 29] suggest that cholinergic stimulation has several effects on dreaming, we analyse the effect of α-GPC on dreams in

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general. Based on Mamelak and Hobson's [12] hypothesis of a direct correlation between cholinergic activation and dream bizarreness, we expect an increase in overall dream bizarreness as well as a change of dream emotions such as fear or aggression. Additionally, due to the memory-enhancing effects of α-GPC [15], we expect to find an increase in dream recall.

Methods

Participants

The sample included 40 participants (mean age 24.21 ± 6.42 years; 20 female, 20 male). Participants were recruited through the mailing list of the University of Osnabrück and from two online lucid dreaming boards. Exclusion criteria were smoking, sleep disorders, age above 50 years and low dream recall (fewer than three dreams per week). Among the participants were 30 participants with no or little experience in lucid dreaming (fewer than 20 lucid dreams in total, less than once per month; 15 female, 15 male) and 10 advanced lucid dreamers (more than 20 lucid dreams in total, more frequent than once per month; 5 female, 5 male). The study was completed by 33 participants (novice: $N = 24$, advanced: $N = 9$). Dropouts were due to personal reasons as well as loss of documents during the post delivery process. Participants were tested for sleep disorders using the Landecker Inventory for Sleep Disorders (LISST) questionnaire [20]. All volunteers provided signed informed consent for the study, which was approved by the ethics committee of the University of Osnabrück. Students received participation hours needed for their degree and participants had the opportunity to win one of four 10 € purchase vouchers for completed participation (10% chance of winning).

Procedure

The study was conducted as a field experiment. All participants were instructed to take the supplement on three non-consecutive nights. As a baseline and to ease adaptation to the experimental situation, all participants received a placebo for the first night (single-blinded, baseline night). The following two nights were randomized double blind, with two groups in a crossover design. As it was not possible to get placebos that matched in visual appearance, two different placebos containing lactose were used. Participants were verbally screened for dietary restrictions concerning lactose. White placebo tablets were used for the first night and red/transparent hard-shelled capsules for the second or third night, the α-GPC supplement itself was a yellow soft-shelled capsule (see electronic supplementary material). Each night, three pills were administered, which added up to 1.2 g of active component in case of the α-GPC night. This dose has been suggested by Yuschak [29] and is similar to the upper dosage in another clinical trial [15]. In an online prestudy ($N = 60$), we asked participants to judge whether the different pills looked like placebos. Participants judged the α-GPC pills significantly higher in terms of looking like placebos ($F(4, 295) = 2.90$, $p = 0.022$) when comparing them to the placebos. This led us to the conclusion that the α-GPC pills could not be optically revealed as containing an active component. Participants of the prestudy were excluded from participating in the main study. Participants of the main study were also asked to estimate the effectiveness of the pill based on visual evaluation, and once again after substance intake (haptic evaluation). Due to the short half-life and fast plasma peak of α-GPC, participants were instructed to open the envelope containing the supplement and ingest it after 4.5 h of night sleep. This was done to minimize the chances of interfering slow-wave sleep [2]. Prior to each night, a normal night's sleep (no sleep-altering substances, regular sleep pattern) was mandated. Participants were asked to sleep as long as they wanted the next morning. In addition to a written dream report, the Lucidity and Consciousness in Dreams (LuCiD) scale [28] was used to record different aspects of lucidity (lucid insight, control over the dream, logical thought, perceptual realism, access to waking life memory; questions on a scale of 0 = strongly disagree, 5 = strongly agree) via self-reports. The Cronbach's alpha reliability for the subscales are: Insight: 0.91, control: 0.90, thought: 0.82, realism: 0.79 and memory: 0.66. The questionnaire SF-A ("Schlaffragebogen A") [4] was used to assess sleep quality indicators (subscales: sleep quality, SQ; feeling rested after the night, GES; mental balance in the evening, PSYAA; mental fatigue in the evening, PSYEA; psychosomatic symptoms during sleeping, PSS; ratings on a five-point scale for different adjectives to describe the physical and mental state before and after the night). The Cronbach's reliability scores for the subscales are: SQ: 0.89, GES: 0.91, PSYAA: 0.87, PSYEA: 0.80 and PSS: 0.41. Participants were asked "Do you think this pill is effective?" (1 = not effective to 6 = very effective) once before intake of the substance and once directly after swallowing the pills. Documents and drugs were handed out on December 13, 2014; participants were told to finish within roughly 5 weeks. The last participant finished on March 28, 2015.

Statistical analysis

Statistical analysis was performed using MATLAB 2014b for Linux (MathWorks, Natick, MA, USA). We used a repeated measurement analysis of variance (ANOVA) to compare the scores of the SF-A and, due to their non-parametric distribution, a Friedman test for the scores of the LuCiD scale. Single variable analysis was carried out using a three-fold Kolmogorow–Smirnow test as well as a variance permutation test.

Dream content analysis

Dream content analysis was performed by two independent evaluators using the following items: Clues for dream lucidity (0 = no, 1 = some, 2 = clear), closeness to reality (based on [16]), positive and negative feelings (0 to 3: none to strong), explicit mention of fear (0 = no, 1 = yes), number of people in the dream, number of bizarre elements (based on [17]), verbal and physical aggression (0 = no, 1 = yes). Dream reports were anonymised and randomized prior to the analysis. Overall inter-rater reliability was k = 0.60 (Cohen's kappa coefficient; range: 0.27–0.81 for 11 different scales). To prevent a subjective bias, we only used the external raters' judgement of clues for dream lucidity to classify the dreams. The LuCiD scale values were used to measure possible overall differences in variables concerning dream lucidity.

Results

Lucid dreaming

There were a total of 75 dream reports (52 from inexperienced lucid dreamers). Ten participants reported dreams on two nights and 17 participants reported dreams on all three nights. Another four participants reported dreams on one night. One participant reported no dream at all. One of the participants reported dreams on all three nights but did not want to specify the content.

A total number of six lucid dreams were judged by the raters to contain clear clues of lucidity. Two advanced lucid dreamers had clear signs of a lucid dream in the α-GPC condition, two novice lucid dreamers in the baseline night and two novice lucid dreamers in the placebo condition.

The scores of the LuCiD scale were analysed using a Friedman test including all participants that remembered a dream on all three nights ($N = 17$). There was a slightly higher mean of the CONTROL variable of the LuCiD scale when comparing the α-GPC condition to the placebo condition; however, results were not significant. Overall, there were no significant differences between the three conditions. Results can be seen in Table 1 (the extended version is available in the electronic supplementary material).

Dream content analysis and dream recall

There were no significant differences regarding dream content between the experimental conditions (aggression, fear, positive and negative emotions, or dream bizarreness). In contrast to four dreams in the placebo condition and six dreams in the α-GPC condition, two dreams of

Abstract · Zusammenfassung

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No effect of α-GPC on lucid dream induction or dream content

Abstract

Background. A lucid dream is a dream in which one is aware of the fact that one is dreaming. Various cognitive and technical methods exist to induce lucid dreaming, most of which show only little success when tested scientifically. Until now, only few studies have dealt with inducing lucid dreaming by supplements, with, however, promising results.
Objective. We have continued this line of research by conducting a double-blind randomized placebo-controlled field study in order to investigate pharmacological lucid dream induction using L-alpha-glycerylphosphorylcholine (α-GPC), a prescription-free drug acting as an acetylcholine precursor. Additionally, we tested whether cholinergic activation changes dream emotions or bizarreness.
Materials and methods. Following the baseline night with placebo, 23 participants with little lucid dreaming experience and 10 participants with advanced experience were administered a placebo on one night and 1200 mg of α-GPC on one night. The Lucidity and Consciousness in Dreams (LuCiD) scale was used to measure the level of dream lucidity. In addition, dream reports were collected to analyse dream content alterations.
Results and conclusion. Out of 75 dreams in total, six were rated as lucid: two in the baseline condition, two in the placebo condition and two in the α-GPC condition. There was no significant alteration of dream content such as dream emotions or bizarreness. Thus, previous anecdotal findings about lucidity-promoting or dream-altering effects of α-GPC were not confirmed in our study.

Keywords
Sleep · REM-Sleep · Glycerylphosphorylcholine · Awareness · Acetylcholine

Keine Wirkung von α-GPC auf die Induktion von Klarträumen oder Trauminhalte

Zusammenfassung

Hintergrund. Ein Klartraum ist ein Traum, in dem man sich der Tatsache bewusst ist, dass man träumt. Es gibt verschiedene kognitive und technische Verfahren, um Klarträume zu induzieren, jedoch sind die meisten davon in wissenschaftlichen Untersuchungen nur wenig erfolgreich. Bisher haben sich nur wenige Studien mit der Induktion von Klarträumen durch Präparate befasst, allerdings mit vielversprechenden Ergebnissen.
Ziel der Arbeit. Die Autoren haben diesen Forschungsansatz fortgeführt, indem sie eine doppelblinde randomisierte placebokontrollierte Feldstudie durchführten, um die pharmakologische Klartrauminduktion unter Einsatz von L-alpha-Glycerylphosphorylcholin (α-GPC), einem rezeptfreien Nahrungsergänzungsmittel mit der Wirkung einer Vorstufe von Acetylcholin, zu untersuchen. Zusätzlich wurde untersucht, ob eine cholinerge Aktivierung die Traumemotionen oder die Skurrilität der Träume veränderte.
Material und Methoden. Nach der ersten Nacht als Ausgangswert mit Placebo wurde 23 Teilnehmern mit geringer Klartraumerfahrung und 10 Teilnehmern mit fortgeschrittener Erfahrung in der einen Nacht ein Placebo und in der anderen Nacht 1200 mg α-GPC verabreicht. Zur Messung des Maßes der Traumluzidität wurde die Skala Lucidity and Consciousness in Dreams (LuCiD) verwendet. Darüber hinaus wurden Traumberichte erfasst, um Veränderung von Trauminhalten auszuwerten.
Ergebnisse und Schlussfolgerung. Von 75 Träumen insgesamt wurden 6 als Klartraum eingestuft: 2 in der Ausgangssituation, 2 in der Placebosituation und 2 in der α-GPC-Situation. Es bestand keine wesentliche Abweichung der Trauminhalte in Bezug auf Traumemotionen oder -skurrilität. Somit wurden in der vorliegenden Studie anekdotische Angaben zur luziditätsfördernden oder traumverändernden Wirkung von α-GPC nicht bestätigt.

