Application of real-time HRV biofeedback in the scenario of meditation practice

Feasibility, usability and medical fidelity
Abstract

Chronic stress is a prevalent and universally present hazard in modern society. It lowers the quality of life for individuals and significantly contributes to unsustainable health care costs. Therefore it is important to have natural and noninvasive ways of controlling stress. One such way is meditation, a technique which has been practiced for over five thousand years to improve stress regulation. Also, proceedings in sensing technologies lead to the discovery of biofeedback as another cost-effective technique for stress assessment and reduction. In continuation of research on real-time reflective human-computer-interfaces, this thesis combines these techniques by exploring the application of electrocardiography sensing technology in a heart rate variability (HRV) biofeedback system for the scenario of meditation practice. A proof-of-concept prototype was designed and implemented which quantifies stress and gives feedback on meditation effectiveness. For evaluation, a user study has been performed. Results were analysed in a systematic way to evaluate the feasibility and acceptance of the solution as well as the fidelity of HRV data that was measured during user tests. The prototype was found to be feasible in the context of technology acceptance while the fidelity of data, acquired by an algorithm for time and frequency domain analysis of HRV, was confirmed. A final conclusion is that the reflective aspect of the implemented real-time biofeedback system helps to improve regulatory capacity and thus lowers stress in individuals.

Keywords: heart rate variability analysis, autonomic nervous system, stress quantification, meditation, real-time biofeedback, electrocardiography, Lomb method
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1 Introduction

Chronic stress is a prevalent and universally present hazard in modern society. Information load and demands for work performance are continually increasing due to technological advancements and globalisation of our economy, causing deleterious and cumulative effects on the human body which represent a risk of developing cardiovascular problems, cancer, autoimmune conditions and other illnesses [1, 2, 3].

According to Koolhaas, stress describes "conditions where an environmental demand exceeds the natural regulatory capacity of an organism" [4]. Thus stress lowers the quality of life for individuals and contributes significantly to unsustainable health care costs [5].

Challenged by this phenomenon, medical research, on the one hand, has investigated treatments that might be able to counteract as well as prevent the negative effects of stress on human health. Meditation has been identified as a cost-effective technique for reversing such effects while reducing reactivity to stressors and lowering risks of developing diseases [2, 6, 7].

On the other hand, proceedings in the development of sensing technology and biofeedback allowed medical research to measure and quantify human regulatory systems, leading to the discovery of parameters that indicate positive or negative change in human health. This opened a challenging design space for systems to be used by non-expert users. Stress management systems emerged using wearable biosensors to either display the raw bodily data to the user or take an expert role by interpreting the data into a level of stress [8].

In this work we focus on heart rate variability (HRV) analysis, a method to investigate the "variation in individual cardiac periods regulated by the influence of the sympathetic and parasympathetic branches of the autonomic nervous system (ANS)" [9]. Short-term changes in HRV are indicative of an individuals stress response and disease state [10].

Using electrocardiography (ECG) or other sensing technology to measure psychophysiological indicators like HRV enables the possibility of individualised health care for non-experts. Already existing applications in this domain suggest that in the context of stress-reduction real-time affective reflection can be even more effective than traditional approaches like yoga and meditation [11].

In continuation of research of real-time reflective human-computer-interfaces, this work proposes a system that uses HRV analysis to quantify human stress response during the practice of meditation. The main goal is to
understand whether the application of real-time biofeedback in the scenario of meditation practice can help to improve regulatory capacity in individuals.

The following chapter 2 - Research Problem - explains the challenges that arise in this context and defines the research questions addressed in this work.

Chapter 3 - Background - gives an overview of aspects which need to be considered for the design of a real-time HRV biofeedback system in the context of meditation. It provides definitions of meditation, biofeedback and heart rate variability to build the context of this work.

In Chapter 4 - Related Work - research projects and studies with similar goals or functionality are presented and positioned in context to this work.

Chapter 5 - Methodology - presents the methods used in this work according to traditional software development life cycle.

Chapter 6 - Requirements - represents the specification of functional and non-functional requirements as well as characterises the stakeholders in the proposed usage scenario.

The purpose of Chapter 7 - Design - is to describe the functional, visual and architectural design elements based on specified requirements.

Chapter 8 - Implementation - documents the technical setup and software components used in the development of a system prototype.

Chapter 9 - Evaluation: Experimental Setup & Results - describes the setup and results of the experiments for evaluating feasibility, usability and fidelity of the system.

In Chapter 10 - Discussion - the results of the system evaluation are discussed in the light of other works in the problem domain and judgements are made as to what has been learned in this work.

Chapter 11 - Conclusion - summarises the activities, insights and results and concludes this thesis work with a focus on future research in the problem domain.
2 Research Problem

To recap, meditation and biofeedback are viable methods for improving self-regulation of human stress-response and represent a cost-efficient and effective way of preventing or dealing with stress-related illnesses. Both methods have been extensively studied by research. However, few efforts have been documented that investigate the development of a system addressing both methods in combination.

In the field of Human-Computer-Interaction it is an important research challenge to inform development and evaluate feasibility of such applications. The goal of this work is to build an interface that exploits real-time biofeedback to improve users awareness and self-regulation by quantifying psychophysiological effects of meditation on the human body and relate them to the meditation practice.

It explores if the information gathered by a commercially available ECG sensor can be utilised to inform the user about the stress-reducing capability of the practice. For this purpose, the application of heart rate variability analysis to infer human stress is to be investigated and tested in an experimental setup. Besides evaluating feasibility and usability, it is another important aspect to analyse the fidelity of the physiological data that is to be recorded by the system. In conclusion, the following questions define the research goals of this work:

- (RQ1) How can heart rate variability biofeedback provide valuable information during the practice of meditation?
- (RQ2) What are the challenges of and requirements for building the proposed real-time biofeedback system?
- (RQ3) What is the level of acceptance of the system from the perspective of the meditation practitioner?
- (RQ4) What are the medical results gathered during the experimental evaluation of the system and how consistent are they in the context of results of similar research?
3 Background

The following chapter provides the background to understand the aspects that are involved in this work. Meditation, biofeedback and heart rate variability build the foundation of the proposed solution.

3.1 Meditation

Meditation is a method for stress-reduction that has been practiced and developed over the last five thousand years. According to Lee, "Meditation refers to a group of techniques, including mantra meditation and mindfulness meditation, that involve training the mind or inducing some mode of consciousness using a variety of techniques to induce a state of impartial, present moment awareness of sensory, emotional, and cognitive events" [12]. In terms of physiology, meditation is a complex process affecting neural, psychological, behavioural and autonomic functions. The breath plays a central role in the process of meditation, as many traditions consider breath, body and mind to be linked [13].

As a mind-body therapy, meditation can be practiced in various forms. A common form of the practice is called Concentration meditation, on which we will focus in this work. This variation of meditation practice involves focusing the attention on one thing, usually the breath, with the intention to calm the mind. During the practice, the rhythm of inhalation and exhalation may lead to a state of quiet mind sometimes called the Samadhi state [14].

In a more general definition, mind-body therapies engage the mind and body to promote stress reduction. This has become increasingly important in our society, as we are constantly confronted with and influenced by information and environmental or internal stressors. Through meditation individuals can train their body and mind to better respond to these stressors.

While it is not fully known what changes occur in the human body during meditation, it has been proven that meditation has a number of health related benefits, e.g. it helps in the management of chronic pain [12] and reduces baseline stress and reactivity to stressors [2].

In conclusion, meditation is a method for relaxation and stress reduction. The practice of meditation represents the scenario of this work, which aims to measure the stress response of the body during the practice. This way, the amount of stress reduction can be quantified for the practitioner to reflect on using a real-time biofeedback display. The next section introduces the aspect of biofeedback and explains its application in the context of this work.
3.2 Biofeedback

Biofeedback is an increasingly accepted method for alternative medicine and preventive health care [1] that is revolutionising health care by reducing hospitalisation rates, reducing costs for patients and improving physiological monitoring [15]. Barlow et al. define biofeedback as a technology by which individuals can become aware of various physiological functions using biomedical sensors in order to manipulate those physiological functions with the aid of computer systems [16].

