Personalised relaxation therapy in Virtual Reality

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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Computer Science Engineering

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Preface

I would like to thank my supervisors, prof. dr. ir. Filip De Turck and dr. ir. Femke De Backere, for giving me the opportunity of working on this subject. Also, I would like to genuinely thank my counsellors, ir. Joris Heyse and dr. ir. Maria Torres Vega, for their insights, feedback, and continuous guidance throughout this master’s thesis. Finally, I would like to thank my parents for giving me the opportunity of choosing these studies and supporting me throughout them.

Thomas De Jonge, August 2019
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Thomas De Jonge, August 2019
Abstract
Stress, especially when work-related, is one of the most frequent health problems and is considered responsible for many physical and psychological problems. It has been linked to negative effects on employee well-being in many occupations, with teaching and educational professionals at particular risk. Traditional therapy approaches prove to be effective at treating mental health risks. However, despite their effectiveness, they present limitations. Traditional therapy tends to be expensive, time consuming, difficult to organize and control, and is not accessible to everyone. Therefore, researchers show an increasing interest for virtual reality, as this technology overcomes most of these limitations. This master’s thesis presents a system that provides a personalized virtual reality experience for relaxation therapy. The proposed system generates a virtual environment fit to the needs of the user, i.e., based on the user’s personality. During therapy, the system makes changes to the environment by observing the user’s emotional state and deciding autonomously which actions benefit the user. Thus, the system provides both personalized and adaptive therapy. It achieves this by modelling the user’s personality and emotions. These models are analyzed and discussed by using simulated users.

Keywords
Relaxation Therapy, Virtual Reality, Personalization, Emotions Modelling
Personalised Relaxation Therapy in Virtual Reality

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Abstract—One of the most frequent health problems is stress, especially when work-related. It has been linked to negative effects on employee well-being in many occupations, and is considered responsible for many physical and psychological problems. Traditional therapy approaches prove to be effective at treating mental health risks. However, despite their effectiveness, they present limitations. Traditional therapy tends to be expensive, time consuming, difficult to organize and control, and is not accessible to everyone. Therefore, researchers show an increasing interest for virtual reality, as this technology overcomes most of these limitations. This work presents a system that provides a personalized virtual reality experience for relaxation therapy. The proposed system generates a virtual environment fit to the needs of the user. During the therapy session, the system makes changes to the environment by observing the user’s emotional state and deciding autonomously which actions benefit the user. Thus, the system provides both personalized and adaptive therapy. It achieves this by modelling the user’s personality and emotions. These models are analyzed and discussed by using simulated users.

Index Terms—Relaxation Therapy, Virtual Reality, Personalization, Emotions Modelling

I. INTRODUCTION

According to the World Health Organization, stress, especially that relating to work, is the second most frequent health problem, impacting one third of employed people in the European Union [1]–[3]. It has been widely linked with adverse effects on employees, their psychological and physical well-being in many occupations, with teaching and educational professionals at particular risk [4,5]. Excess stress contributes to the development of physical ailments such as hypertension, ulcers, skin disorders, headaches, arteriosclerosis, cardiovascular disease, and other life-threatening diseases [6,7]. Due to the prevalence of these stress-related health conditions, their costs to a nation’s health care system, and the loss of quality of life for individuals, public health professionals are increasingly concerned over the effects of stress [8]. Research has shown that personalized stress management techniques, such as relaxation therapy, are recommended to reduce perceived stress [2].

Despite their effectiveness, traditional therapy presents limitations. It requires high effort in terms of cost and time expenditure, since usually the therapist and the patient meet each other inside or even outside of the therapist’s office [9]. Furthermore, people with limited mobility or people who live in an area where therapy is not available may find it difficult to enter therapy [10]. Lastly, people may be reluctant to enter therapy because of the social stigma of mental disorders. Although this stigma is less of a problem today, visiting a health care center for a mental disorder or therapy is a difficult situation for some people (and communities) and they wish to keep it private [10]. These limitations result in a treatment rate of only 33% of the targeted patients [11]. For these reasons, clinicians are showing an increasing interest for a novel tool to treat anxiety symptoms that overcomes most of these limitations: Virtual Reality (VR) [9].

This paper focuses on using VR for relaxation therapy. The goal is not to create new relaxation techniques and methods, but rather to implement traditional knowledge into VR. Traditional therapy does not apply a ‘one size fits all’ approach, instead, therapy tends to be fit to the needs of the user. Similar, VR relaxation therapy takes into account the personality of the participant when generating a Virtual Environment (VE). Doing this will result in different VEs and relaxation methods for different users. Furthermore, based on how the user feels, the system should adapt the VE in order to guide the user towards maximal relaxation. To achieve this, it has multiple relaxation methods available. Which methods it uses depends on both the personality and the current emotional state of the user. As the emotions of the user change over time, so should the relaxation method. VR therapy may start with a relaxation method that reduces fear and afterwards, when the user is not afraid any more, it may switch to a methods that reduces stress. In summary, this work proposes a personalized and adaptive VR approach to relaxation therapy. To achieve this, the system takes into account both the personality and the emotional state of the user, and makes decisions based on these parameters.

II. RELATED WORK

VR has been used in clinical settings to treat a range of cognitive, emotional and motor problems in various psychological and psychiatric disorders [12]. Despite this, the use of VR in relaxation therapy is very limited if not non-existent. There do exist many VR relaxation applications, but none of them serve as therapy or take into account the personality of the patient. However, VR has found its way into other forms of therapy, e.g., Exposure Therapy (ET). Using VR in ET is consequentially called Virtual Reality Exposure Therapy (VRET). When comparing VRET to control conditions (i.e.,
a control group), VRET has shown to be the most effective treatment method [12]–[14]. When comparing VRET to conventional Cognitive Behavioral Therapy (CBT), this is a psycho-social intervention that is the most widely used evidence-based practice for improving mental health around the world [15], VRET shows at least similar results [12]. The effectiveness of Virtual Reality in psychological treatment (VRT) varies depending on the mental health disorder reviewed. However, it has been confirmed that multiple sessions of VRT can be a valuable treatment for agoraphobia with or without panic disorder, fear of flying, social anxiety, fear of public speaking, spider phobia, and social anxiety [12, 13, 16]–[18]. Also promising are the findings regarding the use of VRT for Post Traumatic Stress Disorder (PTSD). Furthermore, it has been suggested that bio-feedback and the use of a mobile device may offer an added value to the treatment [19].

### III. Methodology

This section will go over the methods used to design a personalized VR approach to relaxation therapy. First, the high-level architecture of the system is discussed. Next, the methods used to realize the different architectural components are presented.

#### A. Architecture

The used high-level architecture is illustrated by Figure 1. It consists of four major components and four types of data. The first type of data is personality data, which describes the personality of the user. In this work, it is provided by the user himself by filling in a questionnaire. The second type of data is emotional data. This data describes the emotions of the user at any time during the therapy session. When creating an environment, both the personality and the emotions of the user are taken into account. However, in order not to break the immersiveness, radical changes in the environment are discouraged. Therefore, a rough outline of the environment is generated first. It is based purely on the personality of the user, and is independent of the user's emotional state. Generating this raw environment is done by the environment generator, resulting in raw environment data. Next, this data is enhanced to create the final environment that is shown to the user. This enhancement is done by the adaptor component and results in environment data. Now, the VE can be shown to the user. This is done by the VE render component. Visualizing the environment will trigger an emotional reaction on the user, which is simulated by the emotional model, resulting in new emotional data. This data is then fed back to the adaptor, completing the cycle. In the next sections, further details on the environment generation, emotional model, and adaptor are given.

#### B. Personality model

The environment generator is responsible for generating a raw environment based on the personality of the user. In order to achieve this, it uses decision trees. The decisions taken at every decision node depend solely on the user’s personality data and each outcome represents a different raw environment. The set of possible raw environments is fixed and thus the same for every user. Therefore users with similar personalities could generate the same raw environment. However, their final environments may still show significant differences as the environment details get decided upon later, and are based on the user’s emotional status.

#### C. Emotional model

This work does not utilize user generated feedback such as physiological data. Instead, a model that simulates the emotional state of the user, is defined. In this section, this model is be presented. Relaxation is influenced by stress, anxiety, fear, and arousal [20]. Both fear and anxiety as stress and anxiety tend to overlap and have similar physiological symptoms. Therefore, not including anxiety will simplify the emotional model without losing much information. The emotional model thus focuses on four parameters: fear, stress, arousal, and relaxation. The generic formula used to compute relaxation is given by Equation 1.

\[
relaxation = r(fear, stress, arousal, \
lc, al, nl, dg, py, ms, cb)
\]  

As Equation 1 indicates, the user’s relaxation depends on his current emotions (fear, stress, and arousal). Furthermore, it depends on the possible system real-time adaptations (lc, al, nl, dg, py, ms, and cb). The adaptations are the possible enhancements the adaptor can make to the environment, and are summarized in Table I. In the following paragraphs, the components of the relaxation equation are discussed.

1) **Preference:** In order to determine the impact of individual adaptations on the user’s emotional state, a function is necessary that indicates how much the user likes the current state of the adaptation. This function is called the preference function and is defined by Equation 2. It can be described a Gaussian with maximum value of 1, centered around the adaptation’s optimal intensity. This optimal intensity is a value derived from the personality data and therefore a constant. Its value lies between zero and one. Zero indicates...
that the user does not like the adaptation, one that he likes it very much. The more an optimal intensity leans towards 0.5, the more the user feels indifferent about the adaptation and thus, the flatter the Gaussian becomes. This is visualized by Figure 2.

\[
\text{pref}(x) = \exp\left(\frac{-\left(x_{\text{opt}} - x\right)^2}{2 \cdot (1.075 - 2 \cdot |0.5 - x_{\text{opt}}|)^2}\right) \tag{2}
\]

2) Fear: Based on the adaptations, three sources of fear can be distinguished. The first is pyrophobia, i.e. fear of fire, and is induced by the fire adaptation. The second is cynophobia, i.e. fear of dogs, and is induced by the dog adaptation. The last source of fear is nyctophobia, i.e. fear of darkness, and is induced by the combination of the fire, natural light, and artificial light adaptations. Equation 3 defines how fear is calculated by the model. This equation contains three instances of the \(\text{fear}(\cdot)\) function, one for every source of fear. \(F_1\), \(F_2\) and \(F_3\) are used to normalize fear and give weights to the different sources. These are constants based on the user’s personality. The resulting function outputs a value between negative and positive 1. Negative fear indicates that the user is not afraid and actually feels comfortable, whilst positive fear indicates the user is afraid.

\[
\text{fear} = F_1 \cdot \text{fear}(dg) + F_2 \cdot \text{fear}(py) + F_3 \cdot \text{fear}(\text{dark}) \tag{3}
\]

\[
dark = 1 - I_1 \cdot al - I_2 \cdot nl - I_3 \cdot py \tag{4}
\]

\[
\text{fear(source)} = (1 - 2 \cdot source_{\text{opt}}) \cdot source \tag{5}
\]

The \(\text{fear}(\cdot)\) function is used to compute the impact of a certain source of fear on the user. It is defined by Equation 5, where \(\text{source}\) is the current intensity of the source and \(\text{source}_{\text{opt}}\) is its optimal intensity. If the source of fear has an optimal intensity value lower than \(\frac{1}{2}\), it frightens the user. A value above \(\frac{1}{2}\) indicates comfort. The magnitude of fear or comfort depends on how much the value leans towards respectively zero or one. The \(\text{fear}(\cdot)\) function is visualized in Figure 3. Based on it, the three sources of fear are defined. Before defining the impact of nyctophobia, a measure for darkness is needed. This measure is given by Equation 4 and defines how dark the environment is. In this equation, \(I_1\), \(I_2\), and \(I_3\) are constants used for giving weights to the adaptations and to achieve normalization. Calculating pyrophobia, cynophobia, and nyctophobia can now be achieved by inserting respectively \(py\), \(dg\), and \(\text{dark}\) into Equation 5.
3) Stress: The equation for calculating stress is given by Equation 6. As with fear, $S_1$ and $S_2$ are constants based on the user’s personality, used to normalize stress and give weights to the different components. This leads to a value for stress between zero and one.

$$stress = \max(fear, stress_{core}, s)$$

$$stress_{core} = \min(stress_{prev}, 1 - cb)$$

$$s = S_1 \cdot (1 - pref(py)) + S_2 \cdot (1 - pref(dg))$$

4) Arousal: Equation 7 presents the definition of arousal. This function can be interpreted as follows: arousal will only increase when fear or stress increases, and it will only decrease when the music is optimal and/or the environment is bright. Again, $A_1$, $A_2$ and $A_3$ ensure the arousal is normalized and give weights to the different components. They are constants based on the user’s personality. The value for arousal always lies between zero and one.

$$arousal = \max(fear, stress, arousal_{core})$$

$$arousal_{core} = \min(arousal_{prev}, a)$$

$$a = A_1 \cdot (1 - pref(ms)) + A_2 \cdot (1 - nl) + A_3 \cdot (1 - al)$$

5) Relaxation: The function for relaxation is given by Equation 8, maximizing this emotion is the goal of this work. As with all other emotions, $R_1$ to $R_8$ ensure the relaxation is normalized and give weights to the different components. $R_1$ to $R_8$ are constants based on the user’s personality.

$$relaxation = R_1 \cdot pref(ms) + R_2 \cdot pref(lc)$$

$$+ R_3 \cdot pref(nl) + R_4 \cdot pref(al)$$

$$- R_5 \cdot cb - R_6 \cdot fear$$

$$- R_7 \cdot arousal - R_8 \cdot stress$$

D. Adaptor

The adaptor is the component in charge of updating the adaptation intensities in real-time. It observes the current state of the VE and the user’s emotional data. Based on this, it decides which adaptation intensity should be changed next. The adaptor updates one adaptation at a time. It calculates which action is best, performs this action, and waits for the user’s emotional data to update. This process is repeated until the user reaches his optimal emotional state, at which point no more adaptations are necessary. Finding this optimal state and the maximal relaxation linked to it, can be formulated as an optimization problem. The emotional model is a non-linear model and can be solved using Mixed Integer Non-Linear Programming (MINLP). As MINLP problems are not easy to solve, the problem (and thus, the model) can be linearized. This results in a linear problem that can be solved using Mixed Integer Linear Programming (MILP). However, even then, it cannot be solved in real-time. Therefore, a heuristic approach is used.

The heuristic approach first determines the absolute maximum relaxation, and the set of adaptation intensities that lead to this. It achieves this by sampling the adaptation intensities and comparing all possible combinations, i.e. a brute force approach. The combination that leads to the maximal relaxation value is the combination the heuristic optimizer should work towards. As it can only change one adaptation intensity per step, it should choose an order in which to change the intensities. The order the heuristic optimizer applies is fixed, and is illustrated by Code Fragment 1.

Code Fragment 1: Order used by the heuristic optimizer.

```python
def run():
    env = application.getEnvironment();
    opt = application.getOptimalCombination();
    env.set("dg", opt.get("dg"));
    env.set("py", opt.get("py"));
    env.set("ni", opt.get("ni"));
    env.set("ai", opt.get("ai"));
    env.set("cb", "on");
    env.set("al", "off");
    env.set("ms", opt.get("ms"));
    env.set("lc", opt.get("lc"));
```

IV. IMPLEMENTATION

This section discusses the implementation of the personalized and adaptive VR application for relaxation therapy. First, an overview of the physical setup and used technologies is given. Next, the questionnaire used to determine the personality data is presented. Afterwards, the environment generator (see Figure 1) is discussed. Finally, the implementation of the emotional model and adaptor are presented.

A. Setup and technologies

The application can be divided into two parts: the dashboard application and the render application. The dashboard application contains the environment generator, the adaptor, and the emotional model, as well as the personality data, emotional data, raw environment data, and environment data. It is a desktop application written using JavaFX (version 12). SceneBuilder (version 11.0.0) is used to create the different views and Apache Maven (version 3.6.1) to compile and build. The render application receives the environment data from the dashboard application, creates the corresponding VE, and displays this to the Head Mounted Display (HMD) worn by the user. The render application is realized using Unity (version 2018.3.10f1). C# is used for writing scripts in Unity. The HMD used is the HTC Vive, and SteamVR software is used to render the Unity scene onto the device. As both applications are desktop applications, they are run on the same physical device. This is a computer with a i7-6700K processor, 16GB memory and a GTX 980ti Graphics card, running Windows 10.