Schlüsselwörter
Schlaf · REM-Schlaf · Glycerylphosphorylcholin · Bewusstsein · Acetylcholin

Table 1 Scores of the LuCiD scale

LuCiD scores	Baseline	Placebo	α-GPC	Friedman (n = 17)
INSIGHT	M = 0.82 SD = 1.22	M = 0.61 SD = 0.88	M = 0.88 SD = 1.41	$\chi^2(2) = 0.5$ $p = 0.78$
CONTROL	M = 0.62 SD = 0.87	M = 0.24 SD = 0.41	M = 0.84 SD = 1.40	$\chi^2(2) = 3.56$ $p = 0.17$
THOUGHT	M = 2.08 SD = 1.27	M = 2.08 SD = 1.29	M = 1.96 SD = 1.14	$\chi^2(2) = 0.59$ $p = 0.74$
REALISM	M = 2.67 SD = 1.00	M = 2.49 SD = 1.09	M = 2.39 SD = 0.98	$\chi^2(2) = 3.73$ $p = 0.15$
MEMORY	M = 1.28 SD = 1.15	M = 1.25 SD = 1.25	M = 1.01 SD = 0.99	$\chi^2(2) = 0.52$ $p = 0.77$

Friedman's test for scores of the LuCiD scale. Not shown are scores for positive and negative emotions, as they were not seen as relevant features of a lucid dream (both non-significant)
M mean, *SD* standard deviation, *LuCiD* Lucidity and Consciousness in Dreams scale, *χ2(2)* Chi-square value of a non-parametric Friedmann test with 2 degrees of freedom

Table 2 Results of the dream content analysis

Dream content	Baseline	Placebo	α-GPC	Friedman (n = 17)
Closeness to reality	M = 2.21 SD = 0.77	M = 2.09 SD = 0.60	M = 2.44 SD = 0.66	$\chi^2(2) = 2.31$ $p = 0.315$
Positive emotions	M = 0.15 SD = 0.48	M = 0.29 SD = 0.73	M = 0.41 SD = 0.91	$\chi^2(2) = 0.64$ $p = 0.727$
Negative emotions	M = 0.41 SD = 0.79	M = 0.53 SD = 0.70	M = 0.38 SD = 0.68	$\chi^2(2) = 2.16$ $p = 0.338$
Fear	M = 0.44 SD = 0.82	M = 0.12 SD = 0.32	M = 0.15 SD = 0.48	$\chi^2(2) = 1.73$ $p = 0.422$
Number of people	M = 3.21 SD = 1.82	M = 2.68 SD = 1.39	M = 3.09 SD = 2.24	$\chi^2(2) = 0.38$ $p = 0.829$
Number of bizarre elements	M = 0.62 SD = 0.90	M = 0.35 SD = 0.72	M = 0.68 SD = 0.71	$\chi^2(2) = 2.17$ $p = 0.338$
Outgoing verbal aggression	M = 0.00 SD = 0.00	M = 0.00 SD = 0.00	M = 0.09 SD = 0.26	$\chi^2(2) = 4$ $p = 0.135$
Incoming verbal aggression	M = 0.06 SD = 0.16	M = 0.00 SD = 0.00	M = 0.12 SD = 0.27	$\chi^2(2) = 2.8$ $p = 0.247$
Outgoing physical aggression	M = 0.00 SD = 0.00	M = 0.06 SD = 0.24	M = 0.15 SD = 0.33	$F(2, 32) = 3.5$ $p = 0.174$
Incoming physical aggression	M = 0.03 SD = 0.12	M = 0.09 SD = 0.26	M = 0.15 SD = 0.33	$F(2, 32) = 1$ $p = 0.607$

M mean, *SD* standard deviation, *χ2(2)* Chi-square value of a non-parametric Friedmann test with 2 degrees of freedom

Table 3 Scores of the sleep quality questionnaire

SF-A scores	Baseline	Placebo	α-GPC	rmANOVA
SQ (n = 31)	M = 3.56 SD = 0.61	M = 3.76 SD = 0.49	M = 3.88 SD = 0.49	$F(2, 30) = 4.19$ $p = 0.02$
GES (n = 29)	M = 3.38 SD = 0.81	M = 3.46 SD = 0.62	M = 3.62 SD = 0.57	$F(2, 28) = 1.17$ $p = 0.32$
PSYAA (n = 31)	M = 3.56 SD = 0.66	M = 3.69 SD = 0.46	M = 3.71 SD = 0.68	$F(2, 30) = 0.98$ $p = 0.38$
PSYEA (n = 30)	M = 2.93 SD = 0.83	M = 3.05 SD = 0.87	M = 3.22 SD = 0.85	$F(2, 29) = 1.66$ $p = 0.20$

SF-A Schlaffragebogen A, *rmANOVA* repeated measures analysis of variance, *SQ* overall sleep quality, *GES* feeling recovered after the night, *PSYAA* feeling mentally balanced in the evening, *PSYEA* feeling exhausted in the evening, *M* mean, *SD* standard deviation

the baseline night contained aggression, but there was no statistical significance.

Results can be seen in **Table 2** (the extended version is available in the electronic supplementary material).

A dream experience was had by 31 participants on the baseline night (four with no dream recall), by 30 on the placebo night (five with no dream recall) and by 30 in the α-GPC condition (seven with no dream recall). When carrying out a Friedman test, no significant group difference in dream recall was observed ($F(2, 64) = 2.91$, $p = 0.234$).

Post-night SF-A sleep questionnaire

Comparing the three groups (baseline, placebo, α-GPC; N = 31), a repeated measures ANOVA revealed a significant difference in SQ ($F(2, 30) = 4.19$, $p = 0.024$). Follow-up paired t-test revealed that baseline SQ (mean, M = 3.56; standard deviation, SD = 0.61) was significantly lower than placebo SQ ($p = 0.096$; M = 3.56, SD = 0.49) and α-GPC SQ ($p = 0.021$; M = 3.87, SD = 0.49). Additionally, people woke up more often during the baseline night ($p = 0.030$; baseline: M = 2.39, SD = 1.17; placebo: M = 1.83, SD = 0.79; α-GPC: M = 1.94, SD = 0.91). None of the participants reported any side effects. All other scores showed no significant difference. Results can be seen in **Table 3** (the extended version in the electronic supplementary material).

Single variable analysis

An exploratory variance permutation test was performed on all 96 variables. We found that participants woke up significantly more often after substance intake when comparing the baseline (M = 1.23, SD = 1.20) to placebo (M = 0.52, SD = 0.77; $p = 0.004$) and baseline to α-GPC (M = 0.77, SD = 1.05; $p = 0.042$). When asked the question "Do you think this pill is effective?", participants attributed a lower efficiency to the baseline night placebo pills (M = 3.29, SD = 1.02) directly after swallowing them. These results were significantly lower than the estimated efficiency of the α-GPC pills (M = 3.77, SD = 1.17; $p = 0.045$) and non-significantly lower when comparing them to the pills of the placebo condition (M = 3.74, SD = 0.94; $p = 0.08$). There was no difference between placebo and α-GPC in terms of estimated efficiency ($p = 0.908$).

Discussion

In the present study, α-GPC seemed to have little effect on dream experience. Contrary to our expectations, it did not increase the likelihood of lucid dreaming, particularly not for inexperienced lucid dreamers. We also found no significant changes in dream content and emotions or dream bizarreness. Most difference was found when comparing the baseline night to the other two nights, confirming the first-night effect found in sleep laboratory studies [1]. This was reflected in a lower sleep quality in the baseline night and in more nocturnal awakenings.

With two lucid dreams in each of the three conditions, we did not find any increase in overall lucid dreaming frequency. Two of the advanced lucid dreamers had a lucid dream in the α-GPC condition versus four inexperienced lucid dreamers in the placebo plus baseline condition. Due to the uneven distribution of lucid dreams among the two groups and three conditions, it is hard to say whether differences in scores can be interpreted as an effect of α-GPC. Due to the low number of lucid dreams and the limited sample size of nine advanced lucid dreamers, it remains unclear whether α-GPC enhances lucid dreaming only in experienced lucid dreamers. Further studies should examine the effect of cholinergic activation on lucid dreams in advanced lucid dreamers in a more balanced sample size. In our sample of inexperienced lucid dreamers, 7.7% of dreams were lucid. Estimates of spontaneous lucid dreams in inexperienced lucid dreamers range from 0.3 to 0.7% [30]. As stated by lucid dreaming researcher LaBerge [9], we can confirm that lucid dreaming is prone to the placebo effect.

We did not find any significant change in dream bizarreness. Deviating from results suggested by previous models [12], the cholinergic activation did not induce more bizarre elements. There was also no significant alteration of dream emotions. The data showed a slight increase in dreams that contain aggression (two dreams containing aggression in baseline, four in placebo and six in α-GPC), but not enough to interpret this as an effect. This is in line with other studies that found no alteration in dream content after cholinergic stimulation [21, 24]. The findings of these studies are in contrast to the hypothesis that PGO waves account for dream bizarreness. If subsequent studies with larger sample sizes show similar results, it would be necessary to reconsider the role of PGO waves in dream bizarreness and imagery. Dream recall was high (75 out of 120 nights), but we could not find an increase in the α-GPC condition. As participants were selected for high dream recall, we cannot exclude that α-GPC has an effect on dream recall in people with low general dream recall.

We were able to demonstrate a significant difference in sleep quality from baseline to the double-blinded nights. Sleep quality was worse in the first night of the experiment, which confirmed the well-known first-night effect on sleep laboratory recordings [1]. Despite the fact that we did not observe an increase of lucidity on the first night, it might be possible that the decrease in sleep quality actually increases the likelihood of lucid dreams. This is an observation also remarked in [28], and might be due to higher alertness during the first night. In our study, participants woke up more often in the baseline night. This frequent shift between two conscious states might lead to wake-induced lucid dreams (WILD), where the dreamer transitions from wakefulness to a dream state while remaining conscious. Further research could focus on whether the 'first-night effect' is beneficial for the induction of lucid dreams.

A major shortcoming of the study was that we conducted it as a home study. No additional means were exerted to ensure that participants followed the protocol at home. Therefore, we relied on the participant's honesty for a correct execution. It is also not possible to report whether α-GPC had any effect on REM sleep variables. Most studies on cholinergic stimulation find an increase in REM sleep time after cholinergic stimulation [7, 22, 24]. We suspect that α-GPC had similar effects. It is known that lucid dreaming correlates with increased REM density [11]. One study found a decrease in REM density after agonist stimulation of acetylcholine [7] and we do not know how α-GPC affected this particular parameter. This should be further investigated using polysomnographic recordings during the experimental nights. It might then also be possible to explore whether the dream reports stem from REM or NREM sleep. One additional shortcoming is that we did not ask the participants whether they themselves judged their dream to be lucid. We decided upon this to avoid a subjective bias and to prevent confounding by different personal definitions of lucid dreaming. We therefore cannot say whether subjective lucidity was increased by α-GPC.