Like meditation, biofeedback can be used as a mind-body technique to gain awareness about unhealthy mental patterns and habits and helps to control bodily functions, for example breathing rate and heart rate [12, 17, 18, 19, 20]. Biofeedback is used as a tool for treating a variety of mental health problems, heart problems [21], pain [22], irritable bowel syndrome, high blood pressure [23] and other illnesses [19, 24] by providing several benefits [25, 26, 27, 28, 29]. This work puts the focus on biofeedback as a promising approach for continuous assessment of stress in real-time which is a very active area of research [3].

According to Zhang et al., a typical biofeedback system includes three parts: "physiological parameter sensor, signal processing and biofeedback algorithm (software), and audio or visual interface to the user" [17]. To create an effective biofeedback application, the biofeedback signal has to convey necessary and sufficient information [30]. In this work, an electrocardiogram (ECG) will be used as a physiological parameter sensor while an algorithm for heart rate variability (HRV) analysis provides information for stress assessment. Research shows that HRV biofeedback helps to treat a variety of stress related conditions [31].

In conclusion, biofeedback is an accepted solution for stress assessment. It is applied in this work to monitor stress in the context of meditation practice. The next section introduces the concept of heart rate variability and explains how the analysis of HRV can be exploited for this purpose.

3.3 Heart Rate Variability

According to Krygier et al., HRV is "a measure of beat-to-beat variability in heart rate that is mediated by the autonomic nervous system (ANS)" [32]. The autonomic nervous system has two branches, the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). By activation of these branches, the ANS affects the cardiac function. SNS activity is linked to the stress-inducing 'fight-or-flight' response of the body that accelerates heart rate and raises blood pressure, while PNS activity is correlated to the
‘rest and digest’ response, slowing down heart rate and decreasing the force of the hearts contractions.

Thus HRV analysis provides insight into the activity in these branches making it possible to quantify the sympathovagal balance and global activity of the ANS. It measures minute changes in beat-to-beat intervals that are correlated with stress response and disease state. High stress reduces HRV while low stress increases HRV [10].

![Figure 3.1: RR interval in ECG signal](image1)

Using the time intervals between heart beats called NN or RR intervals (illustrated in Figure 3.1), HRV is commonly calculated using time domain methods and frequency domain methods. A time series of RR intervals (Figure 3.2) provides the input for both types of calculations. Measures acquired by time domain methods usually include rMSSD, the square root of the mean squared differences of successive RR intervals and pNN50, the proportion derived by dividing the number of interval differences greater than 50 ms by
the total number of intervals. These measurements are highly correlated in terms of estimating high frequency variations in heart rate [33].

Due to the limited ability of time domain methods to reflect the balance between ANS branches [34], this work focuses on the analysis of HRV in the frequency domain. Using power spectral density (PSD) analysis one can determine how variance distributes as a function of frequency [33].

For the assessment of stress, the distribution of power spectral components will be calculated. According to a standard proposed in 1996 by the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology, four main spectral components are computed: ultra low frequency (ULF), very low frequency (VLF), low frequency (LF) and high frequency (HF) components [33]. Figure 3.3 shows a possible power distribution in this frequency spectrum:

![Figure 3.3: Frequency spectrum of HRV](image)

ULF and VLF assessed from short-term recordings should be avoided because it has not been found to be an effective measure in the context of physiological monitoring. In contrast, LF and HF components can estimate the balance of ANS branches. LF is correlated with activation of SNS, while HF is correlated with activation of PNS. Thus the ratio between these components estimates sympathetic modulation (sympathovagal balance) and can be used in the assessment of stress [35]. In contrast to many measures derived from HRV analysis, the LF/HF ratio has the benefit of not being age-dependent [36].
In research, HRV is often used for physiological monitoring of meditation [37, 38, 39, 40, 41, 42, 43, 44, 45]. The practice of meditation and the often implied slow respiration have been shown to improve variability in heart rate and especially to increase HF components of HRV PSD [37, 40, 41, 42, 43, 44, 45]. In this work, these correlations will be used in the application of real-time biofeedback to provide information about the user’s stress level during the meditation practice.

This chapter gives an overview of the aspects that need to be considered in such an application. To apply HRV biofeedback, the use of a sensor providing RR interval measurements, hence an ECG device, is required as well as an algorithm that computes HRV in time and frequency domains. Figure 3.4 shows a simplified view of the required components:

![Figure 3.4: HRV biofeedback for meditation: system components](image)

The algorithm that will be used in this work is based on the Lomb method, a commonly used and accepted method for estimating a frequency spectrum, similar to Fourier analysis [46, 47, 48, 49]. Compared to other approaches it requires less computational power due to direct analysis of RR intervals without resampling or interpolation [46]. Thus, the parameters can be computed within a very short time frame which is required for a real-time biofeedback system. Tests done by Smith showed that it is feasible to apply the Lomb method to short-term HRV analysis [50, 51]. This work focuses on the HRV Toolkit by Physionet [52] which includes the Lomb method as well as the computation of time domain HRV. Chapter 8 describes how the algorithm is applied in this context.
4 Related Work

There is a multitude of research projects that apply HRV biofeedback in the context of stress assessment and stress reduction. These applications use biofeedback to achieve higher self-regulation capacity in individuals.

A common implementation scheme for these applications includes a combination of measuring parameters that indicate stress, quantifying them into higher and lower stress levels and mirroring them back to the user to close the biofeedback loop. Based on these principles, two types of systems can be distinguished: applications for stress intervention in specific scenarios and applications for stress assessment and reflective monitoring.

In the context of addressing specific usage scenarios, NASA developed a biofeedback training method called the Autogenic Feedback Training Exercise (AFTE) based on wearable physiological monitoring device, BioharnessTM from ZEPHYR to prevent and counter motion sickness for astronauts in space [53].

Another example is MoodWings, a wearable device in the form of a butterfly that, based on electrocardiography (ECG) and electrodermal activity (EDA) measurements, responds to the users stress arousal through wing actuation [54]. The device was found to benefit task performance in the scenario of driving by improving affective awareness.

In the context of stress assessment, a biofeedback device called emWave uses the input data from an ECG to estimate power spectral density of HRV [55]. By monitoring this data it helps to induce positive emotional states associated with ”psychophysiological coherence” [28].

Stress assessment based on monitoring breath rate is especially relevant to this work, because breathing is a central component of meditation. Moraveji et al developed BreathTray, a system for continuous display of respiratory feedback [56]. It measures breathing rate to indicate a percentage of how the current breath rate matches the individual resting breath rate and awards 'calm points' for achieving high percentages. Especially in single intensive cognitive tasks, this system was found to help modulate breath rate better than using motivation alone.

InnerBalance, MyCalmBeat and StressEraser, applications with a similar focus on breathing-induced HRV, have been produced to provide stress management biofeedback [57, 58, 59]. Using breath rate as an indicator of coherence, these systems encourage to train and improve stress-response.

Focusing less on breath rate and more on the general monitoring of HRV parameters, SweetBeatLife is an application built for iOS with the main
features of presenting ECG parameters and classifying the users state into stress levels ranging from 1 to 5 [60].

A different approach is made by Quer et al. who propose the Bliss Buzzer framework to generate personalised approaches for stress management to improve work efficiency and all-around wellness [61]. It is designed for individual stress and coherence monitoring based on different biometric sensing systems.

Researching the correlations between visual stress and HRV, Wu et al. describe a system with the purpose of monitoring HRV during different states of visual stress [40]. Their experiments show that HRV is affected by visual stress and suggest the system to be used for visual stress monitoring in daily life.

A mobile HRV biofeedback system proposed by Morris et al focuses on real-time monitoring of physiological state and providing interventions when a drop in HRV is detected [10]. Amongst other things, they found that intuitive metaphors can help individuals to relate the physiologically monitored data to their personal life.

The presented projects have similar goals as the system proposed in this work. Instead of monitoring breath rate, which has been shown to be effective for reducing stress, this work focuses on monitoring HRV for several reasons. First, sensing breath rate requires a sensor that is firmly pressed around the chest to measure contractions which can cause discomfort for users [8]. Second, systems that mechanically induce slow breathing do not always lead to a state of calmness, they sometimes even exasperate it [62]. Third, the effects of meditation cannot be reduced to a change in breath rate alone [63]. In other words, the practice of meditation has mental and physical aspects which, when monitored separately, cannot reflect the overall effectiveness of the practice. In contrast, monitoring autonomic function enables direct feedback that provides the opportunity to learn through self correction [11, 18]. In conclusion, the systems described in this chapter are only indirectly or not at all tailored to be used for the evaluation of meditation practice. Thus there is a lack of research on the application of biofeedback for meditation practice.
5 Methodology

This thesis work is aligned to traditional software development life cycle methodology. The following activities are performed sequentially in a waterfall model to inform and evaluate the development of the proposed system:

- **Requirements engineering**: To understand the research problem and the capabilities of the proposed solution, this activity identifies functional and non-functional system requirements based on background research presented in chapter 3 and provides information on how the system is meant to be used.