B. Questionnaire

A questionnaire is used to gather both the personality data and the initial emotional data. The questions asked to gather the personality data are given by questions one to nine in Table II. This data consists of optimal intensities...
Table II: The questionnaire given to the user at the start of the application.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Question</th>
<th>Derived parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Would you prefer an indoors or outdoors environment to relax?</td>
<td>binindoors</td>
</tr>
<tr>
<td>2</td>
<td>Could the presence of water help you relax?</td>
<td>binwater</td>
</tr>
<tr>
<td>3</td>
<td>Are you afraid of heights?</td>
<td>binheights</td>
</tr>
<tr>
<td>4</td>
<td>What is your favorite season?</td>
<td>binsummer</td>
</tr>
<tr>
<td>5</td>
<td>How does fire make you feel?</td>
<td>binfire, pFire opt</td>
</tr>
<tr>
<td>6</td>
<td>How do you feel when a dog is in your presence?</td>
<td>bindog, ddog opt</td>
</tr>
<tr>
<td>7</td>
<td>How does darkness make you feel?</td>
<td>darkopt, ndopt, dopt</td>
</tr>
<tr>
<td>8</td>
<td>How do you find classical relaxation music?</td>
<td>milopt</td>
</tr>
<tr>
<td>9</td>
<td>Blue light gives you a relaxed feeling, do you agree?</td>
<td>lOpt</td>
</tr>
<tr>
<td>10</td>
<td>How afraid do you feel right now?</td>
<td>fearinitial</td>
</tr>
<tr>
<td>11</td>
<td>How stressed do you feel right now?</td>
<td>stressinitial</td>
</tr>
<tr>
<td>12</td>
<td>How aroused do you feel right now?</td>
<td>arousalinitial</td>
</tr>
</tbody>
</table>

Figure 4: Decision tree used by the environment generator.

Figure 5: Optimization process by the heuristic optimizer.

Results show that the heuristic model achieves maximum relaxation for every outdoors environment, but not for every indoors environment. However, despite not always achieving maximal relaxation, it does get close. The default heuristic model often executes adaptations with higher impact during the later steps. Performing these steps earlier may relax the user sooner, and result in an overall better experience. These observations indicate that more optimal sequences (i.e. the order in which adaptations are changed) may exist. Figure 5 illustrates the process for one user.

V. RESULTS

Different users behave differently and thus, in order perform a comprehensive analysis, a variety of twelve different users is analyzed. This is achieved by simulating the input users can provide to the application, i.e. the questionnaire. For each of these users, the therapy process is simulated. The simulated sessions are ranked first according to the final relaxation value and second to their average relaxation during the session.

Changing the sequence in which the heuristic optimizer performs adaptations leads to the following observations. For outdoors environments, it always is possible to reach the optimal state of relaxation, no matter the sequence. However, despite not always achieving maximal relaxation, it does get close. The default heuristic model often executes adaptations with higher impact during the later steps. Performing these steps earlier may relax the user sooner, and result in an overall better experience. These observations indicate that more optimal sequences (i.e. the order in which adaptations are changed) may exist. Figure 5 illustrates the process for one user.

The environment generator uses the personality data and transforms it into a raw environment using a decision tree. This tree is given in Figure 4. For every possible outcome, a raw VE was created. After choosing a VE using the decision tree, the environment generator decides which version of the VE should be loaded. This version depends on the binary variables binfire, bindog, and binsummer.

D. Emotional model and Adaptor

The emotional model has already been defined in Section III-C. For implementation, an exact value for every constant is selected. They are chosen so that each term has the same impact to the equation and to achieve normalization. These values, together with the emotional model, fully define the implementation of the emotional model. The adaptor uses the heuristic optimizer to find the best sequence that leads to the optimal state of relaxation, as defined in Section III-D. In order to find the optimal state of relaxation, it uses a brute force approach. After this optimal has been found, the heuristic optimizer uses a fixed sequence to get to this state.
An approach that could guarantee an optimal outcome is used, i.e., the heuristic optimizer, did show some flaws. However, the optimization algorithm based on (generating the final environment based on the basic environment and emotional data) has shown to be effective as well. Furthermore, hardware capable of running these applications is independent of the environment as it is based on physiological data and not adoptions. Therefore, different environments do not require a different model, resulting in a more flexible application. Using biofeedback is an interesting topic for future work.

We conclude this work by stating that it is definitely possible to create a system that provides a personalized VR experience for relaxation therapy. However, these kind of systems are still in their infancy stage and require more research. Most importantly, there is a need for a biofeedback model that uses physiological data to define how a user feels. Furthermore, hardware capable of running these applications in real-time should become more widely available in order to fully exploit the strengths of VR.

VI. CONCLUSION AND FUTURE WORK

This work presents a system that provides a personalized VR experience for relaxation therapy. The chosen architecture and setup, as illustrated by Figure 1, is an effective approach. The environment generator component consists of a set of binary variables, used in a decision tree. This is a simple yet effective model that does not need more complication as only a limited set of basic environments are possible. The principle the adaptor component is based on (generating the final environment based on the basic environment and emotional data) has shown to be effective as well. However, the optimization algorithm used, i.e., the heuristic optimizer, did show some flaws. An approach that could guarantee an optimal outcome is a linear optimization approach. In future work, it may be interesting to try and implement this in real-time.

The emotional model also fulfills its purpose. However, it does not take into account the user’s actual emotions. Furthermore, if the environments change, the environment model should be re-defined as it is directly dependent on the adaptations. A more accurate approach would be to use biofeedback, i.e., to measure the user’s physiological data and define an emotional model that transforms this data into emotions. When using biofeedback, the model is independent of the environment as it is based on physiological data and not adoptions. Therefore, different environments do not require a different model, resulting in a more flexible application. Using biofeedback is an interesting topic for future work.

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List of Abbreviations

AAD American Academy of Dermatology. 14
ACR American College of Radiology. 14
AMA American Medical Association. 14
AR Augmented Reality. 10, 11, 13
ARE Augmented Reality Environment. 10, 11
ARET Augmented Reality Exposure Therapy. 13
ATA American Telemedecine Association. 14
AV Augmented Virtuality. 10, 11
BBN Bayesian Belief Network. 23, 81
CBT Cognitive Behavioral Therapy. 5–7, 12, 14
CM Cyclic Meditation. 16, 18
ECPT European Code of Practice for Telehealth. 14
ET Exposure Therapy. 2, 12, 22
HMD Head Mounted Display. 50, 51, 82
ICPTS International Code of Practice for Telehealth Services. 14
IET Imaginary Exposure Therapy. 2
IR Interreality. 11–13
IVET In Vivo Exposure Therapy. 2, 12–14
List of Abbreviations

MBCT  Mindfulness-Based Cognitive Therapy. 8
MBSR  Mindfulness-Based Stress Reduction. 7, 8
MILP  Mixed Integer Linear Programming. 36, 42
MINLP Mixed Integer Non-Linear Programming. 36, 41–43
MR   Mixed Reality. 10, 11
PCT  Person Centered Therapy. 6, 7
PMR  Progressive Muscle Relaxation. 20
PTSD Post Traumatic Stress Disorder. 12, 15
RR   Relaxation Response. 21
TQG  Telehealth Quality Group. 14
VE   Virtual Environment. 3, 9–15, 21, 26–29, 31, 36, 49, 50, 55, 63, 82
VR   Virtual Reality. 2, 3, 5, 9–15, 22, 26, 49, 81, 83
VRET Virtual Reality Exposure Therapy. 12–14
VRGET Virtual Reality Graded Exposure Therapy. 12
VRISE Virtual Reality Induced Symptoms and Effects. 13
VRT  Virtual Reality in psychological treatment. 12
Chapter 1

Introduction

According to the World Health Organization, stress, especially that relating to work, is the second most frequent health problem, impacting one third of employed people in the European Union [1-3]. Also, it may be the single most significant factor related to the increasing rate of suicide in the United States, and is considered responsible for many physical and psychological problems [4]. Over the last decades, stress has been widely linked with adverse effects on employees their well-being in many occupations, with teaching and educational professionals at particular risk [2,5,7].

Although stress at its optimum level can produce positive action, negative influences of stress upon health and disease processes seem to dominate [8]. Excess stress contributes to the development of physical ailments such as hypertension, ulcers, skin disorders, headaches, arteriosclerosis, and other life-threatening diseases [4]. Furthermore, psychological stress contributes to cardiovascular disease at several stages, including the long-term development of coronary heart disease and acute triggering of cardiac events [9]. Due to the prevalence of these stress-related health conditions, their costs to a nation’s health care system, and the loss of quality of life for individuals, public health professionals are increasingly concerned over the effects of stress [10]. As a result, the U.S. Department of Health and Human Services listed stress reduction as an objective in its publication Healthy People 2010. Research has shown that short-term practice of relaxation therapy can improve autonomic balance and promote cardiovascular health [11], and that personalized stress management techniques, such as relaxation therapy, are recommended to reduce perceived stress [2].

During their lives, about 25% of the human population is confronted with one or more mental disorders, which are negatively affected by stress [8,12]. Common, disabling dis-
orders, characterized by feelings of fear, are known as anxiety disorders. A widespread traditional treatment method for these is Exposure Therapy (ET). Exposure-based treatments show some of the largest effect sizes for anxiety disorders in literature [13]. In ET, the patient is repeatedly confronted with the feared stimulus in a preferably graded manner [12]. Traditionally, exposure can be achieved by either In Vivo Exposure Therapy (IVET), this is through direct contact with the stimulus, or by Imaginary Exposure Therapy (IET) [14], in which the patient has to imagine the feared situation.

Despite their effectiveness, traditional therapy presents limitations. With IET, patients may report difficulties when asked to imagine the feared situation because of poor abilities in creating mental images and getting inside a specific situation. Furthermore, emotions have been shown to modulate visual imagery and perception. In particular, fear seems to impair visualization of detailed scenes, making the mental reconstruction of the stimulus, to some extent, biased and inaccurate [14]. IVET bypasses these limitations, but has other limitations itself. Many patients are rather unwilling to expose themselves to the real situation, since it is conceived too frightening. Also, the real situation is not always fully under the control of the therapist. Traditional therapy requires high effort in terms of money and time expenditure, since usually the therapist and the patient meet each other inside or even outside of the therapist’s office to work together [14]. Furthermore, people with limited mobility or people who live in an area where therapy is not available may find it difficult to enter therapy [15]. Lastly, people may be unwilling to enter therapy because of the social stigma of mental disorders. Although this stigma is less of a problem today, visiting a health care center for a mental disorder is a difficult situation for some people (and communities) and they wish to keep it private [15]. These limitations result in a treatment rate of only 33% of the targeted patients [12]. For these reasons, clinicians are showing an increasing interest for a novel tool to treat anxiety symptoms that overcomes most of these limitations: Virtual Reality (VR) [14].

This master’s thesis will focus on using VR for relaxation therapy. VR is used to provide more cost- and time-efficient therapy, whilst also allowing more people access to therapy. Traditional relaxation therapy has proven to be a useful stress management approach, as well as a valid method for reducing anxiety in people suffering from anxiety disorders [2,16,17]. Therefore, the goal is not to create new relaxation techniques and methods, but rather to introduce traditional knowledge into VR. Traditional therapy does not apply a 'one size fits all' approach, instead, therapy tends to be personalized and fit to the needs of the user. Similar, a VR system in which every user is treated the
same will not be effective. Therefore, VR relaxation therapy should take into account the personality of the participant and based on this, generate a Virtual Environment (VE). Doing this will result in different environments and relaxation methods for different users, i.e. personalized therapy. Furthermore, when using VR, a therapist will not always be present. Even if a therapist is present, he will not be in control of the VE as this would defeat the purpose of using VR. Therefore, the VR system should be able to make decisions autonomously. Based on how the user feels, it should adapt the VE in order to guide the user towards maximal relaxation, using the relaxation methods available. This master’s thesis will research if generating a personalized VE is feasible, and if so, how to implement this. Depending on the user, this VE will not only look different, but also contain different relaxation methods. It also focuses on which of these methods to use at which point in time. This decision process takes into account the emotional state of the user and based on this, selects a relaxation method. Different relaxation methods therefore server different purposes. E.g., one method’s purpose could be to reduce fear, whilst another method could reduce stress. Depending of how the user feels, one of these methods is then selected. As the emotions of the user change over time, so does the relaxation method. In summary, this master’s thesis will propose a personalized and adaptive VR approach to relaxation therapy. To achieve this, the system takes into account both the personality and the emotional state of the user, and makes decisions based on these parameters.

Chapter 2 starts by giving an overview of the current state-of-the-art in literature. It focuses on traditional relaxation therapy and reviews frequently used relaxation techniques. Furthermore, it discusses how VR is currently used for therapy purposes, without restricting to relaxation therapy. Lastly, it gives an overview of how personalities and emotions are modelled. Next, Chapter 3 examines the methods used in this master’s thesis. It first gives a high level view of the used architecture. Afterwards, it focuses on the methods used to realize the different architectural components. These are (1) the methods used for modelling personalities, (2) the approach taken to modelling emotions, and (3) the methods used by the component responsible for updating the VE based on the user’s emotional state. Chapter 4 presents the implementation of the personalized and adaptive relaxation therapy system. It starts by giving an overview of the used architecture and technologies, and how these are connected. This included the physical setup. Afterwards, it presents how personalized environments are generated and how emotions are modelled. Finally, the implementation of the component responsible for updating the VE based on the user’s emotional state is given. Chapter 5 then analyzes this implementation; it achieves this
by using simulated users instead of real users. Finally, Chapter 6 concludes this master’s thesis by discussing these results and giving references for future work. It also proposes an updated architecture based on this future work.
Chapter 2

Literature study

This chapter presents an overview of related work and topics needed for this thesis. First, Section 2.1 gives an overview of how traditional therapy is organized. Afterwards, an overview of how VR is currently used in therapy is given by Section 2.2. In Section 2.3, methods and techniques that could induce a relaxed feeling with people are discussed. Finally, Section 2.4 gives a deeper look on emotions, personalities, and how to model these.

2.1 Traditional therapy

Stress management is the common denominator of an assortment of interventions ranging from relaxation methods to cognitive behavioural therapy and client or person centered therapy [18]. In this section, traditional therapy approaches are discussed. This includes cognitive behavioural therapy, person centered therapy, psychodynamic therapy, mindfulness-based stress reduction, mindfulness-based cognitive therapy, and biofeedback therapy.

Cognitive behavioural therapy

Cognitive Behavioral Therapy (CBT) is a psycho-social intervention that is the most widely used evidence-based practice for improving mental health around the world [19]. Guided by empirical research, CBT focuses on the development of personal coping strategies that target solving current problems and changing unhelpful patterns in cognitions, e.g., thoughts, beliefs, attitudes, behaviors and emotional regulation [19]. Cognitive change and the resulting behavioural change relate to cognitive restructuring, which proposes that people are directly responsible for generating dysfunctional emotions and their resultant behaviours, like stress, depression, anxiety, something that can be prevented by
changing thought patterns. Cognitive restructuring is the process of learning to refute cognitive distortions, aiming to replace one’s irrational, counter-factual beliefs with more accurate and beneficial ones [1]. The effectiveness of CBT has been shown in numerous randomized clinical trials for both childhood and adolescent anxiety disorders, depression, cardiovascular disorder, diabetes, chronic fatigue syndrome, pain management, headaches, overweight and obesity, eating disorders, stress related to infertility, and stress management [1][20][21]. Due to its effectiveness, CBT has been recommended as the treatment of choice in a number of clinical guidelines [20]. However, in spite of its efficacy, CBT is not free of limitations: the therapist has to be present during the whole therapeutic process, there is a lack of trained therapists, there are generally long waiting lists for treatment, and there is a lack of access to face-to-face therapy in rural areas [20].

**Person centered therapy**

Person Centered Therapy (PCT), on the other hand, places a strong emphasis on the therapeutic relationship. In PCT, patients experience dysfunction when there is no congruence between the way they see themselves (self concept), the way they would like to be (ideal self), and the way they actually are (real self) [22]. PCT maintains a deep respect for each person’s natural movement toward self-actualization, and these conditions are seen as a way to tap into, strengthen, or restart this naturally occurring positive growth potential [23]. This means that each patient’s path is individual rather than assuming that all persons from certain groups need to learn certain skills or that a therapist should decide what new actions or directions are best in a patient’s life [23]. Over the last few decades, many authors have proposed a mixed approach to therapy. Josefowitz and Myran, for example, propose person centred cognitive behaviour therapy [24]. They consider the definitions of the core conditions of PCT and examine ways in which interventions, developed by cognitive behaviour therapy (CBT), can be informed by these conditions. They argue that CBT, while using different interventions than those traditionally used by PCT, can be practiced as a highly empathic, person centred form of therapy. Rodriguez applied this approach to a case example and concluded that the case study demonstrated how the use of an integrated CBT and PCT can be used to bring about positive changes in therapy [22].