To summarize, our results illustrate that cholinergic activation via α-GPC did not alter the dream experience significantly nor did it facilitate the induction of lucid dreams. We also found no alterations of dream emotions or bizarreness, which is in accordance with previous research. This is the second double-blind study known to the authors examining the effect of cholinergic stimulation to induce lucid dreams. Our findings are in contrast to [9], who found a strong effect for lucid dream induction using cholinergic stimulation. It is important to note here that the other study used an acetylcholinesterase inhibitor, whereas we used an acetylcholine precursor, and their psychoactive effects might differ. It is therefore necessary to further research whether and what role the cholinergic system plays in lucid dreaming.

Practical conclusion

- **α-GPC has no effect on dream experience.**
- **α-GPC did not cause more lucid dreams in this study.**
- **No significant effect of α-GPC on subjective sleep experience was observed.**

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Compliance with ethical guidelines

Conflict of interest. S. Kern, K. Appel, M. Schredl and G. Pipa declare that they have no competing interests.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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XVIII – 3.9.1 Phänomenologie luzider Träume und Induktionstechniken

Kristoffer Appel, Simon Kern, Osnabrück

Zusammenfassung

Als „luzider Traum“ oder auch „Klartraum“ wird ein Traum bezeichnet, in dem sich der Träumende bewusst darüber ist, dass er gerade träumt. Dies kann dem Träumenden ermöglichen, den Traum bewusst zu beeinflussen oder zu verändern. Die Mehrheit der Menschen hat in ihrem Leben schon mindestens einen luziden Traum erlebt, etwa jeder Fünfte erlebt diese monatlich oder öfter. Es gibt eine Vielzahl von Anwendungen für Klarträume. Der Träumende kann sich vergnügen, z. B. fliegen oder eigene Traumwelten erschaffen. Es ist möglich, den Traum spirituell zu erkunden, ihn als Quelle der Kreativität zu nutzen, Probleme zu lösen oder motorische Fähigkeiten zu trainieren. Im therapeutischen Kontext wird luzides Träumen verwendet, um Albträume zu behandeln. Es gibt verschiedene Methoden, luzides Träumen zu erlernen. Diese Methoden verwenden unterschiedliche Ansatzpunkte, z. B. kognitives Training oder den Einsatz technischer Geräte.

Einführung

Bereits Aristoteles sinnierte: „Oft nämlich sagt einem, wenn man schläft, etwas in seinem Bewusstsein: Was dir da erscheint, ist nur ein Traum“ (Dönt 1997). Der zugehörige Fachbegriff „Luzider Traum“ (synonym: „Klartraum“) wurde Anfang des 20. Jahrhunderts vom niederländischen Psychologen Frederik van Eeden erstmals wissenschaftlich definiert: „Ein luzider Traum ist ein Traum, in dem der Träumer weiß, dass er träumt.“ (van Eeden 1913). Diese Definition wird auch heute noch in der Wissenschaft verwendet, wobei es auch Erweiterungen um zusätzliche Kriterien gibt. Der deutsche Klartraumforscher Paul Tholey (1937-1998) etwa verlangte die Einbeziehung weiterer Bewusstseinskomponenten, z. B. zu wissen, dass über die Traumhandlung frei entschieden werden kann, oder den Zugriff auf Gedächtnisinhalte des Wachlebens, welcher insbesondere für die vorher gefassten Aktionen, die im Klartraum durchgeführt werden sollen, wichtig ist (Tholey 1988).

Wissenschaftlicher Nachweis

Lange Zeit wurden luzide Träume in den Bereich der Parapsychologie eingeordnet, da ihre Existenz für schwer beweisbar gehalten wurde. Erst Ende der 1970er und Anfang der 1980er Jahre wurde luzides Träumen durch die voneinander unabhängig durchgeführten Pionierarbeiten von Keith Hearne (1978) in Liverpool und Stephen LaBerge (1980a) in Stanford wissenschaftlich nachgewiesen und ist seitdem fester Bestandteil der Traumforschung. Dazu verwendeten die beiden Forscher einen Trick, der hier kurz skizziert werden soll. Die meisten „klassischen“ Träume und auch luziden Träume treten im REM-Schlaf auf, auch wenn es Einzelfallberichte über NREM-Klarträume gibt (Stumbrys und Erlacher 2012). Fast alle Muskeln sind während des REM-Schlafes jedoch gelähmt, da die efferenten Muskelbefehle aktiv von neuronalen Strukturen im Hirnstamm unterdrückt werden (Hobson et al. 2000). Es ist daher nicht möglich, beispielsweise mittels Handgesten oder Sprache zu erkennen zu geben, dass man sich seines Traumzustandes bewusst ist. Ausgenommen von der Muskelhemmung ist jedoch die Augenmuskulatur. Diese Tatsache machten sich LaBerge und Hearne zunutze. Sobald eine luzide träumende Versuchsperson erkannte, dass sie träumte, bewegte sie die Augen willentlich mehrmals in einem zuvor abgesprochenen Bewegungsmuster nach links und nach rechts. Diese Augenbewegungen lassen sich als eindeutiges Muster in der polysomnografischen Aufzeichnung des Schlafes detektieren und klar von normalen schnellen Augenbewegungen (REMs) abgrenzen. Auch heutzutage wird diese Methode dazu benutzt, um in wissenschaftlichen Studien den Beginn eines Klartraums zu markieren, und um z. B. in Experimenten bestimmte Zeitpunkte im Traum zu markieren.

Obwohl sich der Träumer gemäß der oben genannten Definition über die Tatsache bewusst ist, dass sein Erleben rein illusorischer Natur ist, verliert der Traum nicht vollständig seinen kreativ-spontanen Charakter. In der Tat kann mittels standardisierter Fragebögen erfasst werden, inwieweit der Träumende den Klartraum steuern und beeinflussen kann und in welchem Grad die Klarheit in verschiedenen Bewusstseinskategorien ausgeprägt ist (vgl. z. B. die LuCiD scale von Voss et al. 2013).

Anwendungsgebiete

In Fachkreisen und unter interessierten Laien gibt es zahlreiche Ideen darüber, zu welchen Zwecken der Klartraumzustand genutzt werden kann. Eine kurze Beschreibung verschiedener Nutzungsmöglichkeiten soll dem Leser die Mannigfaltigkeit dieses Phänomens aufzeigen.

Einer Online-Studie von Schädlich und Erlacher (2012) zufolge, bei der über 300 Klarträumer zu ihren Klartraumzielen befragt wurden, ist die populärste Anwendung von Klarträumen „Spaß haben" (81,4%). So vielfältig die eigene Phantasie, so vielseitig auch die Dinge, die diesbezüglich im Klartraum erlebt werden können. Häufige Themen des Klartraums sind Fliegen, Ausprobieren von Extremsportarten, eine berühmte Persönlichkeit treffen, Entdeckungsreisen in ferne Länder unternehmen, sich in ein Tier verwandeln, sexuelle Aktivitäten oder auch Zeitreisen. Dabei ist der Klartraum, vergleichbar mit gewöhnlichen Träumen, hinsichtlich des sensorischen Erlebens erstaunlich realistisch.

Doch auch abseits des Vergnügens bietet der luzide Traum dem „Oneironauten", wie Klarträumer auch bezeichnet werden, viele Möglichkeiten, zum Beispiel im Bereich der Selbsterfahrung. Einige geübte Klarträumer nutzen diese Möglichkeit, um sich mit Traumfiguren über Lösungsmöglichkeiten für persönliche Probleme auszutauschen. Ebenso ist es möglich, sich mit bereits verstorbenen Personen zu treffen, um beispielsweise Trauer zu verarbeiten. Ganz in der Tradition der Freudschen Traumanalyse benutzen manche Menschen ihre Klartraumfähigkeit dazu, mehr über ihr eigenes Unterbewusstsein herauszufinden. Künstler nutzen die luzide Traumwelt um Inspirationen für neue Gemälde zu erhalten. Ebenso gibt es Berichte von Komponisten, die erfolgreich im Traum komponieren (Barrett 2001). Manche Klarträumer nutzen luzide Träume zu spirituellen Zwecken, etwa im Rahmen der buddhistischen Tradition des Traumyogas.

Auch aus psychologisch-medizinischer Sicht besitzen Klarträume ein großes Potential. So ist es möglich, sie erfolgreich zur Behandlung von Albträumen einzusetzen (Spoormaker et al. 2006). Hierbei wird dem Patienten eine Technik zur Klartrauminduktion beigebracht. Nun ist es das Ziel, während des Albtraums den Traumzustand zu erkennen. Durch die gewonnene Einsicht ist es dem Träumer anschließend möglich, den Traum zu verändern oder absichtlich aufzuwachen. Diese Technik zeigt gute Erfolge, insbesondere bei der Behandlung von wiederkehrenden Albträumen (Holzinger 2014).

Des Weiteren können luzide Träume dazu verwendet werden, motorische Fähigkeiten zu trainieren. Studien haben gezeigt, dass Bewegungen im luziden Traum den Bewegungen der echten Welt bezüglich ihrer Aktivierung des Gehirns ähneln (Dresler et al. 2011, Erlacher und Schredl 2008) Dadurch wird es möglich, Bewegungsabläufe im Traum für das Wachleben zu üben. Der luzide Traum bietet eine hervorragende Simulation der Realität mit einigen Vorteilen: Zum Beispiel kann der Träumer die Zeit verlangsamen und feine Bewegungsabläufe genau einstudieren oder riskante Bewegungen mit Verletzungspotenzial beliebig oft gefahrlos trainieren. Eine Umfrage unter 840 deutschen Sportlern hat ergeben, dass knapp 10% der befragten Leistungssportler die Möglichkeit des motorischen Lernens im Klartraum regelmäßig nutzen, um ihre Leistung im Wachleben zu steigern (Erlacher et al. 2012).

In wissenschaftlichen Experimenten kann der Klartraum als nützliches Werkzeug eingesetzt werden. So war es beispielsweise möglich zu bestätigen, dass eine Zählsequenz im Traum in etwa dieselbe Zeit benötigt wie im Wachleben (LaBerge und Rheingold 1990). Auch können die Unterschiede in der Hirnaktivität von gewöhnlichen zu Klarträumen Hinweise auf neuronale Grundlagen des Bewusstseins liefern (Hobson 2009).