- **Design**: To meet the specified requirements, the next step is to plan a solution. This includes describing the behaviour and components of the system while considering possible constraints.

- **Implementation**: After a design for the proposed system has been specified, implementation follows to translate the plan into running application code. The system is implemented in the form of a proof-of-concept prototype that can be used for testing. Software and hardware components, libraries and platforms are documented in this process.

- **Testing and evaluation**: The main goal of testing is to compare the developed system prototype with the collected requirements and to identify inconsistencies between them. This is done in form of an experiment. The prototype is tested by real users, who evaluate the system via a questionnaire in terms of perceived usability and feasibility. In the context of results of previous research that has been done in the same problem domain, the fidelity of medical data which is collected during these tests is analysed. Chapter 9 describes the setup and results of these experiments. To conclude this work, results are analysed and discussed.

As the goal of this thesis is to inform and document the development of a system prototype tailored for the use in an experiment, activities like deployment, maintenance or evolution, usually part of the software development life cycle, are not relevant here.
6 Requirements

The following chapter describes the functional requirements, referring to what the system should do, and the non-functional requirements, referring to how the system should work. It also defines the stakeholders that require the proposed solution and the usage environment, referring to how the system should be used.

The requirement specifications imply identifying the goals and ideas behind the system. The main goal of the system is to facilitate and enhance the practice of meditation by providing real-time as well as post-meditation biofeedback to indicate the effectiveness of the practice. To accomplish this, an important feature is to record and process ECG input to produce comparable HRV data that can be used in the evaluation of the system.

6.1 Stakeholders

The system is tailored to meet the needs of two types of stakeholders, the target user and the research conductor. The main focus is on the role of the user who expects to be guided through meditation and to receive immediate feedback on the effectiveness of the current practice.

6.1.1 Target User: Usage Scenario

The following use case describes a possible interaction with the system here referred to as Guided Meditation System (GMS) and the underlying motivations of the scenario. Please keep in mind that this scenario presents the system as a deployed application in the context of a final usage environment and does not describe the planned usage scenario of the prototype developed in this work. Its sole purpose is to characterise the motivations and goals of the target user.

Lately, John has been so stressed out that he is starting to worry about his health. Getting ill more frequently these days he realises that he has to do something about it, so he tries out meditation. A friend from work tells him it is very effective to calm the body and mind. "Just sit down, close your eyes and breathe deeply", his friend suggests. Now it’s been a week since John started meditating. So far it helped quite a bit with his agitated mind but he keeps coming back to wondering if he is doing the practice right. He likes to see measurable results in anything he does and meditation doesn’t provide that. Fortunately, after searching through the internet, he finds out about GMS, a system that guides meditators through the practice while
helping them see how well they are doing in terms of relaxing the body. He immediately orders it and two days later, it is ready to use. After putting on earphones and the ECG chest strap and connecting it via Bluetooth to the GMS interface on his computer, he is ready to go and clicks on a green button in the middle of the screen labelled ‘Start Meditation’. John is excited, because the system shows him his stress level and how balanced his autonomic nervous system works. It asks him to breathe deeper and more effortlessly. After a few minutes of deep and calm breathing, John notices on the screen how his autonomic nervous system is balancing itself out and his stress starts to lower. Breathing deeper and relaxing his muscles in this phase, he is amazed at seeing his stress reduce even more. To deepen the meditation, he is then instructed by the system to close his eyes while slowing the mind, opening the eyes again after a bell rings to indicate the end of the session. John is already more relaxed than when he practiced without GMS. He sees that his stress is quite low. He is enthusiastic when GMS shows him how efficient his meditation was. All in all, the system increased his motivation to meditate as well as the effectiveness of his meditation and also made him more aware of how his body regulates itself. He likes how it lets him compare his practice from different days. After another week of meditating, John slowly increased his ability to calm his body and mind and feels much more relaxed at work.

To summarise, the system is addressing users who experience high stress in their daily life and look for a way to learn how to meditate and reduce their stress as well as measure and quantify their progress. It is designed for daily/regular use at home to slowly improve meditation practice effectiveness thus self-regulatory capacity.

6.1.2 Research conductor

In order to evaluate the system for feasibility, usability and fidelity of its results, the system should also be tailored for use in an experimental evaluation. Thus, another stakeholder is the person conducting the experiments with the system prototype, requiring the functionality to provide measurable and comparable output.

6.2 Functional Requirements

Based on the goals and stakeholders of the system, the following list describes a set of functions that are expected from the prototypical implementation of
the system:

- **ECG Data Collection**: The system should be able to accurately record input data provided by a wireless ECG sensor, enabling the real-time measurement of heart rate and RR intervals.

- **ECG data processing**: The system should process the measured data in real-time to be used as an input for an HRV analysis algorithm.

- **HRV biofeedback**: The system should be able to record the HRV data acquired by the algorithm and present it to the user in a way that is relevant for the practice of meditation.

- **Biofeedback interface**: The system should provide an interface that indicates whether the meditation practitioner is reducing or increasing the level of stress and thus give immediate feedback on the current effectiveness of the practice.

- **Instructional interface**: The system is expected to instruct the users according to the current phase of the meditation session. The interface should indicate the current phase, the remaining time in this phase as well as a description of what the user is expected to do in each phase.

- **Meditation session management**: The system should provide the possibility to initiate a new session by connecting to the wireless ECG. To reflect on the meditation afterwards, the system should signal the end of the meditation session and offer a retrospective overview of progress throughout the practice.

### 6.3 Non-functional Requirements

The following list represents a set of qualities that describe how the system prototype should work:

- **Performance and Reliability**: The system should be working in a way that allows recording of ECG input, processing of ECG input via an HRV algorithm and presenting the algorithm output in an understandable way to the meditation practitioner. To provide real-time feedback, the system should be able to accomplish these operations in the time between two consecutive heart beat measurements, because each heart beat and the sequence of heart beats represent the input for the system. The system should also be reliable by recording and storing data without too much distortion or loss.
• **Accessibility**: The system should collect and record the measured data in a way that is accessible by the meditator during the meditation practice and the post-meditation progress overview as well as by the researcher for the analysis of medical results.

• **Usability**: The system should be easy to use by facilitating the recording of the meditation practice and guiding the user through the session.

• **Unobtrusiveness**: Using the system should not be obtrusive or annoying to the person practicing meditation. Applied sensor devices should be comfortably worn throughout the meditation session without disrupting the relaxation process.

• **Testability**: The feasibility and output quality of the system should be testable in an experiment. The data that is collected and stored by the system should be comparable in the context of previous research in the problem domain.

• **Security and Anonymity**: The system should be secure. This means that all data should be stored in a secure location that prevents its access by other parties. Also, no connection should be made between user identity and the data collected during the meditation sessions.
7 Design

The following chapter describes the specific aspects and components of the system prototype that is implemented in this work.

7.1 Functionality and User Interface Design

Based on the requirements specified in the previous chapter, this section explains the functional and visual components of the system and how they work together during the use in a meditation practice, presented in chronological sequence. It also presents the visual states of the user interface as screenshots which were taken after the implementation activities. They were included here to illustrate the functional design.

7.1.1 Initialisation and ECG Connection

Before starting the meditation session, the user is required to put on an ECG sensor. For the implementation of the system prototype, the Polar H7 wearable chest strap [64] is selected, because it provides accurate heart beat detection and RR interval measurements while being comfortable enough to wear in a full meditation session. The sensor is attached to a chest strap which is placed on the body, as shown in Figure 7.1. The sensor uses Bluetooth low energy to transmit data wirelessly with any paired device that supports the technology. In this work, a computer running Mac OS X is used to host the proposed application and pair with the ECG device, representing a suitable tool for the use in a daily and domestic environment.