**Psychodynamic therapy**

Rather than focusing on behaviour, psychodynamic therapy is the psychological interpretation of mental and emotional processes [25]. Psychodynamic therapy, also known as
insight-oriented therapy, focuses on unconscious processes as they are manifested in a person’s present behavior. The goals of psychodynamic therapy are a patient’s self-awareness and understanding of the influence of the past on present behavior [26]. Psychodynamic therapists attempt to help patients find patterns in their emotions, thoughts, and beliefs in order to gain insight into their current self. These patterns are often found to begin in the patient’s childhood since psychodynamic theory holds that early life experiences are extremely influential in the psychological development and functioning of an adult [27].

When comparing different therapies, we stumble upon the psychotherapy’s equivalence paradox that states that treatments tend to have equivalently positive outcomes despite non-equivalent theories and techniques [28]. This was tested and confirmed for a group of 5613 patients who received CBT, PCT, or psychodynamic therapy [28].

**Mindfulness based stress management**

One of the most well-researched stress management programs is Mindfulness-Based Stress Reduction (MBSR). MBSR teaches mindfulness, which is the ability to attend to thoughts and emotions as they arise and to be fully conscious of the present-moment experience [10]. It is a structured group program that employs mindfulness meditation to alleviate suffering associated with physical, psychosomatic and psychiatric disorders [29]. The construct of mindful awareness originated in earliest Buddhist documents but is neither religious nor esoteric in nature [29]. It describes a virtue to be cultivated by meditation and practice in everyday life, and refers to an alert mode of perceiving all mental contents (perceptions, sensations, cognitions and affects) [30]. The approach assumes that greater awareness will provide more veridical perception, reduce negative affect and improve vitality and coping [29]. Typically, MBSR is a structured 8 to 10 week group program instructing mindfulness through the practice of meditation, body scan (a type of guided awareness), and yoga [10]. One of its strengths, in contrast to most stress-reduction programs, is that it offers participants different mindfulness practices from which to choose. Research indicates that participants often find one of the three practices more beneficial or preferred for personal reasons [10]. In the past, MBSR has shown consistent efficacy for many mental and physical disorders [31]. Patients showed a significant decline in anxiety and depression symptoms, stress, negative affect, rumination, state and trait anxiety, and significant increases in positive affect, self-esteem, self-compassion and quality of life [32–35].
Mindfulness based cognitive therapy

While cognitive behavior therapy has been found to be effective in the treatment of generalized anxiety disorder (GAD), a significant percentage of patients struggle with residual symptoms [36]. In order to help these patients, an adaptation of the MBSR program, called Mindfulness-Based Cognitive Therapy (MBCT), was designed. MBCT is a group treatment that incorporates elements of cognitive therapy facilitating a detached or decentered view of one’s thoughts and is designed to prevent depressive relapse [35]. MBCT has been found effective in reducing relapse in patients with major depression [37], and is recommended for recovered recurrently depressed patients to prevent depressive relapse [35]. Furthermore, MBCT was associated with enhanced quality of life and decreased stress symptoms in breast and prostate cancer patients [38]. MBCT is moderately effective in reducing stress, depression, anxiety and distress and in ameliorating the quality of life of healthy individuals. However, most of these researches do note that more research is necessary to identify the most effective elements of MBCT.

Biofeedback therapy

Biofeedback is a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance [1]. It has been applied, often in conjunction with relaxation training, to numerous clinical problems, ranging from cardiovascular disease to stress, anxiety, depression, and the treatment of pain syndromes [39,40]. To enhance efficacy, biofeedback is often combined with relaxation and cognitive-behavioral elements such as stress management. The measurement of treatment success, therefore, mostly includes psychophysiological and behavioral variables in addition to the symptom-related ones [41]. In biofeedback therapy, the client is trained to develop an increased awareness of the specific physiological response (e.g., muscular tension, skin temperature, heart rate, blood pressure), this response depends on the focus of the specific training [42]. In order to achieve this, precise instruments measure physiological activity such as brainwaves, heart function, breathing, muscle activity, and skin temperature [1]. Possible technologies used to measure these responses are electroencephalography, electrocardiography, electromyography, galvanic skin response, photoplethysmography, eye tracking, and facial expression analysis [43-47]. Although each of these sensor technologies can individually be used to measure the anxiety level, multiple studies and research have shown that even better measurements can be achieved when combining multiple of these technologies together [48,49]. These instruments then rapidly and accurately feed back information to the user. The presentation of this information,
often in conjunction with changes in thinking, emotions, and behavior, supports desired physiological changes [1]. Afterwards, the client has to learn to control his physiological response voluntarily without these technologies, by means of biofeedback [42].

This section gave an overview of frequently used traditional therapy approaches. However, despite their effectiveness, these approaches present limitations. They require high effort in terms of money and time expenditure, since usually the therapist and the patient meet each other inside or even outside of the therapist’s office to work together [14]. Furthermore, people with limited mobility or people who live in an area where therapy is not available may find it difficult to enter therapy [15]. Lastly, people may be unwilling to enter therapy because of the social stigma of mental disorders. Although this stigma is less of a problem today, visiting a health care center for a mental disorder is a difficult situation for some people (and communities) and they wish to keep it private [15]. For these reasons, clinicians are showing an increasing interest for a novel tool to treat anxiety symptoms that overcomes most of these limitations: VR [14].

2.2 Virtual Reality based Therapy

VR enables manipulation of the environment and can be used to activate environmental triggers that elicit distress in people with mental health problems, allowing them to learn to better manage their difficulties [50]. In this section, the different types of VR will be discussed as well as their advantages and disadvantages compared to in-vivo therapy. Afterwards, an overview will be presented of how VR is used in therapy today. Moreover, the effectiveness of VR based therapy and clinical and ethical issues will be briefly described.

2.2.1 Types of Virtual Reality

In VR based therapy, different types of VR can be distinguished. These types are "pure" VR, mixed reality, and interreality and will be discussed and compared in this section. It should be noted that in literature, the term VR is used both as a generalizing term for all types of VR based therapies, as well as for "pure" VR. Overall, it should be clear out of context what the author means by VR.

Virtual Reality

In VR, a VE is created. This environment is completely virtual and is not affected by the physical world. Although the VE can be based on the psychical world, both worlds do not
interact with each other, i.e., if something happens in the real world, the VE will remain unaffected and vice versa. When trying to measure the quality of VR it is important to determine the feeling of presence, the level of realism and the degree of reality of the system [51]. The level of realism corresponds to the degree of convergence between the expectations of the user and the actual experience in the VE. The level of reality refers to the level on which the user experiences the immersion as authentic. Thus, a higher level of realism should be associated with a higher level of reality [51]. In VR, bio-sensors can be used to combine virtual environments and bio-feedback, so that the virtual world is directly modified by the physiological activation of the patient. Bio-feedback can also be used to give information on the emotional/health status of the patient so the therapist will know the best direction to proceed in with therapy [14].

**Mixed Reality**

Mixed Reality (MR) is the merging of real and virtual worlds to produce new environments and visualizations where physical and virtual objects co-exist and interact in real time [52]. MR refers to the incorporation of virtual computer graphics objects into a real three dimensional scene, or alternatively the inclusion of real world elements into a VE [53]. The former case is generally referred to as Augmented Reality (AR), and the latter as Augmented Virtuality (AV). This behavior is illustrated by *Milgram’s Reality-Virtuality Continuum*, as shown in Figure 2.1.

**AR** Whereas VR generally immerses the user into a fully computer generated virtual world, in AR the user still sees the physical world, but with virtual objects superimposed into it [54]. This environment is called an Augmented Reality Environment (ARE). AR does not only introduce virtual objects into the physical world, but may also inhibit the perception of physical objects by overlaying them by virtual representations, such as virtual objects or even virtual empty spaces [51]. It is important to note that AR can be extended to hearing, touch and smell as well. In AR, the same quality attributes as in VR need to be considered, namely the feeling of presence, the level of realism and the degree of reality. Although the feeling of presence is different it still holds. Moreover, the
alignment of physical and virtual elements also contributes to the quality of the ARE \[51\]. It is important to notice that, in literature, the term MR is sometimes used for AR.

**Augmented Virtuality** AV refers to predominantly virtual spaces, where physical elements, e.g., physical objects or people, are dynamically integrated into, and can interact with, the virtual world in real time \[52\]. Just as in VR, in AV a VE is created. In fact, in literature the term AV is rarely used and the term VR is used instead.

**Interreality**

Interreality (IR) is an ubiquitous computing paradigm for behavioral health care that integrates telehealth and VR in a seamless clinical experience \[53\]. Telehealth resources, such as telecare, telemedicine and telepsychology, are procedures in the professional-patient relationship that do not involve direct face-to-face contact between the therapist and the patient \[15\]. They include a range of possibilities from telephone calls to video conferencing. The therapist-patient relationship can be facilitated through advice or references provided by telephone, e-mail or real-time interaction systems.

Whereas VR and AR focus on the virtual experience itself, IR covers the entire treatment process. If virtual worlds are considered to be closed experiences, separated from the feelings and emotions by the patient in real life, then IR can be considered as a hybrid, closed-loop empowering experience that bridges both the psychical and virtual worlds \[14\]. The main feature of IR is a twofold link between the virtual and the real world: behavior in the physical world influences the experience in the virtual one and vice versa \[56\]. This is achieved through three technologies. The first technology is 3D individual or shared virtual worlds. In shared virtual worlds, users can interact with each other. Using 3D virtual worlds, the user can socialize and participate in individual and group activities. Virtual worlds allow controlled exposure, objective assessment and can provide motivating feedback \[55\]. The second technology is bio-monitoring systems. These are used to track the emotional/health/activity status of the user in the real world and to influence his/her experience in the virtual world \[56\]. The last technology is mobile phones. These make it possible to always be connected with the virtual world. Users can receive feedback, warnings and assignments or can meet other users on a social network \[14\].

### 2.2.2 Virtual Reality in Therapy

VR has been used in clinical settings to treat a range of cognitive, emotional and motor problems in various psychological and psychiatric disorders \[50\]. Despite this, the use
of VR in relaxation therapy is very limited if not non-existent. There do exist many VR relaxation applications, but none of them serve as therapy or take into account the personality of the patient. However, VR has already found its way other of therapies, e.g., ET. Using VR in ET is consequentially called Virtual Reality Exposure Therapy (VRET). In VRET the patient is directly exposed to his/her anxiety in a VE. These exposure scenarios can either be active or passive. Compared to passive scenarios, active scenarios dynamically require actions and decisions during the exposure\textsuperscript{57}. VRET is mostly used in the form of Virtual Reality Graded Exposure Therapy (VRGET). In fact, in literature, most authors do not use the term VRGET, they simply use VRET. In VRGET, a fear hierarchy is constructed by the therapist in which feared objects, activities or situations are ranked according to difficulty for the patient\textsuperscript{58}. The patient begins the ET by being exposed to mildly difficult exposures and during the treatment the patient progresses to harder difficulties. Overall, Virtual Reality in psychological treatment (VRT) has potential within mental health research. VRT has been shown to be more effective than treatment as usual or waiting list control, and has similar results as conventional CBT and or IVET\textsuperscript{50}. The effectiveness varies depending on the mental health disorder reviewed. However, it has been confirmed that multiple sessions treatment protocols of VRT can be a valuable treatment for agoraphobia with or without panic disorder, fear of flying, social anxiety, fear of public speaking, and spider phobia\textsuperscript{50}. Also promising are the findings regarding the use of VRT for Post Traumatic Stress Disorder (PTSD).

2.2.3 Advantages

VR offers multiple advantages over traditional in-vivo therapy. First, the treatment can be conducted in the therapist’s office rather than having to move to another location\textsuperscript{13}. Furthermore, it allows the creation of idiosyncratic exposure (bizarre/exceptional/unusual scenarios) and provide the possibility to create more gradual assignments and thus build up the treatment at each patient’s pace\textsuperscript{13}. The therapist has a better control over the exposure and the exposure can be repeated as much as needed\textsuperscript{59}. Because patients cannot receive social cues from the therapist, patients often feel less inhibited in discussing certain topics and opening up to the therapist when using VR\textsuperscript{60}. Further, for ET, multiple studies have concluded that the drop-out and refusal rate of VRET are lower compared to these of IVET\textsuperscript{50}, which suggests that VRET could help increase the number of people who seek ET\textsuperscript{50,61,62}.

When considering the concept of IR, people can gain access to the virtual world from their homes, which has numerous advantages as well. It is important to mention that in
literature, some authors see this as an extension of VR rather than assigning this to IR exclusively. People with restricted mobility, for example, may find it difficult to attend face-to-face therapy, thus participating in VR treatment from their homes may offer a solution [15]. The same applies to people who live in an area where treatment simply is not available or for people who would prefer to keep their treatment private. This could possibly be because of the social stigma on mental disorders [15]. Also, VR treatment may help people who suffer from anxieties, such as agoraphobia, that simply restrict them from leaving their homes or undergo real-life exposure [13]. Lastly, IR offers more flexibility as to when a patient wants to start a session. This way people with difficult time schedules can gain easier access to treatment [15].

In the treatment of phobias, Augmented Reality Exposure Therapy (ARET) enjoys the same advantages over IVET as VRET does [51]. In contrast to VRET, ARET requires less virtual elements to be designed and AR will therefore have a lower cost for producing the environment [51]. Furthermore, AR does not place the user into another environment. This means the experience will not depend on the user’s ability to build a feeling of presence, which is clearly an advantage. Also, by embedding the virtual fear element in the real environment and allowing a direct “own-body” perception of that environment, the ecological validity of the scenario is increased [51].

2.2.4 Disadvantages

The quality of VR therapy relies on the quality of the VE itself [15]. When the quality of the VE, and thus the immersion, goes down, so does the quality of the treatment. For example, the VE may not look realistic enough for the participant. Because of this, the patient will not be properly exposed to his/her anxiety. This specific problem occurs especially when dealing with virtual human characters [63]. Also, there are some medical conditions that represent significant contraindications for the use of VR, such as migraine, headache and seizure disorder [14]. When using VR with patients affected by psychosis or personality disorders, it should be noted that they are predisposed to become confused by real versus virtual worlds [14]. Finally, simulated motion in a VE has been shown to increase the level of Virtual Reality Induced Symptoms and Effects (VRISE) [64]. VRISE may strengthen the feeling of anxiety. Therefore it is important to develop the VE carefully [64].
2.2.5 Effectiveness

In therapy, the treatment group is the group that receives treatment. The control group is identical to the treatment group in every single way except that the control group does not get the treatment. These two groups can then be compared to determine the effectiveness of the treatment. When comparing VRET to control conditions (i.e., the control group), VRET has shown to be the most effective treatment method [13, 50, 59]. When comparing VRET to conventional CBT or IVET however, VRET shows at least similar results [50]. Depending on the mental health disorder, VRET may even outperform IVET. Examples of this are fear of flying and acrophobia [13, 20, 62]. Both passive and active VR scenarios have been found to be effective to elicit social anxiety, with active scenarios being the most effective [57]. Furthermore, it has been suggested that bio-feedback and the use of a mobile device may offer an added value to the treatment [65].

2.2.6 Clinical and ethical issues

As VR is increasingly implemented for the treatment of psychological disorders, ethical standards and guidelines must be considered. As in any other medical setting, patient confidentiality must be protected [66]. Information must only be released with the patient’s permission and the patient must be informed of any exceptions to confidentiality. When the user is in control of an avatar, the rights of the avatar are analogous to those of the individual controlling it and as a logical result, the avatar must be treated as an extension of the self [66]. This means that treatment standards and ethical guidelines for patients in a VE should mirror those of clinical practice in the physical world and that a clinician must follow the laws and guidelines of their field [66]. Telemedicine guidelines have been established for mental health and should be applied to the virtual world as well [66]. The American Telemedicine Association (ATA) has developed a number of practice guidelines, and will continue doing so [67]. Other professional societies have also developed guidelines for telemedicine, including the American College of Radiology (ACR), the American Academy of Dermatology (AAD) and the American Medical Association (AMA). There are also many international guidelines, such as the European Code of Practice for Telehealth (ECPT), all of which are based on research efforts that validated the technologies being used, assessed practice protocols and examined relative costs and benefits [67]. In 2014, the ECPT has been taken forward as an international code by the Telehealth Quality Group (TQG) and is now known as the International Code of Practice for Telehealth Services (ICPTS) [68]. Many users of telemedicine guidelines indicate that they have adopted various guidelines because they reduce liability. However, guidelines
are inherently developed to improve patient safety, but they are not legal documents [67]. As a result of their experiences developing VE treatment platforms for PTSD treatment and other findings, Yellowlees et al. [66] recommended a set of preliminary guidelines to guide future research and practice in this area.