Verbreitung in der Bevölkerung, Einflussfaktoren

Bezüglich der Frage, wie viele Menschen schon mindestens einen Klartraum in ihrem Leben erlebt haben, gibt es widersprüchliche Umfrageergebnisse, die unter anderem auf verschiedene Vorgehensweisen bei der Stichprobenbildung und der gewählten Definition des Begriffes „Klartraum" beruhen. Es wird angenommen, dass etwa die Hälfte der Bevölkerung schon einmal einen luziden Traum erlebt hat und ca. 20% der Bevölkerung laut eigener Aussage mehr als einmal pro Monat klarträumen (Schredl und Erlacher 2011, repäsentative Stichprobe). Voss et al (2012) fanden, dass luzide Träume insbesondere unter Kindern und Jugendlichen bis zum Alter von etwa 16 Jahren weit verbreitet sind, und anschließend die Häufigkeit stark abnimmt. Geschlechtsspezifische Unterschiede in der Klartraumhäufigkeit konnten in groß angelegten Studien nicht gefunden werden (Watson 2001). Jedoch scheinen die Fähigkeit der Traumerinnerung und die Klartraumhäufigkeit zu korrelieren (Schredl und Erlacher 2004). Meditation scheint ebenfalls ein Klarträume begünstigender Faktor zu sein, möglicherweise, weil in beiden Fällen ähnliche Hirnareale aktiviert werden (Gackenbach 1978, Gackenbach et al. 1986, Hunt 1991).

Methoden der Klartrauminduktion

Auch wenn es einige Menschen gibt, die spontan regelmäßig luzide Träume erleben, ist es für die meisten Personen nicht leicht, im Traum zu erkennen, dass sie träumen. Es gibt viele verschiedene Ansätze und Hilfsmittel, die verwendet werden können, um die Wahrscheinlichkeit für Klarträume zu erhöhen. Trotzdem kann keine der bislang bekannten Methoden zuverlässig einen Klartraum provozieren. Zudem ist es von Person zu Person unterschiedlich, welche Technik gut funktioniert und welche nicht (Stubrys et al. 2012).

Die Methoden zur Induktion luzider Träume lassen sich grob unterteilen in a) kognitive Methoden, b) externe Stimulation, c) sonstige. Die Methoden stehen jeweils für sich, können teilweise jedoch auch kombiniert werden. Zudem existieren Varianten der im Folgenden vorgestellten Techniken.

Kognitive Induktionsmethoden

Bei den kognitiven Methoden werden Bewusstseins- oder Konzentrationsübungen eingesetzt, um die Klartraumwahrscheinlichkeit zu erhöhen. Dabei gibt es die sogenannten DILD („*Dream-Initiated Lucid Dream*", wörtlich: Traum-induzierter Klartraum)- und die WILD („*Wake-Initiated Lucid Dream*", wörtlich: Wach-induzierter Klartraum)-Techniken. Erstere zielen darauf ab, den Traumzustand erst im Traum zu erkennen, wofür bestimmte kognitive Übungen tagsüber, abends oder nachts als Hilfestellung dienen. Bei den WILD-Techniken wird versucht, das Bewusstsein beim Einschlafprozess des Körpers aufrechtzuerhalten und abzuwarten, bis sich eine Traumszene entwickelt (LaBerge und Rheingold 1990).

Die Grundideen zweier bekannter DILD-Techniken sollen hier kurz zur Illustration dargestellt werden. Eine DILD-Variante, die MILD („*Mnemonic-Initiated Lucid Dream*", wörtlich: Gedächtnisinduzierter Klartraum)-Methode, besteht darin, dass sich der Klartraum-Übende während des Einschlafens gedanklich in einen Traum hineinversetzt und visualisiert, wie er sich seines Traumzustandes bewusst wird. Gleichzeitig fokussiert sich der „Oneironaut" auf seine Intention sich zu erinnern, dass er träumt, indem er den Satz „Das nächste Mal, wenn ich träume, will ich daran denken zu erkennen, dass ich träume." mantraartig wiederholt (LaBerge 1980b).

Eine weitere Methode der DILD-Kategorie ist das kritische Reflektieren oder Realitätstesten (Tholey 1983). Dabei fragt sich der Klarträumer tagsüber sehr häufig, ob er sich gerade in einem Traum befindet, oder nicht, und sucht die Umgebung nach Inkongruenzen ab. Die Idee dabei ist, dass dieses Verhalten nach einiger Zeit auch in den Traum übergeht, und so zu Klarheit führt. Um mit großer Sicherheit feststellen zu können, ob es sich aktuell um Traum oder Wirklichkeit handelt, gibt es eine ganze Reihe von Tests, die im Wachleben fehlschlagen, im Traum jedoch oftmals funktionieren: etwa das Ausatmen durch die zugehaltene Nase, der Versuch zu schweben, oder das Bohren von Löchern mit dem Finger durch feste Materialien wie Tisch oder Wand. Ebenso gibt es Tests, die im Traum fehlschlagen, aber im Wachleben normalerweise funktionieren: etwa das wiederholte Lesen eines Textes (der Text verändert sich im Traum für gewöhnlich) oder die Nutzung von technischen Geräten (die im Traum oftmals fehlerhaft bzw. funktionsuntüchtig sind).

Klartrauminduktion mittels externer Stimulation

Bei Techniken, die auf externe Stimulation setzen, werden Geräte genutzt, die den Trauminhalt so beeinflussen, dass sich der Träumende aufgrund dieser Traumänderung seines Zustandes bewusst wird. Klassischerweise wird dies mit Hilfe von visuellen (LaBerge 1988, Paul et al. 2014), auditiven (LaBerge 1981) oder haptischen Stimuli (Reis 1989) versucht. Hierbei wird üblicherweise abgewartet, bis sich der Schlafende in einer REM-Schlafphase befindet, da dort die Wahrscheinlichkeit für einen Traum am höchsten ist. Dann wird ein Stimulus abgespielt, beispielsweise eine Sprachnachricht „[Name], du träumst!". Dieser Stimulus darf nicht zu intensiv (zu laut, zu hell etc.) sein, da sonst die Gefahr besteht, den Träumer aufzuwecken. Er darf jedoch auch nicht zu schwach sein, da er sonst möglicherweise nicht in die Traumwelt inkorporiert wird. Heutzutage gibt es eine Reihe kommerzieller Geräte und Schlafbrillen verschiedener Komplexität, die die nötigen Stimuli generieren und auch teilweise automatisch REM-Schlaf detektieren können.

Ebenso gibt es seit kurzem vielversprechende Versuche, mittels externer Hirnstimulation einen luziden Traum auszulösen, indem ein leichter Stromfluss durch die bei Klarträumen aktiveren Hirnareale appliziert wird (Stumbrys et al. 2013, und Voss et al. 2014).

Sonstige Induktionsmethoden

Das Führen eines Traumtagebuchs wird häufig als Grundlage für das Erlernen des Klarträumens vorgeschlagen, da dieses die Traumerinnerung generell erhöht (Schredl 2002). Ebenso soll dies zum einen dazu dienen, regelmäßig auftretende Trauminhalte erkennen zu können und als Luziditätstrigger zu nutzen: Wer regelmäßig von Schiffen träumt, fragt sich das nächste Mal, wenn er sich auf einem Boot befindet, ob dies vielleicht gerade ein Traum ist. Zum anderen lässt sich mittels eines Traumtagebuchs die Traumerinnerungsfähigkeit trainieren, was die Klartraumwahrscheinlichkeit allgemein erhöht (s.o.). Außerdem wird vorgeschlagen, die gewählte Induktionstechnik nachts durchzuführen, nachdem der Klartraum-Übende bereits etwa sechs Stunden geschlafen hat (sog. WBTB („*Wake-Back-To-Bed*", wörtlich: Aufwachen und wieder schlafen gehen)-Methode (Erlacher 2010). Der Hintergrund ist, dass der meiste REM-Schlaf früh morgens stattfindet und REM-Schlafphasen zu dieser Zeit besonders lang ssein können. Insbesondere kognitive Methoden profitieren von der dann oft kurzen Latenz bis zur nächsten REM-Schlafphase. Zudem sind die erlebten Klarträume früh morgens länger. Wenig bekannt ist über den Einfluss von ZNS-aktiven Medikamenten oder Substanzen auf das Klarträumen. LaBerge (2004) untersuchte in einer doppelverblindeten placebokontrollierten Pilot-Studie Donepezil, einen Acetylcholinesteraseinhibitor, und fand eine klartrauminduzierende Wirkung. Weitere Forschung ist jedoch nötig, um diese vorläufigen Ergebnisse abzusichern und Nebenwirkungen dieses Ansatzes abzuklären.

Bedauerlicherweise konnte trotz nunmehr über 30-jähriger intensiver Forschung im Bereich der Klartrauminduktion noch keine Methodik gefunden werden, um Klarträume zuverlässig bei jedermann und in einer beliebigen Nacht hervorzurufen. Junge Forschungsansätze, wie beispielsweise externe Stimulation oder ZNS-aktive Medikamente, erscheinen vor diesem Hintergrund vielversprechend, wenngleich deren Potential und deren Nebenwirkungen noch näherer Untersuchung bedürfen.

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It was just a dream...

Exploiting our ability to lucid dream could help erase real-life traumas, finds sleep researcher Michelle Carr

I WAS scrambling away from a monstrous dark figure when I started to have the sneaking feeling that I had been here before, running from this man. I realised that I was in a bad dream, one I'd had several times recently. Only this time, I stopped mid-stride and turned around to face my attacker. "Who are you?" I screamed. "What do you want?"

I was in a lucid dream, a state of consciousness in between waking and sleeping, in which people are in a dream world but remain aware and able to control their actions. I normally use the dreams for fun – flying, say, or exploring – but sometimes I become lucid within bad dreams or nightmares. At first, I would simply wake myself up whenever this happened, but over time I realised I could change the dreams from within.

Psychologists have long been interested in using dreams to rewrite nightmares or help people overcome persistent fears. But the ability to use lucid dreams has been limited because they are difficult to trigger, and, as with all dreams, memories of them evaporate so quickly upon waking.

That could be about to change, however, as more consistent ways to induce these dreams are uncovered. It is even becoming possible to communicate with the dreamer and record what's happening within dreams. These advances raise the tantalising prospect of unlocking this unique state of mind to create therapies for people with nightmares, anxiety and other conditions. We may soon be able to treat people within their dreams.

I learned to lucid dream several years ago, initially by accident. When I went to bed or as I woke up, I would often get caught in a scary half-awake state where I was alert but unable to move or speak – something called sleep paralysis. To get out of this, I found it easier to fall back asleep than force myself awake. Since I maintained some awareness while drifting off, this often resulted in a lucid dream. It turns out that what I was doing isn't so different from techniques used to induce lucid dreams deliberately (see "Lucid dreaming for beginners", page 34).