![Figure 7.1: Polar H7 - position during measurements](image)

After putting on the chest strap, the user is asked to sit in a comfortable position in front of the application interface which is initiated. The first view, illustrated in Figure 7.2, shows the starting point for a new meditation session. In this screen, the user is asked to type in a reference number that is
necessary for the experimental evaluation of the system, described in chapter 9. Subsequently, the user can click on a button labelled ‘Connect’ to trigger the connection between the ECG and the application. The screen also shows a text for instruction on the bottom, which changes at the beginning of each phase of the session, and a heart rate display on the top. Upon ECG connection this indicator shows the current heart rate and the screen changes to indicate the start of the next step of the session.

Figure 7.2: UI view: start screen

7.1.2 Data Preparation

The first phase of the session has the purpose to prepare the measured ECG data for HRV analysis by creating an RR interval series. Illustrated in Figure 7.3, the screen shows a countdown in the top right corner to indicate the length of this phase, a loading icon in the middle and an instruction text signalling that no user action is required in this phase.
7.1.3 Baseline Recording

After the time series is long enough for HRV analysis, the baseline recording phase begins. Like in the previous phase, no user action is required. For testability, the baseline recording is implemented to produce control data that is needed in the evaluation of the system. Continuous measurement of ECG data provides the input for the algorithm which calculates HRV using time and frequency domain methods. The acquired HRV data is chronologically recorded on the application server and consists of the following HRV indices: LF, HF, rMSSD, pNN50. Figure 7.4 shows the interface of this state.
7.1.4 Meditation Phase A

When the baseline recording ends, the view changes to present meditation phase A. In this phase, the user is instructed to meditate while observing the biofeedback display which appears in the middle of the screen. The real-time HRV data provided by the application server is used to calculate and display the balance of the branches of the ANS, represented by low (LF) and high (HF) frequency components. The ratio between the two (LF/HF) forms a stress indicator. In a simple and understandable way, a graph illustrates the changes in HRV and interpreted stress levels to help the user reflect on the efficiency of the meditation practice. Figure 7.5 shows an example of the visualised ANS balance and the displayed stress level (see Chapter 8 for more details on how the ANS balance is visualised):
As identified in chapter 3, concentration on breath and muscle-relaxation are important elements in most forms of meditation. Thus, the instruction text of this phase implies to focus on breathing with as little effort as possible and to relax the body. In the meantime, the display changes to give feedback on whether or not the user is able to reduce stress and respectively to help him learn about the efficiency of the practice. Figure 7.6 shows an example of the biofeedback display a few minutes later where the user was able to lower his stress level, depicted by a decrease in the LF/HF ratio.
This phase is the most important one in the recording of the session as it represents the proposed biofeedback solution for meditation practice. Like in the previous phase, the acquired HRV data is recorded on the application server.

7.1.5 Meditation Phase B

The last phase of the meditation session is implemented to compare the measured data during meditation with the biofeedback display and meditation with eyes closed. Closing the eyes is another common element of meditation practice which helps to increase focus on the breath, to turn attention inward and to reduce cognitive load [65]. Thus, the user is asked to close his eyes upon the beginning of meditation phase B. The biofeedback display is removed to not encourage the user to open his eyes (Figure 7.7). At the end of this phase, a meditation gong is played by the interface to indicate the end of the session.

![Figure 7.7: UI view: meditation phase B](image)

7.1.6 Progress Review

The session is concluded by the session review, a statistical overview of the completed meditation. This phase has the purpose of enabling the user to reflect on the meditation practice in retrospective by showing changes in HRV over the course of the session and its different phases in form of graphs. As illustrated in Figure 7.8, these graphs show changes in heart rate, RR intervals, ANS balance (here labelled spectral power because it shows the...
distribution of spectral power in LF and HF components of HRV) and LF/HF ratio. In the top of the screen users see average values for the total duration of the session as well as for each of the phases where data has been recorded.

7.2 Architectural Design

This section gives a structural overview of the functionality of the proposed system.

7.2.1 Components

Based on the specified requirements and functional design, the system prototype consists of the following components illustrated by Figure 7.9:
7.2.2 Data Structure

To calculate HRV, display it to the user and save it in a database at the end of the session, data has to be transmitted between the different components of the system. The following class diagram (Figure 7.10) illustrates how this data is structured and stored.

Figure 7.9: Functional components

Figure 7.10: Data structure
Pseudo code methods represent functions of data interaction. Once connected to an ECG via `connectToECG`, the user data contains the ECG object which uses a notification method, here `notifyOnRead`, to send heart rate measurements. These measurements are stored in an object called `HRData` from which they can be prepared for HRV analysis. Using a method called `getHRV`, HRV data is obtained from the HRV algorithm. Together with other session-related data like the reference number and the date of the session, HRV data is stored in an object called `SessionData`. At the end of the session, `saveToDB` inserts the `SessionData` into a database.
8 Implementation

This chapter describes how the functional components of the prototype are implemented to meet the design specification.

8.1 Technical Setup

The prototype is implemented to be used in a domestic environment and is required to support Bluetooth low energy protocol for pairing with the Polar H7 heart rate sensor. A computer running Mac OS X hosts the application logic, including the application server, the algorithm server and the client interface. The HRV algorithm described in section 8.2.1 has Linux dependencies and is thus accessed as an API running on an Ubuntu virtual machine. For high consistency and interoperability, all software components except the algorithm shell script are written in JavaScript. In the context of prototyping, this approach aims for a fast and unified development process.

The application server as well as the algorithm server are implemented on the Node.js platform. According to its creators, ”Node.js is a platform built on Chrome’s JavaScript runtime for easily building fast, scalable network applications. Node.js uses an event-driven, non-blocking I/O model that makes it lightweight and efficient, perfect for data-intensive real-time applications that run across distributed devices” [66]. Hence, it is a suitable platform for the proposed functionality and can easily be extended with the use of Node.js modules, packaged code libraries, in this case providing logic for ECG connection, client communication and database interaction.

For hosting the client-side logic of the application, the AngularJS framework [67] is used to avoid code redundancy across multiple views. It enables easy maintenance for gateways built with pure HTML5, JavaScript and REST services while encouraging developers to use declarative programming for building the user interface and imperative programming for business logic. In addition, automatic DOM manipulation reduces complexity in cases where data changes periodically in real-time [68].

The following section describes the logic of the different software components. The technical setup of the system prototype can be summarised by Figure 8.1:
8.2 Software Components

The logic of the system prototype can be described as different components addressing different functional aspects of the system.

8.2.1 ECG Connection

In order to pair the Polar H7 heart rate sensor with the computer hosting the application, Bluetooth low energy protocol is used. A Node.js module called noble [69] provides methods to connect to the ECG and receive its data by subscribing to its heart beat characteristics. When a Bluetooth low energy device is discovered it gives access to the peripheral object which handles service discovery, connection and notification events. Upon connection, heart rate and RR intervals are measured each second.

8.2.2 HRV Biofeedback

The HRV toolkit described in chapter 3.3 is used for acquiring HRV data that will be displayed in the real-time biofeedback interface. A shell script called get_hrv is included which calculates time domain (C program statnn) and frequency domain (Lomb method) HRV statistics and requires an input in the form of an RR interval series.

This script requires to be run in a Linux environment, here provided by a virtual machine with Ubuntu installed. On this virtual machine, the algorithm server is implemented with Node.js. Upon receiving heart rate
measurements from the ECG, the application server sends the ECG data to the algorithm server, where the algorithm input is generated.

First, the number of consecutive RR intervals in the interval series needs to be specified. A lot of research has been done on determining how many consecutive heart beat measurements are needed to provide significant HRV calculations. While in 1996 the standard of using 5 minutes of heart rate data, consisting of 300 consecutive beats, was proposed, researches later found out that the same HRV data quality can be achieved for shorter RR series length.

In 2011, Lim et al. compared different time window lengths and were able to reproduce the HRV data acquired in a window of 300 seconds by using a 40 second window [70]. They concluded that 40 second windows give valid measurements of time-domain statistics (rMSSD and pNN50) as well as LF and HF components of HRV. To create a sliding window of the last 40 RR intervals, the measured RR intervals are inserted as a list into a text file. Once this list reaches the length of 40 RR interval values, each consecutive second the first value of the list is removed while the new measurement received by the application server is inserted at the end.

The text file containing the sliding window of 40 RR intervals can then be used as the input for the get_hrv script which is run using a Node.js child process [71] on the algorithm server. Once the calculation is completed, the shell script returns the output in form of an HRV object containing several time and frequency domain measures and sends it to the application server.