This section introduced the different types of VR and how they are used in therapy. Although VR based therapy is still in its infancy, it has been implemented and proven to be effective in a number of fields already. Sadly, relaxation therapy is not one of these. In order to implement VR based relaxation therapy, different techniques used in relaxation therapy should be transformed to VR. An overview of frequently used techniques and methods is given by the next session.

### 2.3 Relaxation methods and techniques

In order to create a system that allows for people to relax using VR, it should be known what methods or techniques can help people to relax. Popular techniques include yoga, meditation, controlled breathing, music therapy, relaxation response, and progressive muscle relaxation.

**Yoga**

Yoga includes a number of practices such as physical postures (asanas), regulated breathing (pranayama), meditation, and lectures on philosophical aspects of yoga [69]. Essentially, the word “yoga” has come to describe a means of uniting or a method of discipline: to join the body to the mind and together join to the self (soul), or the union between the individual self and the transcendental self [70]. Hatha yoga, the yoga of activity, addresses the body and mind and requires discipline and effort [70]. It is through hatha yoga that most (Western) people are introduced to the philosophy. Many people believe that this is yoga and are unaware of the totality of yoga as a philosophy of life, and that it is meant to be practiced in the larger context of conscious spiritual discipline [70, 71]. Yoga is proposed to be a preventive as well as curative system of the body, mind, and spirit [70]. As a mind–body exercise, hatha yoga tends to offer multiple benefits to its practitioners. Through its gentle, yet demanding physical postures, hatha yoga offers opportunities for participants to become more aware of their bodies [10]. It tends to promotes flexibility, strength, and balance, as well as increase flexibility, energy, mental clarity, concentration, and overall cognitive performance [10, 72, 73]. Apart from being used in stress management, yoga is also recommended by many physicians to patients at risk for heart diseases,
as well as those with back pain, arthritis, depression and other chronic diseases [74]. Yoga practice has benefited mentally handicapped subjects by improving their mental ability, motor coordination and social skills. Physically handicapped subjects had a restoration of some degree of functional ability after practicing yoga and visually impaired children showed a significant decrease in their abnormal anxiety levels when they practiced yoga for three weeks [75]. More into detail, yoga practice decreases levels of salivary cortisol as well as plasma rennin levels, and 24-h urine norepinephrine and epinephrine levels, and improves blood glucose (fasting and post-prandial), lipid profile and serum insulin levels. These may be the possible mechanisms for effects of yoga on stress and stress-related diseases like diabetes, hypertension, and coronary heart disease [71,76].

Meditation

Meditation and any form of rest or relaxation acts to reduce sympathetic activation by reducing the release of catecholamines and other stress hormones such as cortisol, and promoting increased parasympathetic activity which in turn slows the heart rate and improves the flow of blood to the viscera and away from the periphery [77]. In both Eastern and Western culture, many different meditation techniques have existed for centuries. Records of meditation techniques were found in Christianity, Islam and Judaism. However, the most popular techniques of meditation in the Western world over the last half-century are the Buddhist and Indian forms, including various Yoga forms [78]. This rich history results in a wide variety of different meditation techniques available today, summarized in Table 2.1. Meditation is seen by a number of researchers as potentially one of the most effective forms of stress reduction [77]. If practised regularly, meditation is thought to help develop habitual, unconscious microbehaviours that can potentially produce widespread positive effects on physical and psychological functioning [77]. Among yoga techniques, meditation particularly has been shown to reduce stress and increase feelings of calm [69].

Cyclic Meditation

Cyclic Meditation (CM) is a technique that combines ‘stimulating’ and ‘calming’ practices, based on a statement in ancient yoga texts suggesting that such a combination may be especially helpful to reach a state of mental equilibrium [79]. This statement reads: ’In a state of mental inactivity awaken the mind; when agitated, calm it; between these two states realize the possible abilities of the mind. If the mind has reached states of perfect equilibrium do not disturb it again’. The underlying idea is that, for most persons,
<table>
<thead>
<tr>
<th>Meditation Technique</th>
<th>Physical activity and goal</th>
<th>Mental activity and goal</th>
<th>Additional training content</th>
<th>Authentic?</th>
<th>Relaxation response?</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mindfulness meditation</td>
<td>Sitting, lying down, or walking</td>
<td>Thoughtless awareness</td>
<td>Varies</td>
<td>Yes</td>
<td>Yes</td>
<td>Varies</td>
</tr>
<tr>
<td>Transcendental meditation</td>
<td></td>
<td>Focus on mantra, return to mantra as thoughts stray</td>
<td>Varies</td>
<td>Yes</td>
<td>Yes</td>
<td>Usually suggested 15-20 min, twice a day or more</td>
</tr>
<tr>
<td>Sahaja Yoga</td>
<td>Sitting</td>
<td>Two parts: Thoughtless awareness and Self-affirmations</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Usually suggested 15 minutes, twice a day</td>
</tr>
<tr>
<td>Kundalini Yoga</td>
<td>Various combinations of breathing patterns, mantras, eye postures, and hand and arm postures. Usually sitting</td>
<td>Thoughtless awareness, expansion towards transcendent states, amelioration of psychiatric symptoms and disorders</td>
<td>Yes</td>
<td>Varies</td>
<td>Varies</td>
<td>Varies</td>
</tr>
<tr>
<td>Meditative Prayer</td>
<td>Varies</td>
<td>Varies, can include imagery</td>
<td>Varies</td>
<td>Sometimes</td>
<td>Sometimes</td>
<td>Varies</td>
</tr>
<tr>
<td>Relaxation response</td>
<td>Sitting</td>
<td>Thoughtless awareness, but varies</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
<td>10–20 minutes, once or twice a day</td>
</tr>
<tr>
<td>Hatha Yoga</td>
<td>Obtaining and maintaining different positions to build strength, flexibility and balance. Also includes breathing exercises.</td>
<td>Varies. Usually a relaxation component. Sometimes combined with more typical meditative techniques</td>
<td>Varies</td>
<td>Sometimes</td>
<td>Varies</td>
<td>Varies</td>
</tr>
</tbody>
</table>

Table 2.1: Multidimensional description of meditation techniques [78].
the mental state is routinely somewhere between the extremes of being ’inactive’ or of being ’agitated’ and hence to reach a balanced/relaxed state the most suitable technique would be one which combines ’awakening’ and ’calming’ practices [80]. CM combines yoga postures interspersed with periods of supine rest, during which the person is given instructions to help reach a meditative state. During CM, the patient goes through a series of phases, each phase typically taking from 30 seconds to 10 minutes and consisting of different activities, e.g., listening to yoga texts, supine relaxation, practicing postures. This is illustrated by an example in Figure 2.2. During the supine rest phase, the subjects lay supine in a certain posture that induces rest [69]. The supine rest phase typically lasts as long as all previous phases together, so that the duration of supine rest equals that of the CM [69]. In normal volunteers, practicing CM reduced psychophysiological arousal based on a decrease in oxygen consumption and changes in heart rate variability suggestive of a shift towards vagal dominance [81]. Practicing CM twice a day has shown to reduce the heart rate and breath rates during sleep, the following night, and also influenced time and frequency domain measures of the heart rate variability recorded during sleep [69]. Furthermore, studies on CM found improvement in the metabolic cost, autonomic function, and attention measure [79, 80].
Breathing Therapy

Breathing therapy generally aims to either correct dysfunctions of breathing or enhance its functions. Breathing, unlike most physiological functions, can be controlled voluntarily and it can serve as an entry point for physiological and psychological regulation [83]. Breathing therapy is known to be a part of yogic techniques [74]. Yogic breathing (also known as pranayama) is a unique method for balancing the autonomic nervous system and influencing psychologic and stress-related disorders [84]. There are various methods of pranayam, mostly characterised by breath holding at the end of maximal inspiration or maximal expiration and slowing of the respiratory rate [85]. Savitri Pranayama, Kapalbhati, Bhasrika Pranayama, Nadi siddhi Pranayama are well known among them [86]. Yogic breathing exercises not only help in relieving the stresses of life but also improve the antioxidant status of the individual [86]. These breathing exercises are reported to influence cardio-respiratory and autonomic functions [74] and can alleviate anxiety, depression, everyday stress, post-traumatic stress, and stress-related medical illnesses [84]. Breathing techniques can be classified into two basic classes: diaphragmatic breathing (relaxed breathing) and chest breathing (stress breathing). In yogic breathing however, there are four kinds of breathing: upper breathing, mid breathing, down breathing, and complete breathing [87]. The technique of breathing is designated with many names according to the muscles and techniques used for breathing, and for control of stress, diaphragmatic breathing is explained as a basic technique best used to manage of stress [87][89]. Diaphragmatic breathing, or abdominal or belly or deep breathing is marked by expansion of the abdomen rather than the chest when breathing [1]. Diaphragmatic breathing shows potential to improve cognitive performance and reduce negative subjective and physiological consequences of stress in healthy adults [90]. The theoretical explanation of the positive therapeutic effect of breathing therapy techniques exemplifies good brain function, sufficient air flow through the nasal passages, diaphragmatic movement, light vagal stimulation, CO2 changes and cognitive diversion but in most studies, the hypothesis of CO2 is supported [87]. The relaxed breathing includes slow diaphragmatic breathing, breath meditation, nasal breathing, yogic abdominal breathing, Benson’s relaxed response, and quiet response [87].

Music Therapy

Music therapy is a health profession in which a music therapist uses music and its facets – physical, emotional, mental, social, aesthetic, and spiritual, to help patients improve and maintain their health [91]. Although the power of music to alleviate illness and distress has
been recognized for centuries, it is only in the twentieth century that systematic research into the reasons for its efficacy has really begun [92]. Music is widely used to enhance well-being, reduce stress, and distract patients from unpleasant symptoms. Although there are wide variations in individual preferences, music appears to exert direct physiologic effects through the autonomic nervous system. Music effectively reduces anxiety and improves mood for medical and surgical patients, for patients in intensive care units and patients undergoing procedures, both children as adults [93]. Listening to classical music increases heart rate variability, a measure of cardiac autonomic balance (in which increased levels reflect less stress and greater resilience), whereas listening to noise or rock music decreases heart rate variability (reflecting greater stress) [93]. However, in general, it has been observed that music that is preferred by the listener may have the most beneficial effects on the relaxation and stress reduction responses of that listener [94]. Individual preferences must thus be considered when using music to aid relaxation, precategorized soothing music may not always be soothing [95]. The cognitive function, motor skills, emotional and affective development, behavior and social skills, and quality of life of the patients are clinically proven to be improved through music therapy [91]. Furthermore, carefully selected music can reduce stress, enhance a sense of comfort and relaxation, offer distraction from pain, and enhance clinical performance [94].

Progressive Muscle Relaxation

Another technique for reducing stress and anxiety is Progressive Muscle Relaxation (PMR). In PMR, relaxation is achieved by by alternately tensing and relaxing the muscles [96]. PMR involves the tensing and relaxing of muscle groups over the legs, abdomen, chest, arms and face. In a sequential pattern, with eyes closed, the patient places a tension in a given muscle group purposefully for approximately 10 seconds and then releases it for 20 seconds before continuing with the next muscle group. The mental component requires that the individual focuses on the distinction between the feelings of the tension and relaxation. With practice, the patient learns how to effectively relax in a short period of time [1]. Empirical evidence supports the use of PMR in high level tension responses and mind body techniques such as: reducing tension headaches, insomnia, adjunct treatment in cancer, chronic pain management in inflammatory arthritis and irritable bowel syndrome [97]. Furthermore, long-term benefits include: reduction of salivary cortisol levels and generalized anxiety, decreased blood pressure and heart rate, better management of cardiac rehabilitation, improvement of quality of life of patients after bypass surgery and improvement of quality of life of patients with multiple sclerosis [1].
Relaxation Response

Just as stimulating an area of the hypothalamus can cause the stress response, activating other areas of the brain may result in its reduction. This opposite state has been defined by Benson as the Relaxation Response (RR) [1]. The RR can be described as an integrated hypothalamic response which results in generalized decreased sympathetic nervous system activity, and perhaps also increased parasympathetic activity. This response was first observed by Hess who termed it the trophotropic response [98]. Hess was awarded the Nobel Prize for his work. He electrically stimulated anterior hypothalamic areas of the cat brain and induced physiologic changes similar to those later noted during the elicitation of the RR in humans [99]. Benson drew heavily on Hess’s work and proposed what he termed the RR model, a model in which Benson suggested that all mind–body techniques, including biofeedback, meditation, progressive muscle relaxation, autogenic training, tai chi, chigong, yoga, and other techniques, elicit a common physiologic response called the relaxation response [99][100]. The RR is a simple practice that once learned takes 10 to 20 minutes a day to achieve relaxation. The important characteristics of a relaxation program are: 1) repetition of a word, sound, prayer, thought, phrase or muscular movement, through which concentration is achieved, and 2) passive return to the repetition when other thoughts intrude [1]. During the RR, the body moves from a state of physiological arousal, including increased heart rate and blood pressure, slowed digestive functioning, decreased blood flow to the extremities, increased release of stress hormones, and other responses preparing the body to fight or flight, to a state of physiological relaxation, where blood pressure, heart rate, digestive functioning and hormonal levels return to their normal state [1]. Overall, it has been stated that relaxation techniques appear to be highly recommendable for the therapeutic use of relaxation response in stress-related diseases [8][101].

2.4 Personalization

It has been shown that by using physiological data, real time specific features of a VE can be changed to improve the effectiveness of the VE [65]. This indicates that making the VE adapt to the personality and emotional state of the patient could be beneficial to the patient. To achieve this, a model of the user’s personality and emotional state has to be defined. The first part of this section will explore how the user’s personality could be modelled, whilst the second part section will focus on specific emotions.
2.4.1 Modelling personalities

Semantics in combination with different areas of artificial intelligence is recently becoming more popular. It allows to structure data in order to get better insights and could increase the performance of personalisation systems \[102\]. Semantic ontologies are used to model relevant domain knowledge, it models the concepts and defines relationships between these concepts in an unambiguous way \[103\]. Additionally, semantic reasoners are able to unveil hidden, high-level, knowledge from low-level data in an ontology \[104\]. By defining logical rules, new interesting knowledge can be inferred from the data in the model. Designing an ontology is a complex task, as it should model the required knowledge for the given application in enough detail. An example of such an approach is given by Heyse et al. In their work, they presented a semantic ontology specifically for ET in VR. Their method for ontology design is an iterative process that requires close interaction with domain experts and (semantic) engineers \[105\].

In psychology research, the five factor model of personality is one of the most recent models proposed so far. The model was proposed not only for a general understanding of human behavior but also for psychologists to treat personality disorders \[106\]. The five factor model of personality is a hierarchical organization of personality traits in terms of five basic dimensions: Extraversion, Agreeableness, Conscientiousness, Neuroticism, and Openness to Experience. Research using both natural language adjectives and theoretically based personality questionnaires supports the comprehensiveness of the model and its applicability across observers and cultures \[107\]. The five factors are considered to be the basis or dimensions of the personality space and are detailed further in Table 2.2.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Adjectives used to describe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraversion</td>
<td>Preference for and behavior in social situations</td>
<td>Talkative, energetic, social</td>
</tr>
<tr>
<td>Agreeableness</td>
<td>Interactions with others</td>
<td>Trusting, friendly, cooperative</td>
</tr>
<tr>
<td>Conscientiousness</td>
<td>Organized, persistent in achieving goals</td>
<td>Methodical, well organized, dutiful</td>
</tr>
<tr>
<td>Neuroticism</td>
<td>Tendency to experience negative thoughts</td>
<td>Insecure, emotionally distressed</td>
</tr>
<tr>
<td>Openness</td>
<td>Open mindedness, interest in culture</td>
<td>Imaginative, creative, explorative</td>
</tr>
</tbody>
</table>

**Table 2.2:** The five factor model \[106\].

The five factor model describes the personality, but it is still a high level description. Kshirsagar proposed a layered personality model to link the personality with emotions...
Linking personality and emotions however, is difficult to do unless an extra layer between the personality and the expressions is introduced. This approach has been illustrated in Figure 2.3. Knowing the emotional personality definitions and emotion classifications, it could be possible to write rules, mapping personality to emotional states. However, such rule-based systems are unlikely to succeed in simulating believable behaviors, mainly because uncertainty is an important aspect of human behavior. Thus, a computational model that can handle uncertainty while retaining the underlying principles is needed. The Bayesian Belief Network (BBN) is the natural choice as it is used to model domains containing uncertainty [106,108]. Figure 2.4 shows a typical BBN as used by Kshirsagar.