"It's a step toward conveying the content of dreams to the outside world – in real time"

People have been experiencing and writing about lucid dreams for thousands of years. Now with the advent of brain imaging, we have been able to learn much more about what goes on during them. Comparing the brain scans of people who were awake, asleep or in lucid dreams revealed what many had long suspected: lucid dreaming is a state in between REM sleep – the phase in which most of our dreams occur – and waking. Unlike regular dreams, lucid dreams involve brain activity in areas associated with working memory and regions thought to play a role in higher cognitive functions, such as planning and behavioural control.

Dreams have long been a focus of psychological therapy, for many reasons. Recurring nightmares can be symptomatic of anxiety, post-traumatic stress disorder and other conditions. Discussing dreams during therapy can provide an insulated way for people to explore traumatic subjects, and attempting to rewrite them can help overcome phobias or grief. For this, patients are encouraged to use a strategy known as imagery rehearsal therapy, in which they rehearse and then try to play out challenging scenarios within their dreams, or change the course of nightmares.

The first hints that lucid dreaming could enhance or even expand on the therapeutic use of dreams came in the past decade, when psychologists found that people who are capable of lucid dreaming may be more resilient to trauma and better able to avoid nightmares. Then, in 2015, Brigitte Holzinger and colleagues at the Institute for Consciousness and Dream Research in Vienna, Austria, showed that lucid dreaming makes therapy for nightmares more effective.

When Holzinger asked people undergoing a variation of imagery rehearsal therapy to try lucid dreaming, those who were successful stopped fearing sleep and began to enjoy their dreaming lives. One person even figured out how, within a nightmare, to go back to a point before a threat had started and continue the dream in another direction. People also found that lucid dreams brought a sense of power and control that translated into waking life, a welcome change from the helplessness often experienced in nightmares. This outcome is the ideal for this kind of therapy: to enable ›

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people to confront the source of their trauma or anxiety by directing or changing the course of their dreams.

But the utility of strategies like these is limited by how well people can learn to lucid dream. Even with the best existing methods, results are spotty. Now, though, researchers have found a way to induce such dreams.

In 2014, Ursula Voss and her colleagues at Goethe University Frankfurt in Germany discovered that a technique known as transcranial alternating current stimulation could spur lucidity in dreams. It involves applying a low electrical current to the brain's frontal cortex during REM sleep, and it works about two-thirds of the time. "Stimulating the frontal area is like putting 'wake' activity into sleep," says Cloé Blanchette-Carrière at the Dream and Nightmare Laboratory in Montreal, Canada.

Blanchette-Carrière is interested in therapies that would trigger lucid dreams instead of relying on people teaching themselves to induce them. "We want to apply this to nightmare sufferers or PTSD patients, to make them able to modify or control their dreams,"she says. She already has promising results from a preliminary study.

The next hurdle in using lucid dreams as a treatment is to communicate with someone once they are asleep, to provide external support as they face a source of trauma, for instance. Many of us have experienced incorporating a noise from the waking world into a dream – a horn honking outside, or music playing on a nearby radio, for instance. But can we deliberately send messages into people's dreams?

To find out, Kristoffer Appel, a sleep and dream researcher at Osnabrück University in Germany, recruited experienced lucid dreamers and monitored their brain waves and eye movements as they slept. When in lucid dreams people are capable of moving their eyes deliberately, so Appel instructed his volunteers to let him know when they were lucid by looking left-right, left-right. Once he got the cue, he tried to send signals into their dreams using audio tones and flashing lights.

Hello in there

Of 10 volunteers, seven reported incorporating the sounds or lights into their dreams. The tone might become a noise from a ship, car or cellphone. Some people registered the flashing lights as the whole dream turning bright and dark; for others, it was the lightning in a thunderstorm, or a lamp that switched on and off. Those who noticed the noises or lights realised that they were messages from the waking world.

But Appel wanted to go further: he wanted to send more complex messages, and he wanted the dreamers to respond. So he asked these same volunteers to learn basic Morse code for numbers. The idea was to use a series of audio tones to send the dreamers simple arithmetic problems, like 3 + 5 or 7 - 2. The dreamers didn't know the numbers in advance, and were told to answer using Morse code eye signals. For instance, a "3" in Morse code is three short and two long dashes, so the subject would look three times to the left and two times to the right.

For Appel and the volunteers, it felt like

there was a lot at stake. Many people who can lucid dream have spent months, if not years, teaching themselves how. Although confident it would be possible to communicate from within their dreams, the volunteers feared they might let the side down by waking too soon or failing to find the signals. But it worked, at least for three of them: they not only got the signals, but gave the correct answers. One participant described how he looked around his dream for something that might convey signals from outside. He was in a bus terminal, and spotted a ticket machine. Soon, it began to beep. "I was thrilled to bits… I decoded the first message, confirmed the numbers, solved the math problem, and answered it back to the wak[ing] world: 4 + 4 = 8. I next walked along the street further, telling other pedestrians that I was solving tasks within a lucid dream."

Relying on eye movements limits how much information can be conveyed, however. So Remington Mallett, a researcher then at the University of Missouri–St Louis, decided to try using a brain-computer interface, a device that – as the name suggests – enables the brain to talk directly to an external device such as a computer. Mallett believed lucid dreamers

LUCID DREAMING FOR BEGINNERS

The simplest method to boost your chance of lucid dreaming is to perform "reality checks" during the day. As often as possible, stop to observe your environment and body, and ask yourself: "Is this a dream?" As this becomes a habit, it will be incorporated into your dreams. One night you will find yourself asking, "Is this a dream?" and realise, in fact, it is.

A more direct way is through the "Wake-Back-To-Bed" technique, which is exactly what it sounds like. Ideally, you should set an alarm about 2 hours before you normally wake up, which will put you at a phase in the sleep cycle when REM sleep is longer and more intense. When the alarm goes off, sit up and stay awake for about 20 minutes. During this time it can help to think or write about the most recent dream you remember, noting anything that could have clued you in to the fact you were dreaming. When you go back to sleep, you should soon enter a dream, and your recently awake and intent mind is likely to follow.

Finally, you can complement these effortful techniques with technology. While there are many apps and sleep masks that are supposed to induce lucid dreams via audio and visual signals, most of them simply run on a timer and send signals randomly while you sleep, so aren't that effective.

The most promising are two new devices, the Aurora Dreamband and the iBand+. Both are small headbands that use actual EEG, among other biosensors, to detect when you are in REM sleep and to trigger LED signals at this time to "wake" you up within your dream. What's more, both are paired with an app that tracks your sleep patterns and an alarm designed to wake you at the best point in the sleep cycle.

should be able to use it, since there is an overlap in the way the brain treats activities during lucid dreams and waking. When lucid dreamers imagine clenching a fist, for example, activity in the brain's motor cortex and even muscle twitches in the wrist of that hand can be detected.

To see whether controlling a brain-computer interface from inside a dream was possible, Mallett recruited two self-taught lucid dreamers to try a simple headset, the Emotiv Epoc. It maps the activity of the brain, and then uses these signals to direct different desired outcomes on the computer. So if you imagine moving the cursor on a screen, it moves. "You basically move virtual objects with your mind," says Mallett, like a "Jedi mind trick".

First, Mallett trained the volunteers – awake and lying down with their eyes closed – to move a block on a computer screen using only their minds. Once they reached 75 per cent accuracy, they were ready to try the task during sleep. When they became lucid, they let Mallett know with quick left-right eye movements, and then began the task. Mallett saw the signal from both volunteers, and then the block steadily moved forward on the screen.

One volunteer said that during the waking task, he was imagining a street fighter character moving the block forward. During the dream he did the same thing. So in his sleeping mind was him as the dreamer, and in the dreamer's mind was the mental image of a little ninja moving the block. "It's fairly meta," says Mallett. "You're imagining about imagining something. We're taking this mental cognitive task and observing it objectively." It's a first step toward being able to convey the content of dreams to the outside world, in real time.

"Imagine halting a recurring nightmare by choosing a different ending"

This approach could also help people learn how to control prosthetic limbs. Like moving blocks on the screen, a brain-computer interface can pick up activity in the motor cortex when you imagine moving your arm, sending the signals to the prosthesis. These devices have even been used to restore brain-controlled walking in people who have had a spinal cord injury.

People with lower limb paralysis who must learn to control an exoskeleton face an added barrier, in that the brain may forget how to send motor signals to their legs. In August, the Walk Again Project – an international collaboration led by Miguel Nicolelis at Duke University in Durham, North Carolina – helped people with partial paralysis regain some muscle control in their lower limbs. To do so, they first learned to use brain activity to control an avatar in virtual reality, getting it to walk around a field. This helped the brain relearn how to send motor signals, which meant that when people moved on to using a real exoskeleton they got the hang of controlling it more quickly. With lucid dreaming, people could exercise their mental muscles in their dream world every night, helping them eventually transition to controlling a real exoskeleton.

As well as the many therapeutic applications, looking into our lucid dreams could also enable us to harness our creativity. Many people find inspiration in their sleep. The melody for *Yesterday* came to Paul McCartney while he was dreaming, and Dmitri Mendeleev famously dreamed up the structure of the periodic table of elements. But as we know, when inspiration strikes in this way it is a race to jot it down once you wake up.

New gadgets, like the headset in Mallett's study, could eventually be used to help us record ideas from within lucid dreams. And Appel is developing a sleep mask that could record eye-movement Morse code for people to transfer messages. He is also experimenting with something more of us are familiar with: texting. "We are trying for dreamers to just follow the keys with their eyes and track the movements."

As techniques for inducing and communicating from within lucid dreams improve, the possibilities will only grow. For mental health professionals and those who study sleep disorders, the potential for psychological therapies is most inspiring. Imagine, after prolonged grief, getting to say the final goodbye you hadn't been able to. Imagine overcoming a persistent fear while receiving messages of support from the waking world, or halting a recurring nightmare by choosing a different ending. As Blanchette-Carrière says, "If people are able to control the dream, they will be empowered to modify their behaviour in real life." ■

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LIFE Niklas Hamburg

Synapsengeflimmer oder Psychohygiene – Wieso träumen wir?

Die Welt, in der wir leben, gehört dem Tag. Für einige gehört sie auch der Nacht, doch ganz egal, wann man schläft, es kommt der Moment, da müssen wir alle mal in die Federn kriechen und für ein paar Stunden die Augen schließen. Und dann ist es Zeit für uns, in eine andere Welt mit scheinbar unbegrenzten Möglichkeiten einzutauchen. Wir fangen an, zu träumen!

Ende des 19. Jahrhunderts beschäftigten sich Neurobiologen erstmals mit dem Thema Traumforschung. Aus dieser Zeit stammt auch die Erkenntnis, dass die Muskelspannung im Schlaf völlig nachlässt. Dass sich Menschen häufig nicht an ihre Träume erinnern können, fand wenig später Alfred Maury, Professor am Collège de France, heraus. Während des Schlafes weckt Maury – im Dienste der Wissenschaft, versteht sich – seine Patienten mehrmals unsanft.