8.2.3 Real-time HRV Display

LF, HF, LF/HF, rMSSD and pNN50 indices of HRV data acquired by the algorithm server is extracted and stored in the session data. Using the fast and reliable real-time engine socket.io [72], a websocket connection is established once a client accesses the application server. This allows to transmit the acquired HRV data in real-time to the client-side interface logic where it is applied to produce the biofeedback display in meditation phase A. HRV indices for LF, HF and LF/HF are displayed directly while LF and HF distribution is also visualised via a pie chart generated by an AngularJS directive based on the Chart.js library [73]. The red part of this chart stands for LF and the green one for HF, while two lines form the outline of the pie chart sections. Every second in this phase the values and chart are updated with new HRV data received by the application server.
8.2.4 Data Collection

For the purpose of testability and evaluation of the system, data needs to be recorded. During the recording phases of the meditation session, data is stored within the application server in form of an object containing session information and array lists of measured and calculated data. At the end of the session, this data is inserted into the document-oriented database MongoDB [74]. In contrast to traditional table-based relational database solutions, MongoDB is structured to favour JSON-like documents. The session data to be saved is already structured in this format so it can be inserted directly without losing computational power.

8.2.5 Session Control

To conduct all phases of the meditation session, the client-side logic includes the functionality to change views between phases and trigger operations and client-server communication. This includes setting timeouts for controlling phase duration and changing instructional text to match the equivalent phase. AngularJS facilitates the implementation of this functionality by offering two-way data binding [75] for real-time updating of session data and directives like ngShow [76] for conditional display of visual interface components or ngClick [77] for easy click handling.

8.2.6 Session Statistics

Upon completion of meditation phase B an mp3 file including a gong sound is played by the client-side logic signalling the end of the session. The application server gets notified to save the session data and also sends it to the client-side where JavaScript is used to calculate the averages of the session in total and separately for each phase. The averages of HRV indices are displayed in a table. To illustrate the statistical course of the meditation session, a JavaScript plugin called Highcharts.js [78] reads the session data and displays it in form of time series charts. Like with Chart.js, the graphs are generated using SVG.

In conclusion, the following sequence diagram (Figure 8.2) illustrates the chronological flow of interactions between the architectural components of the system prototype.
Figure 8.2: Chronological flow of functional interaction
9 Evaluation: Experimental Setup & Results

The purpose of the evaluation activities in this work is to assess the following aspects of the implemented system:

- **Acceptance/Usability**: This aspect is evaluated by using the traditional technology acceptance model [79]. Thus, the metrics of *perceived ease of use* (degree to which the user believes that using the system is free from effort), *perceived usefulness* (degree to which the user believes that using the system is effective), *attitude towards using the system* (degree to which the user is willing to use this or similar systems) and *behavioural intention to use the system* (degree to which the user can imagine regular usage of the system) are measured.

- **Feasibility/Fidelity**: In this context, the system is evaluated by measuring its ability to meet the functional intentions of the proposed solution. The metrics to be measured include the effectiveness of system use and the fidelity of the collected data during its use.

To measure the presented metrics, an experiment is conducted that tests the implemented system prototype during its application with real users. The following sections present the design of the experiment.

9.1 Experimental Setup

The purpose of this experiment is to understand whether the proposed real-time biofeedback system can help in making the practice of meditation more motivating and effective. It also determines if the collected HRV measurements confirm the functional design of the system and reproduce results of previous studies in the context of meditation-induced HRV.

9.1.1 Participants

For experimental evaluation of the system, 23 people were invited to conduct a user test. Of these 23, 17 participated. This group was not selected based on specific criteria and consisted of friends, family and fellow students. The participation in the experiment was voluntary and confidential and followed the ethical principals of the Nuremberg code [80]. Amongst other things, this means that the experiment avoided harm to participants (not causing them to be embarrassed, stressed or ridiculed), ensured informed consent of participants (they were made aware of the aims of the research, who is undertaking it, what kind of information is sought, how much time is required
and that participation is voluntary and anonymous), respected participants privacy (data is kept anonymous and secure, participants had the right to withdraw from the experiment at any time) and avoided deception (by being open and transparent about the procedure).

To participate in the experiment, users are asked to give their permission via the following form for informed consent:

"The following experiment is about evaluating a system for stress-measurement during a 10 minute and 40 seconds long meditation session. During this session your heart rate will be continuously measured so it shouldn’t be interrupted. If you at any time feel the need to cancel the session, please do so. The measured data will be associated with your answers from this questionnaire by using a reference number, everything will be securely and anonymously stored for 6 months. To analyse the data and use it in the documentation of my thesis project, I’d like to ask for your permission in form of a signature. Please confirm that you are voluntarily and anonymously participating in this experiment."

9.1.2 Questionnaire

For measuring metrics related to acceptance and feasibility of the system, a questionnaire was used as part of the experiment. It includes 8 statements, each evaluated by numerical scores based on a Likert-type scale ranging from 0 (I do not agree at all) to 10 (I strongly agree) in equidistant intervals:

- **S1 I have experience in the practice of meditation.** The purpose of this statement is to estimate if users are new to meditation or if they are experienced in its practice. This metric is used to form user groups based on levels of experience.

- **S2 I feel more relaxed after the practiced meditation.** Agreement or disagreement with this statement estimates the generally perceived effectiveness of the system application in context to the goal of stress reduction.

- **S3 The real-time display of stress levels is helpful for meditation.** To evaluate the main functional aspect of the system, this statement is used to derive how feasible and effective the real-time biofeedback display was perceived to be for the meditation practice.

- **S4 The tested system helps to practice meditation more effectively.** This statement helps to evaluate the acceptance of the system in the context stress reduction, its main usage goal.
• **S5** *The system and its results motivate to practice meditation more frequently.* A secondary goal of using the system is to motivate frequent practice of meditation. Perceived effectiveness and usefulness of the system can be derived from answers to this statement.

• **S6** *The system is easy to use.* To evaluate general usability of the system, this statement helps to determine the perceived ease of use.

• **S7** *It is important for me to reduce stress in my daily life.* This statement was used to evaluate participants attitude towards using the system and thus focuses on the motivations by which the target user is characterised.

• **S8** *I can imagine using the system regularly.* In context of system acceptance, this statement measures behavioral intention to use the system.

### 9.1.3 User Test

A user test is part of the experiment to evaluate the system during its application by real users and to record HR/HRV data for analysis. The following data sets are measured:

• **ECG measurements:** Values of heart rate and RR intervals, provided by the ECG device, are required for HRV analysis.

• **Frequency domain HRV:** Frequency domain indices are calculated to estimate autonomic balance. LF indicates sympathetic influence while HF indicates parasympathetic influence. The ratio of these two (LF/HF) is used to infer stress.

• **Time domain HRV:** Time domain indices rMSSD and pNN50, both indicating short term vagal/parasympathetic influence on HRV, are calculated and recorded next to frequency domain indices. These measures are only taken for analysis in the context of similar experiments.

All data that is measured during the test is securely stored in a database for the duration of 6 months after the date of the experiment. To ensure anonymity of participants, the measured data is not attached with names. A 4-digit reference number will be used to associate the collected data with the results of the questionnaire.

To provide a suitable environment for effective meditation practice, it was made sure that each participant was placed in a comfortable sitting position.
within a calm environment while the biofeedback display was positioned to provide optimal visibility. The following picture (Figure 9.1) shows the room where user tests were conducted.

![Figure 9.1: User test environment](image)

### 9.1.4 Procedure

The sequence of activities in the experiment can be divided into three parts. First, for test setup the participants are introduced to the experiment and asked to sign an informed consent. After signing the form, they are required to put on the ECG chest strap and sit down on a comfortable chair in front of the computer which runs the system prototype. To make sure the participants understand the procedure of the user test, the different phases of the meditation session are explained.

Second, the user test is executed. After the participants positioned themselves, a preparation measurement with the duration of 40 seconds is taken. This length is required to start recording HRV indices and helps to avoid distortion of recorded data which could happen due to physical activity right before the test. Then, after participants rested for 40 seconds without action, a baseline recording of 2 minutes is performed. Again, no action is required from participants. Measuring data for a resting baseline is a common procedure in the research of meditation-induced HRV and allows to evaluate the practice of meditation in comparison to the activity of just sitting [6, 38, 45, 81, 82]. Participants are then instructed to complete two meditation segments of 4 minutes length each, where they are required to meditate by breathing calm and without effort while relaxing their muscles. Meditation phase A is implemented to record data for evaluating the func-
tional design of the system. Meditation phase B provides additional control measurements to compare the different meditation styles to each other and to resting baseline.