2.4.2 Modelling emotions

In emotion simulation research so far, appraisal is popularly done by a system based on the OCC (Ortony, Clore and Collins’s) model of emotion [109]. However, as this thesis is focused on relaxation, this section will focus on those emotions or feelings that are important when modelling relaxation. Relaxation in psychology, is the emotional state of a living being, of low tension, in which there is an absence of arousal that could come from sources such as anger, anxiety, or fear [110]. In contrast to relaxation, arousal is a physiological and psychological state of being awake or reactive to stimuli. It results in the state of phasic alertness, a significant temporary boost in the capacity to respond to stimuli. This is in contrast to tonic alertness, which indicates a state of optimal vigilance where attention is sustained for a prolonged period of time. While tonic alertness can happen concurrently with relaxation, phasic alertness is a result of the activity of the sympathetic system, and is elicited by different neurophysiological and cognitive mecha-
nisms than tonic alertness, which are inconsistent with the state of relaxation [111].

In previous sections, relaxation has been connected to stress numerous times. During stress, the activity of the sympathetic nervous system increases (preparing the body for fight or flight) and the activity of the parasympathetic nervous system decreases. During rest and relaxation however, the opposite occurs [112], indicating an inverse relationship between stress and relaxation. Anxiety is a psychological, physiological, and behavioral state induced in animals and humans by a threat to well-being or survival, either actual or potential. It can be characterized by increased arousal and specific behavior patterns. For some, fear and anxiety are indistinguishable, whereas others believe that they are distinct phenomena. Although both are alerting signals, they appear to prepare the body for different actions. Anxiety is a generalized response to an unknown threat or internal conflict, whereas fear is focused on known external danger. The fact that anxiety and fear are probably distinct emotional states does not exclude some overlap in underlying brain and behavioral mechanisms. In fact, anxiety may just be a more elaborate form of fear, which provides the individual with an increased capacity to adapt and plan for the future [113, 114].

These findings indicate that a person should not be stressed, anxious, aroused or afraid
when trying to relax. It should be noted that these are necessary conditions, but not sufficient, i.e., a model in which relaxation only depends on these four parameters is a simplification. Also, these four parameters are not mutually independent. For example, elevated stress appears to indicate the presence of fear \cite{115}. Affective arousal happens when we are emotionally charged up and feel passionate about something. One may be angry, excited, afraid, stressed, anxious or feeling the stimulation of any other emotion \cite{116}, indicating all of these may cause arousal.
Chapter 3

Methods

The goal of this master’s thesis is to create a personalized and adaptive VR experience for relaxation therapy. Personalized indicates that the VE should be fit to the personality of the user, while adaptive means that the VE should adapt itself to the user’s real time emotional state. This chapter focuses on the methods used to realize this goal. First, Section 3.1 presents a high level overview of the system architecture. Afterwards, the individual components are discussed in greater detail.

3.1 High level architecture

The high level architecture used to achieve this thesis’s goal is illustrated by Figure 3.1. It consists of four major components and four types of data. The first type of data is personality data, which describes the personality of the user. It can be provided by multiple sources, e.g., by the user himself, his spouse, his therapist or a combination of these. Alternatively, this data could be generated by an intelligent system that observes the user when executing a certain task. In this thesis, the data is provided by the user himself by filling in a questionnaire. When creating an environment, both the personality and the emotional status of the user are taken into account. However, in order not to break the immersiveness of the VE, radical changes in the environment are typically not done. This indicates that a rough outline of the environment exists that is based purely on the personality of the user and is independent of the user’s emotional state. Generating this raw environment is done by the environment generator. This results in raw environment data, which is data that gives a rough overview of how the environment should look. Next, the raw environment data needs to be enhanced to create the exact environment that is shown to the user. This enhancement is done by the adaptor component and results in environment data. Apart from the raw environment data, the adaptor also uses emotional
data that describes the emotional state and feelings of the user at any time during the therapy session. Once the environment data is generated, the VE is ready to be shown to the user. This is done by the VE render component. Visualizing the environment will trigger an emotional reaction on the user, which is simulated by the emotional model, resulting in new emotional data. This data is then fed back to the adaptor, completing the cycle. In the next sections, further details on the environment generation, emotional model, and adaptor are given.

### 3.2 Environment generator: modelling personalities

The environment generator is responsible for generating a raw environment based on the personality of the user. In order to achieve this, it uses a decision tree. Unlike bayesian networks or other machine learning techniques, decision trees do not require loads of data and are way easier to understand. A decision tree is a flowchart-like structure in which each internal node represents a "test" on an attribute, these are called decision nodes. Each branch represents the outcome of the test, these are called edges, and each end leaf represents a class label, these are called end nodes [117]. An example of such a tree is given in Figure 3.2. Here, edges are represented by lines, decision nodes by rounded rectangles, and end nodes by regular rectangles. One should start at the root of the tree, which is the leftmost decision node in Figure 3.2. At each decision node, a decision has to be made. Each possible decision is represented by an edge starting from the decision node.
and ending in either another decision node or an end node. If another decision node is reached, a decision has to be taken again. If an end node is reached, the process is finished and the outcome is defined by the end node. For example, if the decision tree from Figure 3.2 is used for a user who likes nature and is afraid of heights, the raw environment is a forest environment. The decisions taken at every decision node depend solely on the user’s personality data and each outcome represents a different raw environment. The set of possible raw environments is fixed and thus the same for every user. Therefore users with similar personalities could generate the same raw environment. However, their final environments may still show significant differences as the environment details get decided upon by a user’s emotional status.

### 3.3 Emotional model

This thesis does not use biofeedback mechanics to derive the user’s emotional state as this is considered out of scope. Therefore, a model is needed that simulates the emotional state of the user. In this section, such a model is be proposed. It employs the user’s current emotional state and the last adaptation made to the VE by the adaptor. Based on this, the emotional model simulates the user’s next emotional state. The goal of this emotional model is to model relaxation, therefore, first and foremost relaxation will be defined. As seen in the literature study (see Chapter 2), relaxation is definitely influenced by stress, anxiety, fear, and arousal. Both fear and anxiety as stress and anxiety tend to overlap and have similar physiological symptoms. Therefore, not including anxiety in the emotional model will simplify the model without losing much information. The emotional model thus focuses on four parameters: fear, stress, arousal, and relaxation. The generic

---

**Figure 3.2:** Example of a decision tree for environment selection.
Chapter 3. Methods

formula used to compute relaxation is given by Equation 3.1

\[ \text{relaxation} = r(\text{fear, stress, arousal, } lc, al, nl, dg, py, ms, cb) \]  

(3.1)

As this equation indicates, the user’s relaxation depends on his current emotions (fear, stress, and arousal). Furthermore, it depends on the possible system real-time adaptations (lc, al, nl, dg, py, ms, and cb). In the following subsections all the components of the relaxation equation are discussed. Section 3.3.1 will discuss what these adaptations stand for and how they impact the emotional model. Afterwards, the emotional parameters that shape the model are discussed. Section 3.3.2 will discuss fear, Section 3.3.3 will discuss stress, Section 3.3.4 will discuss arousal, and finally, Section 3.3.5 will discuss relaxation. In order to improve readability, abbreviations will be used when describing the model. All of these abbreviations and variables used in the emotional model are summarized by Table 3.1.

3.3.1 Adaptations

The set of adaptations the adaptor can make depends on the type of environment that is generated. E.g., if an inside environment is rendered, a possible adaptation is to change the color of artificial light, however, this makes little sense for an outside environment as these do not contain artificial light. In this thesis, seven adaptations are defined. These are explained in detail below, and summarized in Table 3.2.

- **Artificial light**: If artificial light is present in the environment, this parameter controls its intensity. The intensity is a real value between zero (no light) and one (maximal light).

- **Natural light**: This parameter controls the intensity of the natural light and can be used to set the time of day. Similar as for artificial light, this intensity is a real value between zero (no light) and one (maximal light).

- **Light color**: Research has shown that for most people, green and blue colors relate to calmness, peacefulness, and relaxation \[118\]. In this master’s thesis, the option for blue light is added to the VE. If artificial light is present in the environment, this parameter controls the color. This parameter is a real value and can take a value between zero and one. Zero corresponds with white light and one corresponds with blue light.

- **Fire**: If a fire such as a campfire or fireplace is present in the environment, this
### Adaptations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>al</td>
<td>Artificial light, can take values in range $[0, 1]$</td>
</tr>
<tr>
<td>nl</td>
<td>Natural light, can take values in range $[0, 1]$</td>
</tr>
<tr>
<td>lc</td>
<td>Light color, can take values in range $[0, 1]$</td>
</tr>
<tr>
<td>py</td>
<td>Fire, can take values in range $[0, 1]$</td>
</tr>
<tr>
<td>dg</td>
<td>Dog, can take values from the set ${0, \frac{1}{2}, 1}$</td>
</tr>
<tr>
<td>ms</td>
<td>Music, can take values from the set ${0, 1}$</td>
</tr>
<tr>
<td>cb</td>
<td>Controlled breathing, can take values from the set ${0, 1}$</td>
</tr>
<tr>
<td>dark</td>
<td>Indicates how dark the environment is. This is not an adaptation itself, but a linear combination of other adaptations, see Equation 3.7. Can take values in range $[0, 1]$</td>
</tr>
</tbody>
</table>

### Functions

<table>
<thead>
<tr>
<th>Notation</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>relaxation</td>
<td>Defines how relaxed the user is</td>
</tr>
<tr>
<td>fear</td>
<td>Defines the total fear of the user</td>
</tr>
<tr>
<td>stress</td>
<td>Defines how stresses the user feels</td>
</tr>
<tr>
<td>arousal</td>
<td>Defines how aroused the user feels</td>
</tr>
<tr>
<td>fear(py)</td>
<td>Impact of pyrophobia on the user’s fear</td>
</tr>
<tr>
<td>fear(dg)</td>
<td>Impact of cynophobia on the user’s fear</td>
</tr>
<tr>
<td>fear(dark)</td>
<td>Impact of nyctophobia on the user’s fear</td>
</tr>
<tr>
<td>pref(x)</td>
<td>The preference of adaptation $x$</td>
</tr>
</tbody>
</table>

### Constants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>al_{opt}</td>
<td>Optimal artificial light intensity</td>
</tr>
<tr>
<td>nl_{opt}</td>
<td>Optimal natural light intensity</td>
</tr>
<tr>
<td>lc_{opt}</td>
<td>Optimal light color intensity</td>
</tr>
<tr>
<td>py_{opt}</td>
<td>Optimal fire intensity</td>
</tr>
<tr>
<td>dg_{opt}</td>
<td>Optimal dog intensity</td>
</tr>
<tr>
<td>ms_{opt}</td>
<td>Optimal music intensity</td>
</tr>
<tr>
<td>cb_{opt}</td>
<td>Optimal controlled breathing intensity</td>
</tr>
<tr>
<td>dark_{opt}</td>
<td>Optimal darkness intensity</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of all possible adaptations, constants, and functions used in the emotional model.
### Adaptation

<table>
<thead>
<tr>
<th>Adaptation</th>
<th>Abbreviation</th>
<th>Possible values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial light</td>
<td>al</td>
<td>[0, 1]</td>
</tr>
<tr>
<td>Natural light</td>
<td>nl</td>
<td>[0, 1]</td>
</tr>
<tr>
<td>Light color</td>
<td>lc</td>
<td>[0, 1]</td>
</tr>
<tr>
<td>Fire</td>
<td>py</td>
<td>[0, 1]</td>
</tr>
<tr>
<td>Dog</td>
<td>dg</td>
<td>{0, 1, 2}</td>
</tr>
<tr>
<td>Music</td>
<td>ms</td>
<td>{0, 1}</td>
</tr>
<tr>
<td>Controlled Breathing</td>
<td>cb</td>
<td>{0, 1}</td>
</tr>
</tbody>
</table>

**Table 3.2:** All possible adaptations with their possible values and abbreviations.

Parameter controls its intensity. The intensity is a real value between zero (no fire) and one (maximal fire).

- **Dog:** Research demonstrates that companion animals reduce individuals’ stress responses to stressful situations or environments [119]. Therefore, if the user is not afraid of dogs, a dog is introduced to the VE. If a dog is present in the environment, this parameter is used to control the distance between the dog and the user. It can take three possible values. A value of zero corresponds with the dog being far away. A value of one corresponds with the dog coming closer, but not yet within reach of the user. The last state, a value of two, corresponds with the dog being very close and within reach of the user.

- **Music:** Section 2.3 stated that music can reduce stress and enhance a sense of comfort and relaxation. Therefore, music is added to the VE if the user prefers it. If present in the environment, this parameter is used to (de)activate music. This parameter can take only two values: either the music is off which corresponds with a value of zero, or the music is on which corresponds with a value of one.

- **Controlled breathing:** Section 2.3 described breathing techniques as basic techniques best used to manage stress. Therefore, it is added to the VE. If present in the environment, this parameter is used to (de)activate controlled breathing therapy. This parameter can take only two values: either breathing therapy is inactive, indicated by a value of zero, or breathing therapy is active, indicated by a value of one.

**Preference**

In order to determine the impact of individual adaptations on the emotional state of the user, a function that indicates how much the user likes the current state of the adaptation is necessary. This function is called the preference function and is defined by Equation
This equation can be described a Gaussian centered around the optimal intensity with maximum value one. It uses the optimal intensity of the adaptation, which is the optimal state of the adaptation if only this adaptation, and not the whole system, is considered. This optimal intensity will be derived from the personality data and therefore is a constant. The value of this optimal intensity lies between zero and one, zero meaning that the user does not like the adaptation, one meaning he likes it very much. The optimal intensities have been summarized in the constants section of Table 3.1. The more the optimal intensity leans towards 0.5, the more the user feels indifferent about the adaptation and thus, the flatter the Gaussian becomes. This is visualized in Figure 3.3.

\[
pref(x) = \exp \left( \frac{-(x_{opt} - x)^2}{2 \cdot (1.075 - 2 \cdot (|0.5 - x_{opt}|))^2} \right)
\]

(3.2)

### 3.3.2 Fear

Based on the adaptations, three sources of fear can be distinguished. The first one is pyrophobia, i.e. fear of fire, and is induced by the fire adaptation. The second one of fear is cynophobia, i.e. fear of dogs, and is induced by the dog adaptation. The last source of fear is nyctophobia, i.e. fear of darkness. Nyctophobia is induced by the combination of the fire, natural light, and artificial light adaptations. Equation 3.3 defines how fear is calculated by this model. This equation contains three instances of the \textit{fear} function, one for every source of fear. \(F_1, F_2\) and \(F_3\) are used to normalize fear and give weights to
the different sources. They are constants based on the user’s personality. The resulting function outputs a value between negative and positive 1. Negative fear indicates that the user is not afraid and actually feels comfortable, whilst positive fear indicates the user is afraid.

\[
fear = F_1 \cdot fear(dg) + F_2 \cdot fear(py) + F_3 \cdot fear(dark) \tag{3.3}
\]

The \textit{fear} function is used to compute the impact of a certain source of fear on the user. It is defined by Equation 3.4, where \textit{source} is the current intensity of the source and \textit{source}_{opt} is the optimal intensity. If the source of fear has an optimal intensity value lower than \(\frac{1}{2}\), it frightens the user. A value above \(\frac{1}{2}\) indicates comfort. The magnitude of fear or comfort depends on how much the value leans towards respectively zero or one. The \textit{fear} function is visualized in Figure 3.4.

\[
fear(source) = (1 - 2 \cdot source_{opt}) \cdot source \tag{3.4}
\]

Based on the fear function, we can define the three sources of fear.