Sigmund Freud: Grundlage der Traumdeutung

1899 erscheint das legendäre Werk „Die Traumdeutung" von Sigmund Freud. Damit legte er den Grundstein der modernen Traumdeutung. Zu seiner Zeit ging er aber noch von universellen Traumsymbolen aus, die bei jedem Mensch gleich wären, unabhängig von seinen individuellen Erfahrungen. Als einer der Ersten ging Freud später von der Deutung allgemeiner Symbole weg und setzte stattdessen die freie Assoziation als Methode ein, um Gedanken, Erinnerungen etc. der Person selbst zu dem Traum zu bekommen.

Daniel Wegner, ein amerikanischer Sozialpsychologe, führte dazu ein Experiment durch. Zwei Personengruppen und eine Kontrollgruppe wurden gebeten, sich eine ihnen bekannte Person vorzustellen. Danach sollten sie fünf Minuten lang ihren Gedanken freien Lauf lassen und sie aufschreiben. Die eine Gruppe wurde zuvor gebeten, sie gedanklich mit der Person, an die sie sich erinnerten, zu beschäftigen, die andere sollte genau dies vermeiden. Der Kontrollgruppe wurde es freigelassen. Am darauf folgenden Morgen sollten sich alle Versuchsteilnehmer daran erinnern, ob sie von der erwähnten Person geträumt hatten. Das Ergebnis war, dass Personen der Gruppe, die den Gedanken verdrängt hatten, sehr viel häufiger von der Person träumten als die Gruppe der Personen, die ihren Gedanken freien Lauf ließen. Wegner nennt dies den „dream rebound effect". Wir haben Dr. Hans-Günter Weeß gefragt, was er von der Freudschen Theorie hält:

„Im Schlaf ist unser Frontalhirn ausgeschaltet. Das ist vor allem für das Rationale zuständig. Hätten wir diesen Bereich im Gehirn nicht, würden wir einfach hemmungslos unseren Trieben nachgehen. Da die rationale Kontrolle nachts aus Kraft gesetzt ist, haben es unterdrückte Wünsche aus dem Unterbewusstsein leichter, an die Oberfläche zu kommen. Daher können wir unsere Träume auch als Hinweis darauf nehmen, was uns unterbewusst beschäftigt."

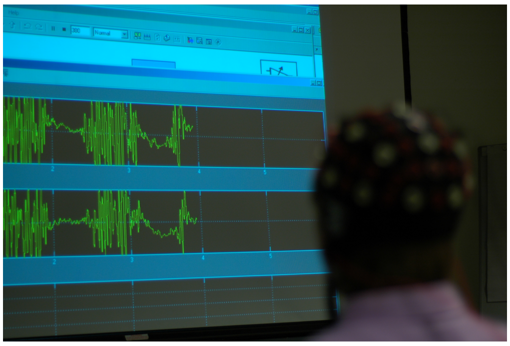
Im Jahr 1944 wird bekannt, dass Männer bis zu fünf Erektionen pro Nacht haben. Man nahm damals jedoch nicht an, dass es eine Verbindungen zu den Schlafphasen geben könnte. Die Erektionen dauern jeweils gut 25 Minuten – und entsprechen damit exakt dem Zyklus der REM-Phasen. Bestimmte erektionsfördernde, neuronale Aktivitäten werden dafür verantwortlich gemacht, unabhängig davon, ob der Trauminhalt sexueller Natur ist oder nicht. Die sprichwörtliche „Morgenlatte" ist meist die letzte dieser Erektionen.

Der französische Neurologe Michel Jouvet war 1959 bei der Entdecker jener REM-Schlafphasen beteiligt, womit die Traumforschung einen großen Schritt machte. Er verbindet die bisherigen Erkenntnisse mit eigenen Forschungen. Zwei Schlafzustände werden entdeckt: während der Slow-Wave-Phase fehlt die Muskelspannung im Körper, aber auch das Gehirn ist in dieser Zeit inaktiv. An Träume kann sich der Schlafende, sollte er jetzt geweckt werden, nicht erinnern. Anders ist es in der REM-Phase, von der Forscher bis heute ausgehen. Auch diese wiederholt sich drei bis vier Mal pro Nacht und es fehlt die Muskelspannung, jedoch ist das Gehirn genauso aktiv wie im Wachzustand. Wird der Schlafende während dieser Phase geweckt, kann er sich sehr wohl an seine Träume erinnern.

Die vier Schlafphasen

Heute ist man in der Schlafforschung etwas weiter. Allgemein anerkannt ist mittlerweile, dass es vier Schlafphasen gibt, die sich ständig wiederholen. Ein Zyklus dauert rund 90 Minuten, davon hat jeder Mensch fünf bis sieben pro Nacht. Ganz zu Beginn setzt die Einschlafphase ein. Die Muskeln lockern sich und der Atem wird gleichmäßiger. Daran schließt sich der leichte Schlaf an – Phase II. Jetzt kommt der Körper zur Ruhe, die Augen bewegen sich nur noch langsam. Die Phase III ist die Tiefschlafphase. Hier schaltet das Gehirn auf Sparflamme und der Körper erreicht maximale

Entspannung. *„In dieser Phase bleibt die Muskulatur noch leicht gespannt. Wer zum Schlafwandeln neigt, tut es hier“*, sagt Dr. Brigitte Holzinger vom Institut für Bewusstseins- und Traumforschung in Wien. Diese Schlafphase ist für die körperliche Erholung wichtig.



Brainwaves“ by delta_avi_delta (CC BY-SA 2.0) via Flickr

In der vierten Phase des Schlafs steigt die Gehirnaktivität wieder an. Schnelle Augenbewegungen (englisch: ‚Rapid Eye Movement‘) setzen ein, deswegen wird diese Phase auch REM-Phase genannt.

Die Scanning-Hypothese bezeichnet die Vorstellung, dass die Augenbewegungen in der REM-Phase mit den Blickbewegungen im Traum übereinstimmen.

Schon 1892 folgerte der amerikanische Psychologe George Trumbull Ladd dies aus entsprechenden Experimenten. Dass es einen Zusammenhang gibt, gilt heute als sicher, es bleibt allerdings unklar, wie stark die Bindung ist. Es wird zwar in allen Phasen geträumt, in dieser jedoch besonders intensiv. Wie bereits erwähnt, gibt es hier auch ein hohes Erinnerungsvermögen. Säuglinge haben während des Schlafs einen besonders hohen Anteil an REM-Phasen, der bis zum etwa achten Lebensjahr von anfänglich neun auf drei Stunden reduziert wird.

Eine Theorie beinhaltet, dass Träume wichtig sind für die Gehirnentwicklung und -reifung. Ist der Schlaf dauerhaft gestört, sodass es nicht zur wichtigen vierten Schlafphase kommt, kann das ernsthafte körperliche und seelische Störungen hervorrufen.

Bloß sinnloses Synapsengeflimmer?

1960 äußert sich der amerikanische Psychiater Allan Hobson kritisch über die starke Bedeutsamkeit, die Menschen den Träumen zuweisen. Sinnloses Synapsengeflimmer sei es, ohne jede Funktion. Später widerruft er seine These und baut ein anderes Modell auf. Dabei stellt er Träume nun als Wirklichkeitssimulation dar. Nachts sei Spielzeit für das Gehirn, es könne Sachen tun, die tagsüber unmöglich sind und Dinge wie Motorik, Wahrnehmung und Triebe für das Wachleben trainieren.

Manchmal sind die Begebenheiten, die wir im Traum wahrnehmen, unlogisch. Das stört uns jedoch nicht, denn die entsprechenden Neuronen im Gehirn, die für das kritische Bewusstsein zuständig sind, ruhen während dieser Zeit und sind somit ausgeschaltet.

Einige Forscher und auch viele Menschen gehen heute nach einigen Entwicklungsschritten wieder davon aus, dass einem die Träume etwas mitteilen wollen. Vielleicht sind es keine Götter oder Dämonen, sondern das Unterbewusstsein. Auch Psychologen sind sich sicher, dass man aus seinen Träumen etwas über sich, über eigene Stärken und Schwächen lernen kann. *„Es geht nicht um die Bilder an sich, sondern um die Grundmuster“*, erklärt Prof. Dr. Michael Schredl vom Zentralinstitut für Seelische Gesundheit in Mannheim.

Verschieden häufige Träume bei Männern und Frauen

In dem 2013 erschienenen Artikel „Geschlechtsunterschiede im Träumen“ erklärt der Forscher, dass wissenschaftliche Studien belegen, welche Unterschiede es zwischen den Träumen von Männern und Frauen gibt. Bei Männern sind die vorherrschenden Themen Sexualität, körperliche Aggression und Waffen. Eine von Schredl durchgeführte Studie aus dem Jahr 2004 zeigt, dass außerdem Geld finden und übernatürliche Kräfte haben häufige Themen in Männerträumen sind.

In Bezug auf die Häufigkeit von Träumen sexueller Natur bei Männern zeigte sich, dass es keinen Zusammenhang gibt zur Häufigkeit sexueller Handlungen, sehr wohl aber zur Häufigkeit sexueller Fantasien am Tage. Forscher gehen davon aus, dass die Tatsache, dass Geld häufig vorkommt, damit zusammen hängt, dass Männer häufiger mit der Aufgabe des Versorgers der Familie betraut sind. Sie denken tagsüber oft darüber nach und daher spielt das Thema auch nachts eine große Rolle. Die Annahme, dass Träume das Wachleben wiederspiegeln, nennt man in der Fachsprache Kontinuitätshypothese.

Frauen träumen häufig davon, durch Prüfungen zu fallen, Teil des anderen Geschlechts zu sein oder davon, dass eine lebende Person tot ist. Am häufigsten träumen sie laut einer Studie davon, verfolgt zu werden. Generell sind Frauen häufiger von Albträumen betroffen, oft handeln diese Träume von sexueller Belästigung oder vom Tod einen ihnen sehr nahe stehenden Person. Haben Männer Albträume, verlieren sie im Traum oft ihren Job, auch die Themen körperliche Aggression und Krieg spielen eine große Rolle. Allgemein handeln Albträumen in den meisten Fälle davon, zu fallen, verfolgt zu werden, gelähmt zu sein oder zu spät zu kommen. Das zeigte eine Studie Michael Schredls aus dem Jahr 2010.