Third, the participants reflect on the results of the user test and conclude the experiment by filling out the questionnaire described earlier. Table 1 gives an overview of the applied procedure:

<table>
<thead>
<tr>
<th>Segments</th>
<th>Activities</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup</td>
<td>Introduction and informed consent</td>
<td>~120s</td>
</tr>
<tr>
<td></td>
<td>ECG sensor placement</td>
<td>~120s</td>
</tr>
<tr>
<td>User test</td>
<td>Preparation</td>
<td>40s</td>
</tr>
<tr>
<td></td>
<td>Baseline recording</td>
<td>120s</td>
</tr>
<tr>
<td></td>
<td>Meditation A (Biofeedback)</td>
<td>240s</td>
</tr>
<tr>
<td></td>
<td>Meditation B</td>
<td>240s</td>
</tr>
<tr>
<td>Reflection</td>
<td>Session review</td>
<td>~120s</td>
</tr>
<tr>
<td></td>
<td>Questionnaire</td>
<td>~120s</td>
</tr>
</tbody>
</table>

Table 1: Procedure of experiments

9.1.5 Limitations

The experimental setup presented here is limited by several aspects which were addressed as follows:

- **Physical activity**: Distortions in HRV recordings, especially the resting baseline, can occur if participants perform physical exercise right before the user test. Thus participants were asked not to do such activities before their test appointment.

- **Physical/mental discomfort**: For accurate data, the environment of the user test has to be suitable to meditation. This was accomplished by setting up the test environment according to the description in section 9.1.3.

- **Application disfunction**: Since the implemented prototype is not built to account for all types of possible errors, a disfunction in one of the systems software components can cause the abrupt ending of a session. This occurred in one of the 17 user tests which was voluntarily retaken by the participant in question.

- **Sensor misplacement/obtrusiveness**: Wrong placement of the ECG sensor obfuscates the measured data while uncomfortable placement reduces the participants capacity to accomplish stress reduction.
These limitations were addressed by carefully instructing the user how to put on the ECG chest strap and making sure the signal quality and wearing comfort is given.

- **Anxiety**: Anxiety and social stress distorts HRV recordings. Participants might be anxious about the data recording or the given instructions. To avoid this, participants are told that they do not take part in a competition and that they shouldn’t take the displayed measurements too serious.

- **No control for user characteristics**: Due to the limited time and people available for this experiment, it is not possible to control for age, gender, health condition or other variables that characterise the test subjects. This limitation could be addressed in future work.

- **Limited comparability of meditation phases**: Meditation phase B follows directly after meditation phase A. Thus, the recordings in the beginning of phase B are affected by the changes that occurred during phase A. To address this limitation, an experiment could be conducted where before each meditation phase a baseline recording is created. In this case the user test would consist of two separate meditation sessions.

- **No qualitative data**: Due to limited time, open-ended questions were not included in the questionnaire. In future work, such questions could be included to acquire qualitative data about the system usage.

### 9.2 Results

This section presents the results of conducting the described experiment with 17 participants.

#### 9.2.1 Questionnaire

Participants agreement to 8 statements was measured as interval data. Results of the questionnaire are presented for the aspects of meditation experience, acceptance and usability.

##### 9.2.1.1 Meditation Experience

The levels of meditation experience can be sorted in two groups. 13 of 17 participants indicated none to very little experience in the practice (0-20% agreement) while 4 participants reported medium to high experience (50-70% agreement)
agreement). Figure 9.2 shows the participants agreement to S1 from 0 (0%) to 10 (100%). The most frequent answer (mode) was 0% agreement.

**Figure 9.2:** Distribution of questionnaire responses to statement 1. The most frequent answer is 0.

### 9.2.1.2 Acceptance and Usability

Results of 4 items of the questionnaire were observed to estimate perceived usefulness of the system. First, 11 of 17 participants reported high agreement (80-90%) that the meditation session in the user test scenario was effective in lowering stress while all participants agreed at least 50% (Figure 9.3). The most frequent answer was 80% agreement.

**Figure 9.3:** Distribution of questionnaire responses to statement 2. The most frequent answer is 8.
Second, all participants agreed at least 50% that the system helps to practice meditation more effectively, 13 of them reporting high agreement (70-100%) (Figure 9.4). The most frequent answer was 60% agreement.

![Figure 9.4: Distribution of questionnaire responses to statement 3. The most frequent answer is 6.](image)

Third, 13 of 17 participants highly agreed that the real-time biofeedback display of stress levels facilitates the practice of meditation (80-100% agreement) (Figure 9.5). The most frequent answer was 80% agreement.

![Figure 9.5: Distribution of questionnaire responses to statement 4. The most frequent answer is 8.](image)

Fourth, 14 of 17 participants confirmed the system’s ability to motivate frequent meditation practice (70-100% agreement) (Figure 9.6). The most frequent answer was 80% agreement.

![Figure 9.6: Distribution of questionnaire responses to statement 5. The most frequent answer is 8.](image)
Figure 9.6: Distribution of questionnaire responses to statement 5. The most frequent answer is 8.

Using these items as variables, they can be combined via the arithmetic mean to give a score for perceived usefulness. This calculation results in a 77% agreement indicating that participants tend to perceive the system as useful.

In terms of usability, 16 of 17 participants highly agreed that the system is easy to use (80-100%) (Figure 9.7). The most frequent answer was 100% agreement.

Figure 9.7: Distribution of questionnaire responses to statement 6. The most frequent answer is 10.

14 of 17 participants agreed that reducing stress in everyday life is important to them (70-100%), indicating a positive attitude towards using methods for stress reduction (Figure 9.8). The most frequent answer was 70% agreement.
When asked specifically about their intention to apply the system in a daily/regular usage scenario, 9 of 17 participants agreed 70-100% that they can imagine regular use while 4 of them showed medium agreement (50-60%) and another 4 did not agree (0-20%) (Figure 9.9). The most frequent answer was 70% agreement.

9.2.2 User Tests

User tests were successfully completed with all 17 participants. The expected result of each test includes recordings with the length of 600 data points (equivalent to 10 minutes, the length of a user test session) for each of the measured indices (LF, HF, LFHF, HR, RR, rMSSD, pNN50). Thus, the highest possible number of data points that could have been measured is

39
71400. After the tests, 70833 data points existed. This means that about 0.8% of data collection operations failed which is an acceptable error rate, indicating the reliability of data collection in 99.2% of operations.

Each set of 571-600 data points represents a time series. The following are examples of time series charts that were created for each user test (Figure 9.10-9.13):

Figure 9.10: Example of LF/HF ratio time series

Figure 9.11: Example of LF and HF spectral power time series
No charts were created for the indices rMSSD and pNN50. They will only be considered for statistical analysis in the following sections where the different phases in the meditation sessions are compared. For this comparison of phases, a simple analysis of variance (ANOVA) was sufficient. Each of the indices of each user test result was combined via the arithmetic mean to acquire average values for each separate phase, for both meditation phases combined and for the whole session. RR intervals were not considered in this calculation since they are indirectly represented by the measured HRV indices. Based on the average values, percental changes were calculated to compare the differences between separate phases. Table 2 presents the combined averages of all 17 user test results.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF (ms²)</td>
<td>Total</td>
<td>1850</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>1275</td>
</tr>
<tr>
<td></td>
<td>Meditation Total</td>
<td>1998</td>
</tr>
<tr>
<td></td>
<td>Meditation A</td>
<td>2307</td>
</tr>
<tr>
<td></td>
<td>Meditation B</td>
<td>1673</td>
</tr>
<tr>
<td>LF (ms²)</td>
<td>Total</td>
<td>1829</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>2127</td>
</tr>
<tr>
<td></td>
<td>Meditation Total</td>
<td>1758</td>
</tr>
<tr>
<td></td>
<td>Meditation A</td>
<td>1983</td>
</tr>
<tr>
<td></td>
<td>Meditation B</td>
<td>1511</td>
</tr>
<tr>
<td>LF/HF</td>
<td>Total</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>1.96</td>
</tr>
<tr>
<td></td>
<td>Meditation Total</td>
<td>0.99</td>
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<tr>
<td></td>
<td>Meditation A</td>
<td>1.01</td>
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<tr>
<td></td>
<td>Meditation B</td>
<td>0.98</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>Total</td>
<td>78.7</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>84.0</td>
</tr>
<tr>
<td></td>
<td>Meditation Total</td>
<td>77.4</td>
</tr>
<tr>
<td></td>
<td>Meditation A</td>
<td>77.2</td>
</tr>
<tr>
<td></td>
<td>Meditation B</td>
<td>77.5</td>
</tr>
<tr>
<td>rMSSD (ms)</td>
<td>Total</td>
<td>55.6</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>59.9</td>
</tr>
<tr>
<td></td>
<td>Meditation Total</td>
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</tr>
<tr>
<td></td>
<td>Meditation A</td>
<td>56.9</td>
</tr>
<tr>
<td></td>
<td>Meditation B</td>
<td>51.9</td>
</tr>
<tr>
<td>pNN50</td>
<td>Total</td>
<td>25.7</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
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<td></td>
<td>Meditation Total</td>
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</tr>
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<td>Meditation A</td>
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<td>Meditation B</td>
<td>24.3</td>
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<tr>
<td>RR interval (s)</td>
<td>Total</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>Meditation Total</td>
<td>0.80</td>
</tr>
<tr>
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<td>Meditation A</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Meditation B</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 2: User test results: combined averages