**Pyrophobia (fear of fire)**

Calculating pyrophobia, or the fear of fire, can be done by inserting fire into Equation 3.4 resulting in Equation 3.5. In this equation, \textit{py} is the current intensity of the fire as
defined in Table 3.1

\[
fear(py) = (1 - 2 \cdot py_{opt}) \cdot py
\]  \hspace{1cm} (3.5)

Cynophobia (fear of dogs)

The process for calculating fear for cynophobia is similar to that of pyrophobia except for one difference. As indicated by Table 3.2, the dog has discrete states in the set \{0, 1, 2\} instead of continuous ones in range [0, 1]. In order to use Equation 3.4, the intensity of the dog should be to the interval [0, 1]. This mapping results in intensities \{0, \frac{1}{2}, 1\}. Cynophobia is then calculated using Equation 3.4 resulting in Equation 3.6. This is visualized in Figure 3.5.

\[
fear(dg) = (1 - 2 \cdot dg_{opt}) \cdot dg
\]  \hspace{1cm} (3.6)

Nyctophobia (fear of darkness)

The impact of nyctophobia to fear is determined by the adaptations natural light, artificial light, and fire. Before defining the impact of nyctophobia, a measure for darkness is needed. This measure is given by Equation 3.7 and defines how dark the environment is. In this equation, \(I_1, I_2,\) and \(I_3\) are constants used for giving weights to the adaptations and to achieve normalization. Inserting this into Equation 3.4 leads to Equation 3.8.
which behaves in the same manner as the original equation, and is visualized by Figure 3.4.

\[
dark = 1 - (I_1 \cdot al + I_2 \cdot nl + I_3 \cdot py) \tag{3.7}
\]

\[
fear(\dark) = (1 - 2 \cdot \dark_{opt}) \cdot \dark \tag{3.8}
\]

### 3.3.3 Stress

The user’s current stress relies on his current fear, previous stress, and the adaptations controlled breathing, fire, and dog. The equation for calculating stress in this model is given by Equation 3.9. As with fear, \( S_1 \) and \( S_2 \) are constants used to normalize stress and give weights to the different components. They are constants based on the user’s personality. Equation 3.9 leads to a value for stress between zero and one.

\[
\text{stress} = s(fear, \text{stress}_{\text{prev}}, dg, py, cb)
\]
\[
= \max(fear, \text{stress}_{\text{core}}, \min(\text{stress}_{\text{prev}}, 1 - cb)) \tag{3.9}
\]

\[
\text{stress}_{\text{core}} = s_c(py, dg)
\]
\[
= S_1 \cdot (1 - \text{pref}(py)) + S_2 \cdot (1 - \text{pref}(dg))
\]

### 3.3.4 Arousal

In this model, arousal relies on the current fear, current stress, previous arousal, and the adaptations music, natural light, and artificial light. The equation for arousal is given in Equation 3.10. This function can be interpreted as follows: Arousal will only increase when fear or stress increases, and it will only decrease when the music is optimal and/or the environment is bright. Again, \( A_1, A_2 \) and \( A_3 \) ensure the arousal is normalized and give weights to the different components. They are constants based on the user’s personality.

\[
\text{arousal} = a(fear, \text{stress}, \text{arousal}_{\text{prev}}, ms, al, nl)
\]
\[
= \max(fear, \text{stress}, \min(\text{arousal}_{\text{prev}}, \text{arousal}_{\text{core}})) \tag{3.10}
\]

\[
\text{arousal}_{\text{core}} = a_c(ms, al, nl)
\]
\[
= A_1 \cdot (1 - \text{pref}(ms)) + A_2 \cdot (1 - nl) + A_3 \cdot (1 - al)
\]

### 3.3.5 Relaxation

Relaxation is the emotion we will try to maximize later on. In this model, relaxation depends on all of the other emotional parameters (fear, stress and arousal) as well as on
the adaptations music, light color, controlled breathing, natural light and artificial light. The function is given by Equation 3.11. As with all of the other emotions, $R_1$ to $R_8$ ensure the relaxation is normalized and give weights to the different components. $R_1$ to $R_8$ are constants based on the user’s personality.

\[
relaxation = r(fear, arousal, stress, ms, lc, cb, nl, al)
= R_1 \cdot pref(ms) + R_2 \cdot pref(lc)
+ R_3 \cdot pref(nl) + R_4 \cdot pref(al)
- R_5 \cdot cb - R_6 \cdot fear - R_7 \cdot arousal - R_8 \cdot stress
\] (3.11)

### 3.4 Adaptor

This section focuses on the adaptor, which is the component in charge of changing the adaptation’s intensities in real-time in order to maximize the user’s relaxation. It observes the current state of the VE and the user’s emotional data, and based on this, decides which adaptation its intensity should be changed next. The adaptor changes one adaptation its intensity at a time, and then waits for the user’s emotional state to update. After the new emotional state has been reached, the adaptor continues by computing what adaptation should be changed next and implements this change. This is repeated until the user reaches his optimal emotional state, at which point no more adaptations are necessary. The emotional model presented in Section 3.3 can now be used by the adaptor to predict the outcome of a certain action, and thus to decide which adaptation’s intensity to change in order to maximize relaxation. Over a series of iterations, this should lead to a sequence that leads to a final, optimal state in which the user has maximal relaxation. Finding this maximum relaxation can be formulated as an optimization problem. The emotional model is a non-linear model and can be solved using Mixed Integer Non-Linear Programming (MINLP), this model will be defined in Section 3.4.1. As MINLP problems are not easy to solve, we will attempt to linearize the problem. Linearization will result in a linear problem that can be solved using Mixed Integer Linear Programming (MILP), this will be discussed in 3.4.2. However, even after linearization of the problem, it cannot be solved in real-time. Therefore, a heuristic approach is presented in Section 3.4.3.

#### 3.4.1 Non-linear optimization

In this section, the emotional model proposed in Section 3.3 will be described as a MINLP problem. The goal of this problem is to maximize relaxation, in order to achieve this a
sequence of adaptations has to be performed. First we define the decision variables, these are the variables the optimizer should solve towards. They are given in Table 3.3.

**Decision variables**

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$nl$</td>
<td>real</td>
</tr>
<tr>
<td>$al$</td>
<td>real</td>
</tr>
<tr>
<td>$lc$</td>
<td>real</td>
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<tr>
<td>$py$</td>
<td>real</td>
</tr>
<tr>
<td>$dg_0$</td>
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<tr>
<td>$dg_1$</td>
<td>binary</td>
</tr>
<tr>
<td>$ms$</td>
<td>binary</td>
</tr>
<tr>
<td>$cb$</td>
<td>binary</td>
</tr>
</tbody>
</table>

**Table 3.3:** The decision variables of the non-linear optimization problem

**Constants**

Constants are values known to the system, they are fixed and are not subject to change. They include the optimal intensities (which will have been derived from the personality of the user), the user’s previous emotional state, and normalization constants used in the model.

$x_{\text{opt}}$, $x \in \{nl, al, lc, py, dg, ms, cb\}$

$x_{\text{prev}}$, $x \in \{nl, al, lc, py, dg, ms, cb\}$

$dark_{\text{opt}}$

$stress_{\text{prev}}$

$arousal_{\text{prev}}$

$F_k$, $A_k$, $I_k$, $k \in \{1, 2, 3\}$

$S_k$, $k \in \{1, 2\}$

$R_k$, $k \in \{1, ..., 8\}$

**Constraints**

The first set of constraints defines the range of the decision variables. The last constraint is necessary to assure that $dg$ can only take values in $\{0, \frac{1}{2}, 1\}$.

$nl$, $al$, $lc$, $py$, $dg \geq 0$

$nl$, $al$, $lc$, $py$, $dg \leq 1$

$dg = \frac{dg_0}{2} + dg_1$
Next, we define that in each step at most one variable should change. When no variable changes any more, the optimal state has been reached and the optimization is complete. Enforcing that at most one variable changes can be achieved by requiring that, for every two consecutive steps, the maximum absolute change over all adaptations equals the sum of all the absolute changes.

$$\sum_{x \in X} |x - x_{prev}| = \max_{x \in X} |x - x_{prev}|, \quad X = \{nl, al, lc, dg, py, ms, cb\}$$

The following constraints describe the core of the optimization problem, i.e., the emotional model from Section 3.3 is introduced. $p(x)$ is the preference function from Equation 3.2 and $f(x)$ is the fear function from Equation 3.4. These abbreviations have been used for readability.

\[
p(x) = \exp\left(\frac{-(x_{opt} - x)^2}{2 \cdot (1.075 - 2 \cdot (|0.5 - x_{opt}|))^2}\right)
\]

\[
f(x) = (1 - 2 \cdot x_{opt}) \cdot x
\]

\[
dark = 1 - (I_1 \cdot al + I_2 \cdot nl + I_3 \cdot py)
\]

\[
fear = F_1 \cdot f(dg) + F_2 \cdot f(py) + F_3 \cdot f(dark)
\]

\[
stress = \max(fear, stress_{core}, \min(stress_{prev}, 1 - cb))
\]

\[
arousal = \max(fear, stress, \min(arousal_{prev}, arousal_{core}))
\]

\[
stress_{core} = S_1 \cdot (1 - p(py)) + S_2 \cdot (1 - p(dg))
\]

\[
arousal_{core} = A_1 \cdot (1 - p(ms)) + A_2 \cdot (1 - nl) + A_3 \cdot (1 - al)
\]

\[
relaxation = R_1 \cdot p(ms) + R_2 \cdot p(lc) + R_3 \cdot p(nl) + R_4 \cdot p(al)
\]

... - $R_5 \cdot cb - R_6 \cdot fear - R_7 \cdot arousal - R_8 \cdot stress$

**Objective function**

maximize relaxation

The problem as defined above is non linear, in order to use a linear solver for the optimization problem, the problem has to be linearized.

### 3.4.2 Linear optimization

This section will discuss the necessary steps to linearize the problem, and then define the problem as a linear optimization problem.
Firstly, a linear optimization problem cannot contain any maximization or minimization functions. If $\max(A, B)$ occurs in the problem, we should choose $M$ as an upper boundary on $\max(A, B)$ (the big-M parameter), define $b$ as an extra binary variable, and introduce the constraints in Equation 3.12 to the linear optimization problem. The newly introduced variable $C$ will now contain the result of $\max(A, B)$. A similar approach can be taken for minimization functions, this is illustrated by Equation 3.13.

\[
\begin{align*}
C & \geq A \\
C & \geq B \\
C & \leq A + M \cdot b \\
C & \leq B + M \cdot (1 - b) \\
C & \leq A \\
C & \leq B \\
C & \geq A - M \cdot b \\
C & \geq B - M \cdot (1 - b)
\end{align*}
\] (3.12)

Secondly, due to the nature of the model, relaxation may first need to reach a local minimum in order to reach the absolute maximum later on. Having this local minimum however, is not allowed if we wish to apply linear programming. In order to circumvent this problem, the weight $R_5$ from Equation 3.11 can be chosen so that the relaxation curve becomes a convex function. This is illustrated by Figure 3.6.

The last step in defining the problem as a linear optimization problem is to linearize the preference function (see Equation 3.2). This is necessary because this function is a Gaussian, which makes the problem non linear. Linearizing the preference function will be achieved by discretization. The preference function is used for every adaptation except $cb$. Every one of the adaptations has a different optimal intensity and thus requires a different discretization. Discretization of the preference function of a generic variable $x$ is achieved by defining $p_x$. $p_x$ is a list of $n_x$ samples, as defined in Equation 3.14. $n_x$ indicates how many sample are calculated and can be chosen, bigger values of $n_x$ leads to higher precision. Both the list $p_x$ and $n_x$ are added to the problem as constants. Next, $i_x$ is introduced as a decision variable, this decision variable is the index of the used value of $p_x$, and thus the preference $p(x)$ is equal to $p_x[i_x]$. The constraints that need introduction
to the problem are given by Equations 3.15 and 3.16

\[ p_x[i] = p \left( \frac{i}{n_x - 1} \right), \quad \forall i \in [0, n_x - 1] \]  
\[ i_x \leq n_x - 1 \]  
\[ x = \frac{i_x}{n_x - 1} \]

Minimisation constraints

There are two minimisation terms in the constraints, one inside of the stress function and one inside of the arousal function, as illustrated by Equations 3.17 and 3.18. Before linearizing the minimization functions, they are defined as separate constraints as illustrated by Equations 3.19 to 3.22

\[ \text{stress} = \max\{\text{fear}, \text{stress}_\text{core}, \min(\text{stress}_{\text{prev}}, 1 - cb)\} \quad (3.17) \]
\[ \text{arousal} = \max\{\text{fear}, \text{stress}, \min(\text{arousal}_{\text{prev}}, \text{arousal}_\text{core})\} \quad (3.18) \]
\[ \text{stress} = \max\{\text{fear}, \text{stress}_\text{core}, \text{stress}_\text{min}\} \quad (3.19) \]
\[ \text{arousal} = \max\{\text{fear}, \text{stress}, \text{arousal}_{\text{min}}\} \quad (3.20) \]
\[ \text{stress}_{\text{min}} = \min(\text{stress}_{\text{prev}}, 1 - cb) \quad (3.21) \]
\[ \text{arousal}_{\text{min}} = \min(\text{arousal}_{\text{prev}}, \text{arousal}_\text{core}) \quad (3.22) \]
We now can remove the minimization functions defined in Equation 3.21 and 3.22 using the method illustrated by Equation 3.13. This results in two sets of equations and is illustrated by Equation 3.23. The big-M parameter has been set to one, as this is a valid upper boundary for the problem.

\[
\begin{align*}
stress_{\min} & \leq stress_{\text{prev}} \\
stress_{\min} & \leq 1 - cb \\
stress_{\min} & \geq stress_{\text{prev}} - b_0 \\
stress_{\min} & \geq 1 - cb - (1 - b_0) \\
\end{align*}
\]

(3.23)

Maximization constraints

The MINLP problem also contains two maximization constraints, these constraints have already been described by Equations 3.19 and 3.20. As these constraints take three arguments in the maximization function instead of two, they will first be rewritten into Equations 3.24 to 3.27. We now can remove the maximization functions in these constraints by applying the methods from Equation 3.12. This results in the set of equations defined by Equations 3.25 and 3.29. Similar as with the minimization constraints, the big-M parameter has chosen to be one.

\[
\begin{align*}
stress & = \max(fear, stress_{\arg}) \\
stress_{\arg} & = \max(stress_{\text{core}}, stress_{\min}) \\
arousal & = \max(fear, arousal_{\arg}) \\
arousal_{\arg} & = \max(stress, arousal_{\min}) \\
\end{align*}
\]

(3.24)  (3.25)  (3.26)  (3.27)
stress $\geq$ fear
stress $\geq$ stress$_{arg}$
stress $\leq$ fear + $b_2$
stress $\leq$ stress$_{arg} + (1 - b_2)$

(3.28)
stress$_{arg} \geq$ stress$_{core}$
stress$_{arg} \geq$ stress$_{min}$
stress$_{arg} \leq$ stress$_{core} + b_3$
stress$_{arg} \leq$ stress$_{min} + (1 - b_3)$

arousal $\geq$ fear
arousal $\geq$ arousal$_{arg}$
arousal $\leq$ fear + $b_4$
arousal $\leq$ arousal$_{arg} + (1 - b_4)$
arousal$_{arg} \geq$ stress
arousal$_{arg} \geq$ arousal$_{min}$
arousal$_{arg} \leq$ stress + $b_5$
arousal$_{arg} \leq$ arousal$_{min} + (1 - b_5)$

(3.29)

Discretization
The last step before defining the problem as a linear optimization problem is to discretize
the preference function constraint. This can be achieved by introducing the decision
variables $i_x$, constants $n_x$ and $p_x[n_x]$, and the constraints as defined by Equation 3.30. $i_x$
represents the index of the preference used for adaptation $x$. $n_x$ represents the amount
of samples used when sampling preference the of $x$. Lastly, $p_x[n_x]$ represents the list of
sampled preferences of $x$ itself. $x \in \{nl, al, lc, py, dg, ms\}$ for all of these variables.

\[
i_x \leq n_x - 1, \quad x \in \{nl, al, lc, py, dg, ms\}
\]

(3.30)

\[
x = \frac{i_x}{n_x - 1}
\]

Linear optimization problem
Using the techniques described earlier in this section, we now will linearize the MINLP
problem from Section 3.4.1. The results in a MILP problem that can be solved using
MILP solvers.
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Decision variables

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Type</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
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<tr>
<td>$i_{al}$</td>
<td>integer</td>
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</tr>
<tr>
<td>$i_{lc}$</td>
<td>integer</td>
<td></td>
</tr>
<tr>
<td>$i_{py}$</td>
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<td></td>
</tr>
<tr>
<td>$i_{dg}$</td>
<td>integer</td>
<td></td>
</tr>
<tr>
<td>$i_{ms}$</td>
<td>integer</td>
<td></td>
</tr>
<tr>
<td>$cb$</td>
<td>binary</td>
<td></td>
</tr>
<tr>
<td>$dg_k$</td>
<td>binary</td>
<td>$k \in {0, 1}$</td>
</tr>
<tr>
<td>$b_k$</td>
<td>binary</td>
<td>$k \in {0, \ldots, 5}$</td>
</tr>
</tbody>
</table>

Table 3.4: The decision variables of the linear optimization problem.

Constants

For discrete adaptations such as $dg$ and $ms$, $n_x$ should equal the amount of possible states, being three and two respectively.