Ein weiterer Unterschied zwischen Männer und Frauen ist, dass Frauen ihren Träumen eine größere Bedeutung zuweisen. Sie berichten eine positivere Einstellung zu Träumen, erzählen Träume häufiger anderen Personen und haben ein größeres Interesse an Trauminterpretationen. Dabei handele es sich laut Schredl aber keineswegs um biologische Unterschiede. Vielmehr sei dies ein gelerntes Verhalten, die Sozialisierung spiele eine große Rolle: Kinder lernten demnach ihre Einstellung gegenüber Träumen innerhalb der Familie, der Peergroup (also von Gleichaltrigen oder Gleichgesinnten) und über die Medien.

Bezüglich des Geschlechts der in Träumen auftauchenden Personen gibt es einen weiteren signifikanten Unterschied. Eine Studie zeigte: konnten Männer die Person in ihrem Traum identifizieren, so war sie in 67 Prozent der Fälle männlich. Bei Frauen halten sich Anteil der weiblichen und der männlichen Personen etwa die Waage. Dazu passt die Auswertung von Studien, die Michael Schredl und sein Team durchführten. Es zeigte sich, dass das häufigere Auftreten von männlichen Personen in den Träumen von Männern schlicht und ergreifend damit zu tun hat, dass sie auch im Wachzustand mehr Zeit mit Männern verbringen. Bei Frauen hingegen ist auch tagsüber das Verhältnis ausgeglichener.

Interessant ist auch, dass sich dieser Unterschied aufhebt, sobald man nicht mehr Singles befragt. Studierende, die in einer festen Beziehung sind, zeigen diesen Unterschied nicht. Bei ihnen tritt in 20 Prozent der Träume der Partner oder die Partnerin auf.

Der REM-Schlaf scheint entscheidend für die Stimmung am nächsten Tag zu sein. Ein zu hoher Anteil dieser Phase verursache daher eine Art Mini-Depression. Schlafentzug unter medizinischer Aufsicht kann dagegen bei Depressionen helfen und die Stimmung – wenn auch nur kurzfristig – aufhellen.

„Während des REM-Schlafs gibt es eine cholinerge (= auf Acetylcholin reagierend) Überaktivität. Diese ist auf ein Ungleichgewicht im amingerg-cholinergen Transmittersystem. Dieselben Auffälligkeiten treten auch bei einer Depression auf. Mehr REM-Schlaf führt also zu höherer cholinerger Aktivität und macht somit lustlos, antriebslos und wirkt leistungshemmend – die sogenannte ‚Mini-Depression.'"

Unterschiede in der Gehirnaktivität

Wenn das Gehirn in der REM-Phase wieder aktiv wird und plant, sich zu bewegen, benutzen wir automatisch auch den Motorcortex. Damit wir uns aber nicht verletzen, hat die Natur eine kleine Änderung eingebaut, die uns nachts zu Gute kommt: Die Übertragung zum Muskel wird im Hirnstamm blockiert.

Aber es gibt noch zwei weitere Unterschiede: Für die Verarbeitung von Emotionen ist die Amygdala zuständig. Sie ist während des Träumens aktiver als im Wachzustand.

Ganz anders der präfrontale Kortex. Dieser Bereich des Gehirns, der vor allem für das planerische und geradlinige Denken und Handel zuständig ist, ist nachts weniger aktiv als tagsüber. Einige Forscher gehen davon aus, dass Träume deswegen oft seltsam sind.

Der Grund, weswegen man sich häufig nicht an seine Träume erinnern kann, ist, dass im Schlaf andere Hirnzentren aktiv sind als tagsüber. Beim Aufwachen wird umgeschaltet – und dabei gehen Informationen verloren.

Was hilft gegen Albträume?

So schön Träumen manchmal sein können, so mancher hat mit Albträumen zu kämpfen. Albträume können belastend sein, wenn sie mehrmals pro Woche auftreten. Ausgelöst werden sie häufig durch belastende Erlebnisse im Alltag. Der Grund dafür ist, dass im Traum Erlebtes aufgearbeitet und nach Lösungen gesucht wird. Eine Lösung könnte für Betroffene die Imagery-Rehearsal-Therapie (IRT): Diese verlangt, dass man sich mit seinen Träumen konfrontiert. Zuerst sollte man anfangen, ein Traumtagebuch zu führen. Darin trägt man seine Träume ein, ein oder mehrere Stichwörter reichen meist, um sich hinterher besser erinnern zu können. Wichtig ist allerdings, es so schnell wie möglich nach dem Aufwachen aufzuschreiben und sich dabei so wenig wie möglich zu bewegen. Die Bewegung beschleunigt den oben beschriebenen Prozess des Umschaltens im Gehirn vom Schlaf- zum Wachmodus.

Als nächstes stellt man sich die angstauslösende Situation vor. Der Trick: man denkt sich ein positives Ende aus, das einem die Angst nimmt und die Situation löst. Und jetzt ist Geduld gefragt. Bis dieser neue Ausgang des Traumes sich so eingeprägt hat, dass es auch ins Unterbewusstsein vordringt, kann es schon mal zwei Wochen dauern. Dann aber sollten die schlimmen Träume nachlassen. Übung macht auch hier den Meister.

Was sind Klarträume?

Eine weitere Möglichkeit stellt das sogenannte luzide Träumen dar. Auch für Menschen, die nicht unter Albträumen leiden, stellt diese Methode einen Weg dar, die nächtlichen Gedankentouren fantastischer zu gestaltet. Wenn man einen solchen Klartraum hat, ist man sich bewusst, dass man gerade träumt. Das ist die Voraussetzung dafür, dass man die Kontrolle über seinen Traum ergreifen kann. Und genau darum geht es auch. Denn wenn man aktiv an seiner Traumgestaltung teilhaben kann, dann wird man es auch zu verhindern wissen, dass aus den nächtlichen Gedanken ein Albtraum wird. Kristoffer Appel ist Schlaf- und Traumforscher am Institut für Kognitionswissenschaft der Universität Osnabrück. Er erklärt gegenüber Netzpiloten, wie man einen Klartraum haben kann:

„Manche Menschen erleben Klarträume regelmäßig auf natürliche Weise, sie merken also einfach im Traum, dass sie gerade träumen. Repräsentativen Umfragen zufolge haben etwa 20 Prozent der Menschen in Deutschland mindestens einmal im Monat einen Klartraum. Es wird angenommen, dass jeder das Klarträumen erlernen kann. Dazu gibt es eine große Anzahl an Techniken, zum Beispiel mittels Autosuggestion oder mittels bestimmter Konzentrationsübungen, oder aber auch mithilfe von technischen Geräten."

Welche Technik wie schnell zum Erfolg führt, ist allerdings von Person zu Person stark unterschiedlich; die eine perfekte Technik für jedermann gibt es leider (noch?) nicht, obwohl seit Jahrzehnten daran geforscht wird. Letztlich hilft dem angehenden Oneironauten (so werden Klarträumer auch genannt) einfach nur viel Ausprobieren und Geduld. Konkrete Anleitungen zu einzelnen Techniken lassen sich zuhauf kostenlos im Internet oder in der Literatur finden."

„Prinzipiell ist im Klartraum alles möglich", so Appel weiter. Man kann *„Naturgesetze brechen, sich in andere Personen oder Tiere verwandeln, Zeitreisen unternehmen, beliebige Orte bereisen oder beliebige Personen treffen. Inwieweit man einen konkreten Klartraum allerdings bewusst steuern kann, ist von Traum zu Traum unterschiedlich und auch Übungs- und Erfahrungssache."*

Solltet ihr diesen Artikel zu später Stunde lesen, wünsche ich euch jetzt herzlich schöne Träume! Vielleicht habt ihr Lust bekommen, das mit dem Klarträumen mal auszuprobieren. Das wäre super, dann würde ich mich freuen, wie ihr unter diesem Artikel von euren Erfahrungen erzählen würdet. Vielen Dank und gute Nacht!

+++ Buchverlosung +++

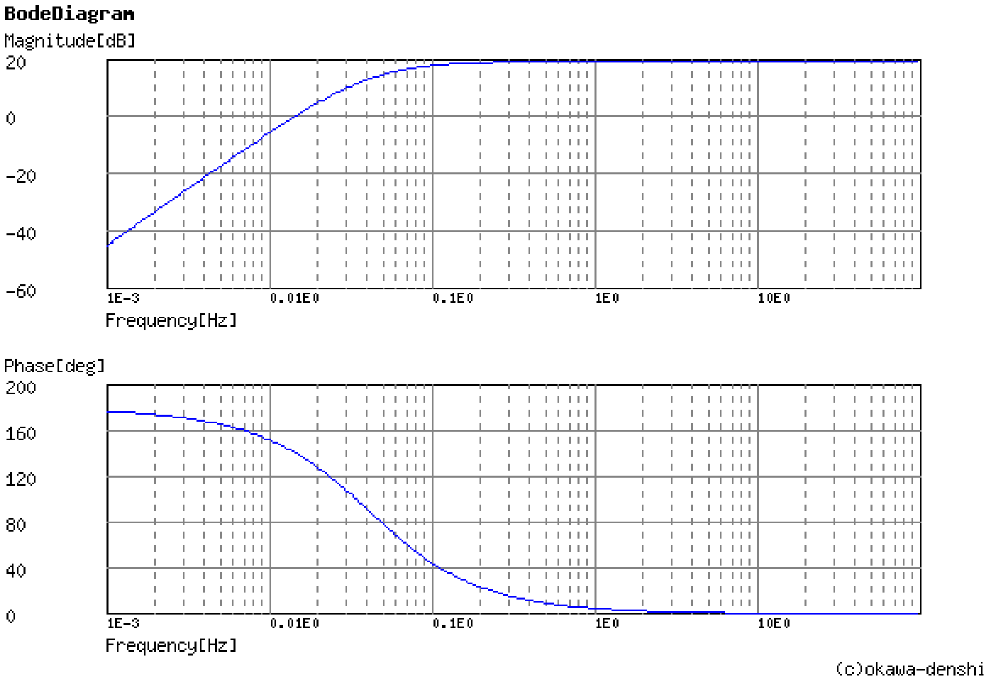
Wer noch mehr wissen will, dem lege ich das Buch „Die schlaflose Gesellschaft: Wege zu erholsamem Schlaf und mehr Leistungsvermögen" von Dr. Hans-Günter Weeß ans Herz. Darin beantwortet er zahlreiche Fragen rund um das Thema Schlaf. Hilfreiche Infos gibt es für Schlafgestörte, aber auch Ärzte, Psychologen und in Gesundheitsberufen Tätige. Dr. Weeß hat uns ein Exemplar zur Verfügung gestellt, dass ihr bei uns gewinnen könnt.

Füllt dazu einfach das verlinkte Formular aus und nutzt eure Chance auf einen kostenlosen Ratgeber. Viel Erfolg!