9.2.2.1 Effectiveness of Meditation Practice

To position the results of the user test in the context of research about meditation-induced HRV, the averages in the baseline phase are compared with the combined averages of both meditation phases. From this perspective, tables 3 and 4 present the percental changes in the measured indices:
### Meditation vs. baseline: percental changes

<table>
<thead>
<tr>
<th>Session ID</th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
</tr>
</thead>
<tbody>
<tr>
<td>3236</td>
<td>-0.11%</td>
<td>57.09%</td>
<td>-34.87%</td>
<td>7.50%</td>
<td>25.58%</td>
<td>-29.92%</td>
</tr>
<tr>
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<td>-42.89%</td>
<td>-39.84%</td>
</tr>
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<td>98.25%</td>
<td>-56.24%</td>
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<td>0.44%</td>
<td>-16.01%</td>
</tr>
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<td>-18.53%</td>
<td>-11.76%</td>
</tr>
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<td>-7.25%</td>
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<td>-15.13%</td>
<td>-15.00%</td>
</tr>
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<td>160.94%</td>
<td>-21.92%</td>
<td>0.00%</td>
<td>37.41%</td>
<td>455.35%</td>
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<tr>
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<td>-75.08%</td>
<td>-55.25%</td>
<td>-3.70%</td>
<td>-41.74%</td>
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</tr>
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<td>36.37%</td>
</tr>
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<td>151.44%</td>
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<td>-46.37%</td>
<td>-90.18%</td>
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<td>-73.72%</td>
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<td>-12.43%</td>
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</tr>
</tbody>
</table>

Table 3: Meditation vs. baseline: percental changes

<table>
<thead>
<tr>
<th>Change (Mean)</th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
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<tbody>
<tr>
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<tr>
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<tr>
<td>Decrease (Count)</td>
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<td>6</td>
<td>16</td>
<td>12</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Decrease (Mean)</td>
<td>-45%</td>
<td>-43.2%</td>
<td>-48.6%</td>
<td>-11.3%</td>
<td>-28.9%</td>
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<td>0</td>
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</tbody>
</table>

Table 4: Meditation vs. baseline: mean and count of change

Compared to resting baseline, 16 of 17 participants showed decreased LF/HF ratio, indicating lower stress, during the practice of meditation. In these cases, stress changed by -48.6% on average while in total it changed by -44.1%. LF component in spectral power was decreased in the results of 14 of 17 participants, where the average change by -45% was calculated. HF component in spectral power was increased, on average by 172.2%, in 11 of 17 participants. For 12 of 17 participants heart rate decreased on average by -11.3%. 10 of 17 participants showed in total a -28.8% decrease of rMSSD during meditation. pNN50 was increased in 9 of 16 (the measurement of pNN50 failed in one user test) participants with an average change of 139%.
As described in chapter 3, increased HF as well as decreased LF/HF ratio are desirable results in the scenario of meditation. They reflect the enhancement of vagal modulation and the reduction of sympathetic modulation. On the one hand, this shows that the practice of meditation is an effective method to lower stress while on the other hand it confirms that the implemented system, from a medical perspective, yields results of high fidelity.

9.2.2.2 Feasibility of Real-time HRV biofeedback

To reflect on the feasibility and effectiveness of the real-time HRV biofeedback display that was applied in the user tests, results of both meditation phases are separately compared to resting baseline while the meditation phases are compared to each other. Please keep in mind that due to phase B directly following after phase A, the results of phase B have limited comparability.

<table>
<thead>
<tr>
<th>Session ID</th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
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<tbody>
<tr>
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<td>5.00%</td>
<td>-9.27%</td>
<td>-29.92%</td>
</tr>
<tr>
<td>8322</td>
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<td>3467</td>
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<td>99.17%</td>
<td>151.77%</td>
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<td>7.08%</td>
<td>62.76%</td>
</tr>
</tbody>
</table>

Table 5: Meditation A vs. baseline: percental changes
Table 6: Meditation A vs. baseline: mean and count of change

<table>
<thead>
<tr>
<th>Change (Mean)</th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase (Count)</td>
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<td>8</td>
<td>10</td>
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<tr>
<td>Increase (Mean)</td>
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<td>-7.4%</td>
<td>12.9%</td>
<td>79.6%</td>
</tr>
<tr>
<td>Decrease (Count)</td>
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<td>4</td>
<td>14</td>
<td>12</td>
<td>9</td>
<td>6</td>
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<tr>
<td>Decrease (Mean)</td>
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<td>-58.4%</td>
<td>-55%</td>
<td>-11.1%</td>
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<td>-28.5%</td>
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</table>

Compared to resting baseline (tables 5 and 6), meditation with the help of the biofeedback display is represented by an average decrease of -55% in LF/HF ratio for 14 of 17 participants. Considering all 17 participants, stress decreased by -41.8%. In 11 of 17 participants, LF was decreased, changing by -43.7% while for the other 6 participants it increased on average by 180.5%. HF was increased in 13 of 17 participants with an average of 186.9%. A decrease in heart rate, on average by -11.1%, was measured in 12 of 17 participants, while 3 showed no change and 2 a slight increase (3.8%). In rMSSD, 9 of 17 participants showed a decrease (-24.7%) while 8 showed an increase (55%). pNN50 was increased in 10 of 16 participants with an average change of 144.4%.

Table 7: Meditation B vs. baseline: percental changes

<table>
<thead>
<tr>
<th>Session ID</th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
</tr>
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<tbody>
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<td>-0.46%</td>
<td>-0.46%</td>
<td>46.68%</td>
<td>11.25%</td>
<td>60.88%</td>
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<td>-31.89%</td>
<td>-43.94%</td>
</tr>
</tbody>
</table>

Table 7: Meditation B vs. baseline
Comparing phase B (tables 7 and 8), where participants meditated with their eyes closed, to the resting baseline, 15 of 17 participants showed a decrease in LF/HF ratio, on average by -51.1%. In total, stress was reduced by -41.8%. LF was decreased in 14 of 17 participants with an average change of -52.9%. In 9 of 17 participants, HF increased on average by 146.9% while the other 8 participants showed a decrease of -42.3%. Heart rate was decreased in 11 of 17 participants, on average by -12.5% while 3 showed no change and 3 an increase (6.9%). Results of 11 of 17 participants document a decrease in rMSSD (average change of -31%), 6 showing an increase (57.4%). pNN50 was decreased for 9 of 16 participants (-36.7) while increased for the other 7 participants (161.6%).