$x_{opt}$, $x \in \{nl, al, lc, py, dg, ms, cb\}$

$x_{prev}$, $x \in \{nl, al, lc, py, dg, ms, cb\}$

dark$_{opt}$

stress$_{prev}$

arousal$_{prev}$

$F_k, A_k, I_k, k \in \{1, 2, 3\}$

$S_k$, $k \in \{1, 2\}$

$R_k$, $k \in \{1, \ldots, 8\}$

$n_x$, $x \in \{nl, al, lc, py, dg, ms\}$

$p_x[n_x]$, $x \in \{nl, al, lc, py, dg, ms\}$

Objective function

maximize relaxation

Constraints

The first two constraints are new constraints that have been introduced due to discretization of the preference function. The other four were already present in the MINLP.
The following constraints describe the core of the optimization problem, i.e., the emotional model. These constraints have been redefined to remove the maximization and minimization functions.

\[
\begin{align*}
    f(x) &= (1 - 2 \cdot x_{opt}) \cdot x \\
    dark &= 1 - (I_1 \cdot al + I_2 \cdot nl + I_3 \cdot py) \\
    fear &= F_1 \cdot f(dg) + F_2 \cdot f(py) + F_3 \cdot f(dark) \\
    stresscore &= S_1 \cdot (1 - p(py)) + S_2 \cdot (1 - p(dg)) \\
    arousalcore &= A_1 \cdot (1 - p(ms)) + A_2 \cdot (1 - nl) + A_3 \cdot (1 - al) \\
    relaxation &= R_1 \cdot p(ms) + R_2 \cdot p(lc) + R_3 \cdot p(nl) + R_4 \cdot p(al) \\
    &\quad - R_5 \cdot cb - R_6 \cdot fear - R_7 \cdot arousal - R_8 \cdot stress
\end{align*}
\]
stress \geq fear
stress \geq stress_{arg}
stress \leq fear + b_2
stress \leq stress_{arg} + (1 - b_2)
stress_{arg} \geq stress_{core}
stress_{arg} \geq stress_{min}
stress_{arg} \leq stress_{core} + b_3
stress_{arg} \leq stress_{min} + (1 - b_3)
stress_{min} \leq stress_{prev}
stress_{min} \leq 1 - cb
stress_{min} \geq stress_{prev} - b_0
stress_{min} \geq 1 - cb - (1 - b_0)

arousal \geq fear
arousal \geq arousal_{arg}
arousal \leq fear + b_4
arousal \leq arousal_{arg} + (1 - b_4)
arousal_{arg} \geq stress
arousal_{arg} \geq arousal_{min}
arousal_{arg} \leq stress + b_5
arousal_{arg} \leq arousal_{min} + (1 - b_5)
arousal_{min} \leq arousal_{prev}
arousal_{min} \leq arousal_{core}
arousal_{min} \geq arousal_{prev} - b_1
arousal_{min} \geq arousal_{core} - (1 - b_1)

3.4.3 Heuristic optimization

As Section 3.4.2 illustrated, applying linear optimization is not a simple task and therefore, a more simple approach is considered for implementation. The following approach is heuristic and does not guarantee optimal relaxation, but tries to approach it. It first determines the absolute maximal relaxation and the adaptation intensities that lead to this maximal relaxation. Afterwards, it determines the sequence in which these adaptations
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<table>
<thead>
<tr>
<th></th>
<th>dg</th>
<th>py</th>
<th>nl</th>
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<th>cb</th>
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<th>relaxation</th>
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</tr>
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<td>arousal</td>
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<td>x</td>
<td>x</td>
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<td>x</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 3.5: Visualization of the relationship between adaptations and emotions in the emotional model.

will be changed to their respective intensities in order to reach this optimum. The heuristic approach relies on a few observations made on the emotional model, which is briefly revised here. Table 3.5 visualizes the emotional model by giving an overview of the relationship between adaptations and emotional variables.

\[
dark = 1 - (I_1 \cdot al + I_2 \cdot nl + I_3 \cdot py)
\]

\[
fear = F_1 \cdot f(dg) + F_2 \cdot f(py) + F_3 \cdot f(dark)
\]

\[
stress = \max(fear, \text{stress}_{\text{core}}, \min(\text{stress}_{\text{prev}}, 1 - cb))
\]

\[
arousal = \max(fear, \text{stress}, \min(\text{arousal}_{\text{prev}}, \text{arousal}_{\text{core}}))
\]

\[
\text{stress}_{\text{core}} = S_1 \cdot (1 - p(py)) + S_2 \cdot (1 - p(dg))
\]

\[
arousal_{\text{core}} = A_1 \cdot (1 - p(ms)) + A_2 \cdot (1 - nl) + A_3 \cdot (1 - al)
\]

\[
\text{relaxation} = R_1 \cdot p(ms) + R_2 \cdot p(lc) + R_3 \cdot p(nl) + R_4 \cdot p(al)
\]

\[
-R_5 \cdot cb - R_6 \cdot fear - R_7 \cdot arousal - R_8 \cdot stress
\]

The first observation states that \(lc\) does only occur in \(\text{relaxation}\) in the term \(p(lc)\). As the overall goal is to maximize \(\text{relaxation}\), we also want to maximize this term. This term reaches a maximum when \(lc = lc_{\text{opt}}\). The second observation is that \(ms\) is used twice, once in \(\text{relaxation}\) and once in \(\text{arousal}\) (in the \(\text{arousal}_{\text{core}}\) term). In both instances \(ms\) is used in the term \(p(ms)\). For \(ms\) in \(\text{relaxation}\), we want to maximize the \(p(ms)\) term.

For \(ms\) in \(\text{arousal}\), we want to minimize minus \(p(ms)\) (as \(\text{arousal}\) has a negative impact on \(\text{relaxation}\)). Minimizing minus \(p(ms)\) equals to maximizing \(p(ms)\), the goal in both instances of \(ms\) is thus the same, i.e. to maximize \(p(ms)\). This leads to \(ms = ms_{\text{opt}}\). The third and final observation states that the final state of \(cb\) should always be zero (\(cb\) stands for controlled breathing and only has two states, on and off, respectively one and zero). This is because if \(cb\) is turned on, turning it off does not impact \(\text{stress}\). Turning it off does however increase \(\text{relaxation}\), so turning it off will always be beneficial to maximizing relaxation. Therefore \(cb\) its final state should always be off (i.e. zero). So far, this heuristic optimizer has inferred that the state of maximal relaxation will be reached if \(lc = lc_{\text{opt}}, ms = ms_{\text{opt}},\) and \(cb = 0\). To find the state of the other adaptations (\(dg, py, nl,\) and \(al\)), the heuristic approach uses a brute force approach. It samples each of these adaptations...
and finds the combination of samples that leads to maximal relaxation, this is illustrated in Table 3.6. This table illustrates that $3 \cdot n^3$ combinations are checked, higher $n$ leads to a higher precision, but also more calculations. The combination that leads to maximal relaxation is selected. The model used to calculate these samples is slightly modified as the recursive behavior of stress and arousal is not desirable. The modified version of stress and arousal are presented by Equations 3.31 and 3.32.

\[
\text{stress} = \max(\text{fear}, \text{stress}_\text{core}) \tag{3.31}
\]

\[
\text{arousal} = \max(\text{fear}, \text{stress}, \text{arousal}_\text{core}) \tag{3.32}
\]

Once the final intensity of each adaptation is determined, the sequence in which to advance to this state should be determined. It should be noted that only one adaptation intensity can be changed per iteration. Table 3.5 and the emotional model state that relaxation depends on all other emotional variables, arousal depends on stress and fear, stress depends on fear, and fear does not rely on any emotional variables. This indicates that the order in which the emotional parameters should be set is fear $\rightarrow$ stress $\rightarrow$ arousal $\rightarrow$ relaxation. Thus, first the adaptations that impact fear should be changed, then those of stress, and so on. It should be noted that when turning $cb$ off, fear and stress$_\text{core}$ should already have reached their minimal value. This is because $cb$ is the only parameter that allows for stress to decrease. So in order to "lock in" the value for stress provided by fear and stress$_\text{core}$, $cb$ should be on. This indicates that all of the adaptations that influence fear and stress$_\text{core}$ should be set before using $cb$. The order in which the heuristic optimizer sets the adaptation intensities is $dg \rightarrow py \rightarrow nl \rightarrow al \rightarrow$ turn $cb$ on $\rightarrow$ turn $cb$ off $\rightarrow$ $ms \rightarrow lc$. The heuristic optimizer works as illustrated by Code Fragment 3.1.

<table>
<thead>
<tr>
<th>Adaptation</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Step size</th>
<th>Amount of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dg$</td>
<td>0</td>
<td>1</td>
<td>0.50</td>
<td>3</td>
</tr>
<tr>
<td>$py$</td>
<td>0</td>
<td>1</td>
<td>$\frac{1}{n-1}$</td>
<td>$n$</td>
</tr>
<tr>
<td>$nl$</td>
<td>0</td>
<td>1</td>
<td>$\frac{1}{n-1}$</td>
<td>$n$</td>
</tr>
<tr>
<td>$al$</td>
<td>0</td>
<td>1</td>
<td>$\frac{1}{n-1}$</td>
<td>$n$</td>
</tr>
</tbody>
</table>

Table 3.6: Illustration of how the heuristic optimizer sample the adaptations.

Code Fragment 3.1: Illustration of how the heuristic optimizer works.

# function used to find the set of intensities that leads to maximal relaxation.
def optimize():
    # final intensities that are fixed
music = personality_data.getOptimalIntensity("music");
light_color = personality_data.getOptimalIntensity("light color");
controlled_breathing = 0.0;

# final intensities to find using brute force approach
dog, fire, natural_light, artificial_light =
    brute_force_maximize_relaxation();

# save the final intensities that lead to maximal relaxation
final_intensities.set("music", music);
final_intensities.set("light color", light_color);
final_intensities.set("controlled breathing", controlled_breathing);
final_intensities.set("dog", dog);
final_intensities.set("fire", fire);
final_intensities.set("natural light", natural_light);
final_intensities.set("artificial light", artificial_light);

# function used to proceed to this final state of relaxation.
def run():
    environment.set("dog", final_intensities.get("dog");
    environment.set("fire", final_intensities.get("fire");
    environment.set("natural light", final_intensities.get("natural light");
    environment.set("artificial light", final_intensities.get("artificial light");
    environment.set("controlled breathing", "on");
    environment.set("controlled breathing", "off");
    environment.set("music", final_intensities.get("music");
    environment.set("light color", final_intensities.get("light color");
Chapter 4

Implementation

This chapter discusses the implementation of the personalized and adaptive VR application for relaxation therapy. First, an overview of the application architecture is given in Section 4.1. The remaining sections (Sections 4.2, 4.3, and 4.4) discuss the individual components from this architecture.

4.1 Architecture

This section presents the application architecture. First the high-level architecture is presented and afterwards physical setup is introduced. Finally, the technologies used to realize this implementation are provided.

4.1.1 High-level architecture

A high-level view of the architecture has already been introduced in Section 3.1. However, the actual implementation of the architecture is slightly different. As we are simulating the emotional state of users, the emotional model does not need to observe the actual user. This observation leads to the implemented architecture as illustrated by Figure 4.1. The application starts by entering the user’s personality data into the system. This personality data is provided by a questionnaire filled in by the user himself, this is further discussed in Section 4.2. The environment generator then creates a raw environment based on this personality data, this is a rough outline of how the environment will look. The environment generator achieves this by using a decision tree, which is discussed in Section 4.3. Afterwards, the adaptor completes the details of this raw environment based on the emotional data of the user. The adaptor’s implementation will be discussed in Section 4.5. Now the environment can be rendered to the user. The VE render component turns the environment data into a real VE and shows it to the user. Finally, the emotional
model simulates the feelings of the user and updates the emotional data, completing the cycle. The implementation of the emotional model is discussed in Section 4.4.

4.1.2 Physical setup

The application can be divided into two parts: the dashboard application and the render application. The dashboard application can be seen as the core of the application. It contains the environment generator, the adaptor, and the emotional model, as well as the personality data, emotional data, raw environment data, and environment data. The dashboard application is a desktop application. The render application receives the environment data from the dashboard application, creates the corresponding VE, and displays this to the Head Mounted Display (HMD) worn by the user. The application type of the render component depends on the technology used, e.g., when using the HTC Vive this is a desktop application, when using the Samsung Gear VR this is a mobile application. In this thesis the render component is a desktop application. As both the dashboard and render component are desktop applications, only one physical device (a computer) is needed. This results in the implemented setup illustrated by Figure 4.2.

4.1.3 Technologies

The dashboard application is written using JavaFX (version 12). SceneBuilder (version 11.0.0) is used to create the different views and Apache Maven (version 3.6.1) to compile
4.2 Questionnaire

A questionnaire is used to gather both the personality data and the initial emotional data. The questions asked to gather the personality data are given by questions one to nine in Table 4.1. The questions asked to gather the initial emotional data are given by questions ten to twelve. How these questions are posed by the dashboard is visualized by Figure 4.3.

4.2.1 Personality data

The personality data consists of optimal intensities and binary variables. The optimal intensities that should be derived are \( p_{y_{\text{opt}}} \), \( d_{g_{\text{opt}}} \), \( n_{l_{\text{opt}}} \), \( a_{l_{\text{opt}}} \), \( m_{s_{\text{opt}}} \), \( l_{c_{\text{opt}}} \), and \( d_{a_{\text{darkopt}}} \) and are derived from questions five to nine. The answer to each of these questions is a value between zero and one. We distinguish two cases: questions that use a threshold and questions that do not.
Table 4.1: The questionnaire given to the user at the start of the application.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Question</th>
<th>Possible answers</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Would you prefer an indoors or outdoors environment to relax?</td>
<td>{Indoors, Outdoors}</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Could the presence of water help you to relax?</td>
<td>{Yes, No}</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Are you afraid of heights?</td>
<td>{Yes, No}</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>What is your favorite season?</td>
<td>{Winter, Summer}</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>How does fire make you feel?</td>
<td>[0, 1]</td>
<td>Afraid → Relaxed</td>
</tr>
<tr>
<td>6</td>
<td>How do you feel when a dog is in your presence?</td>
<td>[0, 1]</td>
<td>Afraid → Relaxed</td>
</tr>
<tr>
<td>7</td>
<td>How does darkness make you feel?</td>
<td>[0, 1]</td>
<td>Afraid → Relaxed</td>
</tr>
<tr>
<td>8</td>
<td>How do you find classical relaxation music?</td>
<td>[0, 1]</td>
<td>Disturbing → Relaxing</td>
</tr>
<tr>
<td>9</td>
<td>Blue light gives you a relaxed feeling, do you agree?</td>
<td>[0, 1]</td>
<td>No → Yes</td>
</tr>
<tr>
<td>10</td>
<td>How afraid do you feel right now?</td>
<td>[−1, 1]</td>
<td>Comfortable → Very afraid</td>
</tr>
<tr>
<td>11</td>
<td>How stressed do you feel right now?</td>
<td>[0, 1]</td>
<td>Not stressed → Very stressed</td>
</tr>
<tr>
<td>12</td>
<td>How aroused do you feel right now?</td>
<td>[0, 1]</td>
<td>Not aroused → Very aroused</td>
</tr>
</tbody>
</table>

**No threshold**  This case is applicable to questions seven to nine and results in optimal intensities $n_{l_{opt}}$, $a_{l_{opt}}$, $m_{s_{opt}}$, $l_{c_{opt}}$, and $d_{ark_{opt}}$.

- The value of $d_{ark_{opt}}$ is equal to the value of the answer to question seven.
- The value of both $a_{l_{opt}}$ and $n_{l_{opt}}$ is equal to the value of one minus the answer to question seven.
- The value of $m_{s_{opt}}$ is equal to the value of the answer to question eight.
- The value of $l_{c_{opt}}$ is equal to the value of the answer to question nine.
- For both artificial light intensity and natural light intensity, the optimal intensity is equal to one minus the value of the slider for the question "How does darkness make you feel?". This is because an increase in darkness equals a decrease in light intensity.
Threshold Questions that use a threshold are directly linked to exactly one adaptation. For these questions, we state that the user could be too afraid of the adaptation to have it in the scene. If a user places the slider of these questions between 0 and 0.25, the corresponding adaptation will not be present in the scene. This case is applicable to $py_{opt}$ and $dg_{opt}$. The optimal intensity is calculated as illustrated by Equation 4.1.