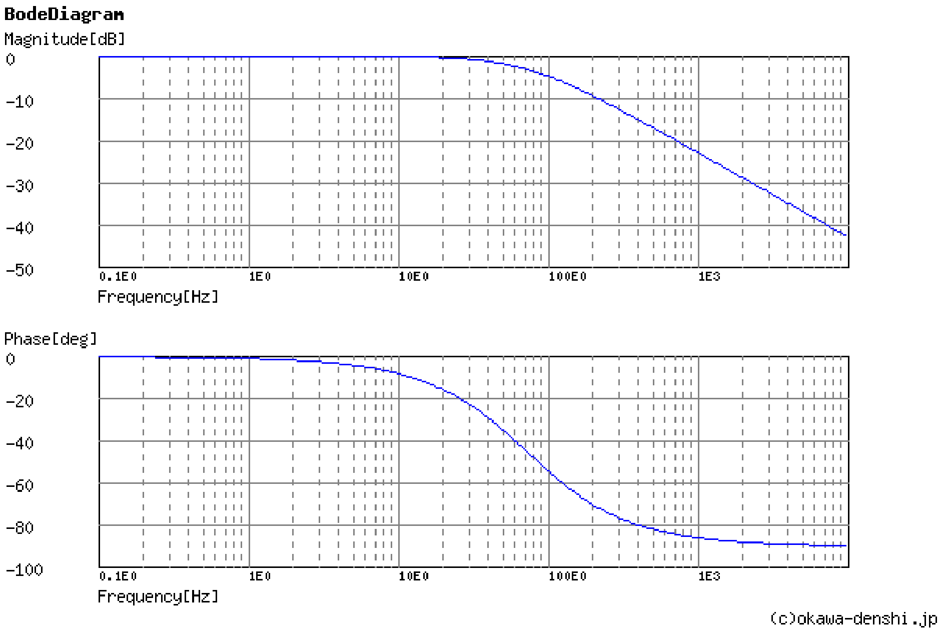
Sollte ihr bei der Verlosung kein Glück gehabt haben – nicht traurig sein! Ihr könnt das Buch von Dr. Hans-Günter Weeß hier bei Amazon bestellen.

Schlagwörter: forscher, Freud, Klartraum, luzides Träumen, REM-Phase, Schlafphase, Sigmund Freud, Traum, Traumdeutung, Traumphase, Traumstadien, Träume

Filter responses of the analog filters in the Traumschreiber sleep mask



High pass filter response



Low pass filter response

Technical specifications of the artificial neural networks used in this dissertation

Please note, that it was not the aim of this dissertation to optimize the performance of the sleep staging algorithm, but only to form a basis, which future implementations can use as a starting point. This means, that the technological foundation (Keras/tensorflow deep neural networks running on the Raspberry Pi minicomputer) is there and functions in real-time.

Technical specifications of the artificial neural network for sleep staging

A neural network has been trained to stage sleep data of seven subjects (one night each), recorded with the Traumschreiber sleep mask. The network expects twelve floats as inputs – which are based on the filtered signal of the three recorded EEG channels of the suggested channel configuration, which is then transformed via a Fast Fourier Transform, and finally four frequency bands (0-4 Hz, 5-8 Hz, 9-16 Hz, 25-35 Hz) of each of the three EEG channels are used as neural network input (i. e. descriptors of the second to be classified). The neural network consists of a sequential model of only four layers: after the input layer of 12 neurons, there is a layer of 64 rectified linear units fully connected to the input layer, followed by a dropout layer with a dropout rate of 0.5, and again a fully connected layer of 5 neurons with a softmax activation function, acting as the output layer with one neuron for each sleep stage. The model was trained using categorical crossentropy as loss function with the adam optimizer and accuracy as metric, using n-fold cross validation with a validation split of 0.33, a batch size of 128, during 800 training epochs, and tested on a separate subset of the data. Training took several hours on a single computer with an octa-core i7 processor (not trained on graphics card). The training and testing performance (accuracy) was 0.579 and 0.580, respectively, meaning that the model classified 58% of the (unseen) seconds during testing correctly. This performance is much worse than what modern classifiers can achieve (using the same underlying technology, about 90% accuracy). However, note that the classification here is done based on single seconds (not 30 sec epochs) and on only four frequency bands, i. e. using a very simplistic approach. Again, it was not the goal of this dissertation to optimize the classification performance, but only to set the technological basis, enabling more sophisticated further investigations with possibly more training data in the future.

Technical specifications of the using artificial neural network for real-time pattern detection

A neural network has been trained to identify specific eye movements in a real-time recording of the *Traumschreiber* sleep mask. The network's task was to differentiate, whether a left-right-left-right eye movement (LRLR), LRLRLR (3 times), LRLRLRLR (4 times) or none of these was conducted by the subject (the author of this dissertation) during a five second interval. Training data were generated by using an experiment xml file, which instructed the minicomputer to record data and simultaneously present in total 99 auditory stimuli ('2', '3', '4'), upon which the subject was asked to move the eyes accordingly twice, three times or four times to the left and right. The time stamps of the stimuli were then used for extracting five second bins of training data *after* each stimulus onset for each of the three types of stimuli. The five second bins of data *before* each stimulus onset were used for the 'none' category. The network expects 1220 floats as inputs (5 seconds @ 244 Hz sampling rate) – which are based on the median and bandpass filtered signal of the HEOG channel of the suggested channel configuration. The neural network consists of a sequential model of ten layers: after the input layer of 1220 neurons, there are several rectified linear unit convolution and max pooling layers, followed by a dropout layer with a dropout rate of 0.5, and a fully connected layer of 5 neurons with a softmax activation function, acting as the output layer with one neuron for each pattern type ('none', '1', '2', '3', '4'; '1' not being trained). The model was trained using categorical crossentropy as loss function with the adam optimizer and accuracy as metric, using n-fold cross validation with a validation split of 0.33, a batch size of 256, during 4000 training epochs, and tested on a separate subset of the data. Training took about 20 minutes on a single computer with an octa-core i7 processor (not trained on graphics card). The training and testing performance (accuracy) was 1.0 and 0.993, respectively, meaning that the model classified 99% of the (unseen) patterns during testing correctly. Note, however, that only data of one person (the author of this dissertation) was used for training and that, thus, the network might not be able to generalize welll. Again, it was not the goal of this dissertation to optimize the classification performance, but only to set the technological basis, enabling more sophisticated further investigations with possibly more training data in the future.

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1	EAME03-01	1 lead snap 4.0mm to Din 1.5mm Length: 30cm	1	PC	1.2	$1.20
2	/	Shipping cost from China to Germany	/	/	37.88	$37.88
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Education

Since 11/2013	Enrolled in the **Cognitive Science PhD** program, Osnabrueck University. Dissertation title: “The Traumschreiber System: Enabling Crowd-based, Machine learning-driven, Complex, Polysomnographic Sleep and Dream Experiments”.
04/2015	Workshop: “Advanced analysis and source modeling of EEG[22] and MEG data”, Donders Institute, Nijmegen, Netherlands.
10/2011 - 09/2013	**Master of Science in Cognitive Science**, Osnabrueck University. Focus areas: Neuroinformatics, Neuroscience. Study project: Multi Timescale Reservoir Computing. Master's Thesis: “Communication with a Sleeping Person”. Master degree awarded with distinction (with best possible grade of 1,00), year’s best student.
06/2013 - 07/2013	6-week summer school “Multimodal Neuroimaging Training Program”, Carnegie Mellon University, Pittsburgh, USA, and University of Pittsburgh, USA, about measuring and analyzing brain activity.
10/2007 - 03/2011	**Bachelor of Science in Computer Science and Business Management**, FH Nordakademie Elmshorn, Germany. Focus areas: Artificial Neural Networks in Theory and Application; Knowledge Engineering. Bachelor’s Thesis: Optimization of Sales Prediction at Quelle Russia using Artificial Neural Networks.
08/2009 - 01/2010	Semester abroad, Study Program “Advanced Information Technologies”, Saint-Petersburg State Polytechnical University, Russia.
07/1997 - 06/2006	Johann-Rist-Gymnasium Wedel, Germany. Abitur (equivalent to A-level). Focus subjects: Mathematics; Politics and Economics.

22EEG, MEG: Electroencephalography, magnetoencephalography. Procedures for measuring the brain activity.

Professional Experience

Since 09/2017	**Neuroscientist / Senior Consultant**, Deloitte Consulting GmbH, Hamburg. Programming, conducting and analyzing EEG and eyetracking experiments as well as online studies for clients from industry. Applying machine learning techniques (Python, Keras/Tensorflow, Javascript).
04/2014 - 05/2017	**Researcher**, Osnabrueck University. Established an own new research group on sleep: Organized a large equipment donation and own laboratory rooms, designed and conducted experiments as well as data analyses (Python), published research results, supervised students, managed the laboratory and the group's finances, raised money for experiments, organized workshops and excursions to other sleep laboratories, managed national and international collaborations with other sleep researchers, acted as an interview partner for national TV and national and international magazines. Developed a high-tech sleep mask for research purposes: Project leadership, defined the requirements from a sleep scientific perspective, managed the experiments, designed and implemented the software and machine learning algorithms (Python, Keras/Tensorflow), co-worked on electrical design, managed the project finances, the sourcing from Chinese factories and customs, and the public relations.
04/2014 - 05/2017	Lecturer, Osnabrueck University. Held four own seminars, supervised a one-year study project of 10 master students and 19 bachelor's and master's theses.
01/2015 - 12/2016	Visiting researcher, Max Planck Institute of Psychiatry, Munich, Germany. Learned how to record and analyze high-density EEG data (MATLAB, Fieldtrip), in Munich and in Osnabrueck.
02/2012 - 01/2014	Laboratory manager, Virtual Reality Laboratory, Osnabrueck University. Built up the new Virtual Reality Laboratory, conducted initial experiments including data recording and data analyses (Python, WorldViz Vizard).
10/2007 - 03/2011	**Trainee**, OTTO GmbH & Co. KG, Hamburg. Worked in various departments of the multinational corporation for 4 to 12 weeks each: purchase, accounting, recruitment, marketing, returns, IT, and the junior company cooperation5, where I was the leader of the E-Business department (customer meetings, supervised and evaluated employees, project management, corporate strategy). Additionally, 2-month internship at the CEO of OTTO Group (first one in the 60-year company history) and 3-month internship at the British subsidiary in Bradford, UK.
08/2006 - 07/2007	Voluntary Civilian Service, The English Theatre of Hamburg. Organized the backstage area, assisted actors during the shows, responsible for props.

Osnabrueck, 02nd March, 2018

K. Appel