<table>
<thead>
<tr>
<th>Change (Mean)</th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
</tr>
</thead>
<tbody>
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<td>57.9%</td>
<td>-41.8%</td>
<td>-6.9%</td>
<td>0.2%</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Increase (Count)</td>
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<td>27.7%</td>
<td>6.9%</td>
<td>57.4%</td>
<td>161.6%</td>
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<tr>
<td>Decrease (Count)</td>
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<td>15</td>
<td>11</td>
<td>11</td>
<td>9</td>
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<tr>
<td>Decrease (Mean)</td>
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<td>-51.1%</td>
<td>-12.5%</td>
<td>-31%</td>
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Table 8: Meditation B vs. baseline: mean and count of change

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<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
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<td>-65.55%</td>
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</tbody>
</table>

Table 9: Meditation A vs. meditation B: percental changes
Comparing the two meditation phases to each other (tables 9 and 10), 9 of 17 participants showed higher stress during meditation phase B (on average by 42.1%) indicated by an increase in LF/HF ratio. For the other 8 participants, LF/HF ratio was decreased showing higher stress during meditation phase A (with an average change of -36.3%). 14 of 17 participants had decreased LF, on average by -30.3%. HF component was also decreased for 12 of 17 participants (-31% change). Heart rate change was evenly distributed in both phases, 6 showing a decrease (-2.1%) and another 6 an increase (3.6%) during meditation phase B (5 showed no change). In phase B, rMSSD was decreased for 14 of 17 participants, on average by -13.2% while pNN50 decreased on average by -22.7% for 13 of 16 participants.

In total, meditation using the real-time biofeedback showed results of similar desirability in measured variables which indicates that the application of biofeedback for meditation practice is feasible and does not reduce the effectiveness of the practice. In the context of meditation experience, participants with higher experience did not produce significantly different results than those with no or little experience. These results are not presented here, they have poor comparability due to different group sizes.

<table>
<thead>
<tr>
<th></th>
<th>LF</th>
<th>HF</th>
<th>LF/HF</th>
<th>HR</th>
<th>rMSSD</th>
<th>pNN50</th>
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<tr>
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<td>-18.9%</td>
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<td>-5.9%</td>
<td>-9.3%</td>
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<tr>
<td>Increase (Count)</td>
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<td>5</td>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Increase (Mean)</td>
<td>6.4%</td>
<td>10.2%</td>
<td>42.2%</td>
<td>3.6%</td>
<td>28.3%</td>
<td>49%</td>
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<tr>
<td>Decrease (Count)</td>
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<td>12</td>
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<td>14</td>
<td>13</td>
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<tr>
<td>Decrease (Mean)</td>
<td>-30.3%</td>
<td>-31%</td>
<td>-36.3%</td>
<td>-2.1%</td>
<td>-13.2%</td>
<td>-22.7%</td>
</tr>
<tr>
<td>No change (Count)</td>
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<td>0</td>
<td>0</td>
<td>5</td>
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</table>

Table 10: Meditation A vs. meditation B: mean and count of change
10 Discussion

The first challenge of this work was to find out how biofeedback can provide valuable information to a meditation practitioner during the practice. Through background research, it was found that HRV biofeedback and meditation are both viable methods in the context of stress reduction. HRV analysis allows to measure and quantify the balance and activation in the sympathetic and parasympathetic branches of the autonomic nervous system. With this information the stress response of individuals can be estimated in real-time which is valuable feedback in the scenario of meditation practice aimed at the reduction of stress. Thus, a system was proposed that gives short-term feedback on stress response in this scenario. The chosen approach to infer and provide valuable parameters for meditation implies the application of an ECG sensor for real-time analysis of frequency domain HRV using the Lomb method.

The next step was to identify the requirements for implementing the proposed solution. The resulting design specification and prototypical implementation were found to meet these requirements. Conducting an experiment including a user test and a questionnaire, the system prototype was evaluated. First, the evaluation focused on how accepted the system is from the perspective of the meditation practitioner. Results of the questionnaire show that the majority of participants found the tested system to be easy to use and perceived it as being useful for meditation. Participants confirmed that they are interested in solutions for stress reduction in daily life and that they have a positive attitude towards using the tested system. From the standpoint of technology acceptance, the proposed solution was found to be feasible.

Second, user tests were performed to evaluate the fidelity of acquired HRV measurements in the medical context. Analysing the HRV recordings it was confirmed that the positive effects of meditation reported by similar research were reproduced in most participants. During meditation phases of the user test, an increase in HF spectral component was found, indicating higher activity in the parasympathetic nervous system which is linked to the 'rest and digest' response of the body. Also, LF spectral component was decreased, indicating less activity in the sympathetic nervous system and thus a reduced 'fight-or-flight' response. Combined, the ratio of these components measures stress which was reduced by -48.6% in 16 of 17 participants. Besides LF and HF, time domain HRV indices pNN50 and rMSSD were recorded. While both measures are reported to be correlated with HF [33], the statistics of rMSSD did not reflect this correlation due to insignificant results. Like HF,
pNN50 was increased during meditation. This is relevant for future research on pNN50 for the assessment of stress-regulation. These results confirm the selected approach to implementing the system and prove that biofeedback can be applied in the scenario of meditation without interfering with the effectiveness of the practice.

When asked about their experience in practicing meditation, most participants reported none or little experience. Nonetheless, HRV measurements show that they were able to effectively practice meditation during the user tests. Aligned with results of the questionnaire, this indicates that the implemented system is able to instruct as well as help to reflect on meditation practice. Thus, the proposed solution extends previous research on real-time reflective human-computer-interfaces. It is shown to be a promising approach in the scenario of personalised health-care, representing a viable and cost-effective method for stress reduction and disease prevention. In contrast to breath-monitoring systems presented in Chapter 4, the application in this work allows to evaluate meditation while not being dependent on specific forms of meditation. For example, the system does not require the meditator to match a fixed breath rate, but instead encourages him to try out different breathing/relaxation techniques to learn how they influence his autonomic function. The results of this work and the implemented prototype suggest that the system has the potential to help people integrate the practice of meditation into daily life as well as learn how to practice it more effectively over time.

However, research on the convergence of meditation and biofeedback is still in an early stage, demanding extensive study of its application in different usage environments. On the one hand, this implies testing of the system in more specific scenarios by controlling for independent variables like age or physical condition of users as well as by experimenting with different sensing devices, algorithm, visualisation methods or meditation techniques. On the other hand, the feasibility of the system needs to be investigated in the context of longer usage periods to show if continuous use confirms and enhances the results of this work, for example by tailoring the application to ongoing personalised stress intervention programs.
11 Conclusion

The purpose of this work was to innovate the application of real-time HRV biofeedback in the scenario of meditation practice to provide a feasible and cost-effective solution for stress reduction. There is a high demand for such solutions due to the negative impacts of stress on modern society and the associated health care costs. Proceedings in the research on sensing technology paved the way for building cost-effective systems for stress assessment which can be used at home by non-experts. According to software development life cycle, a system was proposed and prototypically implemented. It measures and processes heart rate acquired by an ECG sensor and displays an HRV-derived stress level to inform the meditation practitioner about the effectiveness of the practice.

In an experimental setup, studies of medical fidelity of HRV data as well as technology acceptance have proven that the system meets the requirements for being a viable solution. First, it was perceived to be useful and easy to use. Second, positive attitude towards the system and motivation to apply it in a regular usage context was reported. Third, the experiments reproduced measurements of meditation-induced HRV reported by previous research. Based on these results, it can be concluded that the reflective aspect of the implemented biofeedback system helps to improve regulatory capacity and thus lowers stress in individuals. However, further research is required, especially to test if these effects can be reproduced in the context of regular usage.

11.1 Implications for Future Work

Research on real-time reflective human-computer-interfaces for stress assessment and reduction is still in an early stage. The high prevalence of stress, especially in western civilisation, and the related negative impact on our health care systems demand for cost-effective and easily accessible methods for disease prevention and stress reduction. This work proposed such a method and confirmed its feasibility. On the way towards personalised health care, trends indicate that there is a need for solutions like the one presented here. Thus, the challenge of future research is to further evaluate and improve the proposed system in this context, for example in the following ways.

First and foremost, the unsolved limitations in experimental design need to be addressed. For better comparability of meditation phases, the experiment could be split up in multiple sessions to record the data of the phases separately and independent of each other. Second, an obvious enhancement of the system is related to its reflective aspect. Comparing meditation effec-
tiveness throughout several sessions, the system could quantify improvements over time and give feedback on learning curve. It has to be investigated whether this added functionality promotes a learning effect or the motivation to practice regularly. As a third suggestion, the research of this work can be extended by testing the proposed system in different user groups and with different variations of meditation practice and by experimenting with additional sensing methods such as electroencephalography (EEG). Fourth, user studies should be performed on larger groups of participants as well as over longer time periods for more precise and time-tested estimation of the systems effectiveness.
References