- We define $y$ as the value of the answer to question five. The value of $py_{opt}$ is now equal to $optimal\_intensity(y)$.
- We define $z$ as the value of the answer to question five. The value of $dg_{opt}$ is now equal to $optimal\_intensity(z)$.

\[
\text{optimal\_intensity}(x) = \begin{cases} 
0 & \text{if } x < 0.25 \\
\frac{x - 0.25}{0.75} & \text{if } 0.25 \leq x \leq 0.5 \\
x & \text{if } x > 0.5
\end{cases}
\]  

(4.1)

The binary variables are summarized in Table 4.2. The first column states the name of the variable, the second column explains its meaning, and the third column discusses how this parameter is derived from the questionnaire. The questions used to derive the binary variables are questions one to six.
### Variables | Meaning | Derivation
--- | --- | ---
| bin\_indoors | Indicates if an indoors environment should be generated. Zero is no, one is yes. | Equals zero if the answer to question one is "outdoors", equals one if the answer is "indoors".
| bin\_water | Indicates if an environment with water should be generated. Zero is no, one is yes. | Equals zero if the answer to question two is "no", equals one if the answer is "yes".
| bin\_heights | Indicates if an environment with big height differences may be generated. Zero is no, one is yes. | Equals zero if the answer to question three is "yes", equals one if the answer is "no".
| bin\_summer | Indicates if a summer or winter environment should be generated. A value of zero indicates a winter environment, a value of one indicates a summer environment. | Equals zero if the answer to question four is "winter", equals one if the answer is "summer".
| bin\_fire | Indicates if a fire may be present in the environment. Zero is no, one is yes. | Equals zero if the value of answer to question five is lower than the threshold discussed earlier. The value of the threshold is 0.25.
| bin\_dog | Indicates if a dog may be present in the environment. Zero is no, one is yes. | Equals zero if the value of answer to question six is lower than the threshold discussed earlier. The value of the threshold is 0.25.

Table 4.2: Summary of the binary variables defined in the personality data.

### 4.2.2 Emotional data

The initial state of the emotional data is derived from questions ten to twelve. The initial state of \textit{fear} equals to the value of the answer to question ten. Next, the initial state of \textit{stress} equals to the value of the answer to question eleven. Lastly, the initial state of \textit{arousal} equals to the value of the answer to question twelve. Using the initial emotional state, a rough estimation of the initial adaptation intensities is derived from this. Afterwards, the initial state of \textit{relaxation} is computed using these intensities and the emotional model. Code Fragment 4.1 illustrates how this rough estimation is made.

#### Code Fragment 4.1: Rough derivation of the initial adaptation states based on the initial emotional state.

```python
def setInitialAdaptations(emotional_state, adaptations):
    # dog always starts at intensity 0
    adaptations.set("dog", 0);

    # controlled breathing always starts at intensity 0
    adaptations.set("controlled breathing", 0);
```

---

4.2.2 Emotional data

The initial state of the emotional data is derived from questions ten to twelve. The initial state of \textit{fear} equals to the value of the answer to question ten. Next, the initial state of \textit{stress} equals to the value of the answer to question eleven. Lastly, the initial state of \textit{arousal} equals to the value of the answer to question twelve. Using the initial emotional state, a rough estimation of the initial adaptation intensities is derived from this. Afterwards, the initial state of \textit{relaxation} is computed using these intensities and the emotional model. Code Fragment 4.1 illustrates how this rough estimation is made.

#### Code Fragment 4.1: Rough derivation of the initial adaptation states based on the initial emotional state.

```python
def setInitialAdaptations(emotional_state, adaptations):
    # dog always starts at intensity 0
    adaptations.set("dog", 0);

    # controlled breathing always starts at intensity 0
    adaptations.set("controlled breathing", 0);
```
# music always starts at intensity 0
adaptations.set("music", 0);

# light color always starts at intensity 0
adaptations.set("light color", 0);

# fire depends on stress (if no fire -> ignore stress component)
adaptations.set("fire", stressToFire(emotional_state.getStress());

# natural light depends on fear
adaptations.set("natural light",
    fearToNaturalLight(emotional_state.getFear());

# artificial light depends on arousal (no artificial light -> ignore arousal)
adaptations.set("artificial light",
    arousalToArtificialLight(emotional_state.getArousal());

4.3 Environment generator

The environment generator uses the personality data and transforms it into a raw environment. In order to achieve this, the environment generator uses a decision tree. This decision tree uses the binary variables $bin_{indoors}$, $bin_{water}$, and $bin_{heights}$ as defined in Table 4.2. The resulting decision tree is given in Figure 4.4 for every possible outcome of this tree, a fixed VE was created. These VEs are visualized in Figure 4.5. Next, the environment generator decides which version of the chosen VE should be loaded. This version depends on the binary variables $bin_{fire}$, $bin_{dog}$, and $bin_{summer}$. $bin_{summer}$ and $bin_{dog}$ are used in all of the environments, whereas $bin_{fire}$ is only used for outdoors environments as indoors environments can not contain a fire. Table 4.3 summarizes which adaptations every environment may contain. After picking the desired version, the raw environment has been successfully generated and the environment generator is done. The implementation of the environment generator is illustrated by Code Fragment 4.2.

**Code Fragment 4.2:** Implementation of the environment generator.

```python
if bin_indoors:
    if bin_water:
        environment = load(lake_house);
    else:
```
```python
environment = load(forest_cabin);
else:
    if bin_heights:
        environment = load(mountain_camp);
    else:
        environment = load(lake);

if bin_indoors:
    environment.set("fire", bin_fire);

environment.set("dog", bin_dog);
environment.set("summer", bin_summer);
```

**Figure 4.4:** Implementation of the decision tree used by the environment generator.

**Table 4.3:** Summary of possible adaptations every environment may contain.

<table>
<thead>
<tr>
<th></th>
<th>natural light</th>
<th>artificial light</th>
<th>light color</th>
<th>fire</th>
<th>dog</th>
<th>music</th>
<th>controlled breathing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake house</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Forest cabin</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Mountain camp</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Lake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.5: Visualization of the virtual environments.
4.4 Emotional model

The emotional model has already been defined in Section 3.3. When implementing this model, an exact value for every constant was chosen, these values are given below.

\[
S_i = \frac{1}{2 \cdot \max(stress)}, \quad i \in \{1, 2\}
\]

\[
I_i = \frac{1}{3 \cdot \max(dark)}, \quad i \in \{1, 2, 3\}
\]

\[
F_i = \frac{1}{3 \cdot \max(fear)}, \quad i \in \{1, 2, 3\}
\]

\[
A_i = \frac{1}{3 \cdot \max(arousal)}, \quad i \in \{1, 2, 3\}
\]

\[
R_i = \frac{1}{8 \cdot \max(relaxation)}, \quad i \in \{1, 2, ..., 8\}
\]

The constants are chosen to achieve normalization and so that each component has the same impact to the model. These values, together with the emotional model as defined in Section 3.3, fully define the implementation of the emotional model. At every iteration, the function described in Code Fragment 4.3 is executed. After updating the emotional data, the new values are sent to the dashboard and visualized on screen. This allows for an observer to monitor the emotional state. This is illustrated by Figure 4.6.

**Code Fragment 4.3:** Function executed by the emotional model every time the environment updates.

```python
def updateEmotions(emotional_data, adaptations):
    # load the adaptation intensities
    dog = adaptations.getDog();
    fire = adaptations.getFire();
    music = adaptations.getMusic();
    light_color = adaptations.getLightColor();
    natural_light = adaptations.getNaturalLight();
    artificial_light = adaptations.getArtificialLight();
    controlled_breathing = adaptations.getControlledBreathing();

    # load the old emotional values
    stress_old = emotional_data.getStress();
    arousal_old = emotional_data.getArousal();

    # calculate the new emotional values
    fear = calculateFear(dog, fire, natural_light, artificial_light);
    stress = calculateStress(dog, fire, controlled_breathing, stress_old, fear);
```


arousal = calculateArousal(music, natural_light, artificial_light, arousal_old, fear, stress)
relaxation = calculateRelaxation(music, light_color, natural_light, artificial_light, controlled_breathing, fear, stress, arousal);

# update the emotional data
emotional_data.update(fear, stress, arousal, relaxation);

4.5 Adaptor

The task of the adaptor is to perform a sequence of adaptations to the environment that leads to an optimal state of relaxation for the user. The possible adaptations the adaptor can perform in each environment are summarized in Table 4.3, a few illustrations are given by Figure 4.7. In every iteration, the adaptor will determine which action is best and perform this action. It then waits for an update of the emotional data after which the next iteration starts. In order to find this optimal state of relaxation, it uses the heuristic optimizer as defined in Section 3.4.3. This is illustrated by Code Fragment 4.4.

**Code Fragment 4.4:** Illustration of how the heuristic model finds the optimal set of adaptations.

```python
def optimize():
    # final intensities that are fixed
    music = personality_data.getOptimalIntensity("music");
    light_color = personality_data.getOptimalIntensity("light color");
```
controlled_breathing = 0.0;

# final intensities to find using brute force approach
dog, fire, natural_light, artificial_light;

# variable to maximize
optimal_relaxation = 0;

# copy the emotional model. Used for finding the set of final intensities that lead to maximum relaxation without altering the actual emotional model.
EmotionalModel em_simulator = emotional_model;
em_simulator.set("music", music);
em_simulator.set("light color", light_color);
em_simulator.set("controlled breathing", controlled_breathing);

for intensity_dog in range(0, 1, 0.5):
    for intensity_fire in range(0, 1, 0.02):
        for intensity_natural_light in range(0, 1, 0.02):
            for intensity_artificial_light in range(0, 1, 0.02):
                # set the intensities
                em_simulator.set("dog", intensity_dog);
                em_simulator.set("fire", intensity_fire);
                em_simulator.set("natural light", intensity_natural_light);
                em_simulator.set("artificial light",
                                intensity_artificial_light);

                # calculate the corresponding relaxation
                relaxation = em_simulator.calculateRelaxation();

                # check if the new relaxation is better than the old one.
                if relaxation > optimal_relaxation:
                    dog = intensity_dog;
                    fire = intensity_fire;
                    natural_light = intensity_natural_light;
                    artificial_light = intensity_artificial_light;
                    optimal_relaxation = relaxation;

    # save the set of final intensities that lead to maximum relaxation.
final_intensities.set("music", music);
final_intensities.set("light color", light_color);
final_intensities.set("controlled breathing", controlled_breathing);
final_intensities.set("dog", dog);
final_intensities.set("fire", fire);
final_intensities.set("natural light", natural_light);
final_intensities.set("artificial light", artificial_light);

(a) Lake house environment with little natural light, a blue light color, and controlled breathing activated.
(b) Lake environment with dog and fire activated.
(c) Mountain camp environment with little natural light, no dog, a big fire, and in a winter setting.

Figure 4.7: Visualization of the adaptations in the virtual environments.

After the optimal set of intensities has been found, the heuristic optimizer uses a fixed sequence to get to this state. After updating an intensity, the optimizer waits for a signal
of the Render application. This signal indicates that the adaptation has been updated and the optimizer can continue. This process is illustrated in Code Fragment 4.5.

**Code Fragment 4.5:** Illustration of how the heuristic model works towards the optimal set of adaptation intensities.

```python
def run():
    environment.set("dog", final_intensities.get("dog"));
    environment.set("fire", final_intensities.get("fire"));
    environment.set("natural light", final_intensities.get("natural light"));
    environment.set("artificial light", final_intensities.get("artificial light"));
    environment.set("controlled breathing", 1.0);
    environment.set("controlled breathing", 0.0);
    environment.set("music", final_intensities.get("music"));
    environment.set("light color", final_intensities.get("light color"));

def environment.set(string s, double d):
    if environment.contains(s):
        environment.get(s).setState(d);
        thread.waitForNotify();
```
Chapter 5

Analysis

This section analyzes the methods used in this thesis. Section 5.1 discusses how to perform simulations for a big number of users. Section 5.2 then selects a subset of all possible users to be used for simulations. Next, the results of the default heuristic optimizer are discussed in Section 5.3. Afterwards, Section 5.4 analyses the impact of changing the default adaptation order of the heuristic optimizer. Finally, Section 5.5 analyses the impact of splitting an adaptation into two parts. For simulation purposes, the render application is replaced by a dummy. This will speed up simulations as the heuristic optimizer no longer has to wait for the VE to be rendered (see Code Fragment 4.5).

5.1 Simulating users

Different users will behave differently and thus, in order perform a comprehensive analysis, a variety of different users has to be analyzed. In order to achieve this in a time efficient way, users will be simulated. More specific, the input users can provide to the application, i.e. the questionnaire, will be simulated. The most complete approach to this is to generate every possible questionnaire and simulate the behaviour for all of these users. However, doing this is impossible as the questionnaire contains non-discrete values, the sliders. A sample rate therefore has to be chosen, which is illustrated in Table 5.1. As questions 2 to 4 do not have any impact on the emotional model, these questions have only one sampled value. Question 1 does have an impact on the model as an indoors and outdoors environment lead to different adaptations. Therefore, both options remain present among the possible sampled answers. Questions 5 to 9 are used for calculating the optimal intensities as discussed in Section 4.2.1. At least two samples are necessary. One sample lower than $\frac{1}{2}$, indicating that the user dislikes the adaptation, and one sample higher than $\frac{1}{2}$, indicating that the user likes the adaptation. For adaptations using a
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<table>
<thead>
<tr>
<th>Nr.</th>
<th>Question</th>
<th>Nr. possible answers</th>
<th>Nr. sampled answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Would you prefer an indoors or outdoors environment to relax?</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Could the presence of water help you to relax?</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Are you afraid of heights?</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>What is your favorite season?</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>How does fire make you feel?</td>
<td>∞</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>How do you feel when a dog is in your presence?</td>
<td>∞</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>How does darkness make you feel?</td>
<td>∞</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>How do you find classical relaxation music?</td>
<td>∞</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Blue light gives you a relaxed feeling, do you agree?</td>
<td>∞</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>How afraid do you feel right now?</td>
<td>∞</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>How stressed do you feel right now?</td>
<td>∞</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>How aroused do you feel right now?</td>
<td>∞</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1: The amount of possible answers that can be given to every question from the questionnaire.

<table>
<thead>
<tr>
<th>cb</th>
<th>dg</th>
<th>lc</th>
<th>al</th>
<th>nl</th>
<th>ms</th>
<th>fear</th>
<th>stress</th>
<th>arousal</th>
<th>relaxation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0.0</td>
<td>0.14</td>
<td>0.01</td>
<td>0</td>
<td>0.00</td>
<td>0.1</td>
<td>0.10</td>
<td>0.30</td>
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<td>0</td>
<td>1</td>
<td>0.0</td>
<td>0.14</td>
<td>0.98</td>
<td>0</td>
<td>0.91</td>
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</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.0</td>
<td>0.98</td>
<td>0.98</td>
<td>0</td>
<td>0.13</td>
<td>0.98</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.0</td>
<td>0.98</td>
<td>0.98</td>
<td>0</td>
<td>0.00</td>
<td>1.0</td>
<td>1.00</td>
<td>0.61</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.0</td>
<td>0.98</td>
<td>0.98</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.78</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.0</td>
<td>0.98</td>
<td>0.98</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.96</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0.5</td>
<td>0.98</td>
<td>0.98</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Table 5.2: Example of an output table that contains every step in the optimization process for a user. This user has the fire adaptation deactivated as it is not present.

threshold, at least three samples are required. One sample lower than the threshold ($\frac{1}{4}$), which will lead to a deactivation of the adaptation. One sample between the threshold and $\frac{1}{2}$, and one sample higher than $\frac{1}{2}$. For this simulation, four samples are chosen per question. These samples are chosen randomly in the ranges $[0, \frac{1}{4}]$, $[\frac{1}{4}, \frac{3}{4}]$, $[\frac{3}{4}, 1]$, and $[0, \frac{3}{4}]$.

The initial emotional state is always set to the worst case scenario (i.e. fear, stress, and arousal are equal to 1) as this scenario is the most complete. The amount of samples chosen for the initial emotional states is therefore one. This leads to a total of $2 \cdot 4^5 = 2048$ simulated users. Simulating the heuristic optimizer for all of these users leads to a series of tables (one table per simulated user) that contains every step in the optimization process. An example of such a table is given by Table 5.2. The running time for simulating all of the 2048 users is approximately 20 minutes, which corresponds to about half a second per user.

This process of simulating users is helpful for generating huge amounts of detailed data
to analyze. However, it has to be repeated a few thousand times for analysis, making it infeasible. It would not only take several days to generate the data, but it also leads to an amount of data that is impossible to analyze without using intelligent systems. Furthermore, due to the fact that the generated users are semi random, not all of the users are actually meaningful. Narrowing down the amount of simulated users will be discussed in Section 5.2.

5.2 Selecting users

As simulating all of the possible users is infeasible, 12 user profiles are selected out of the 2048 possible ones. A user profile has three main components. The first defines the type of environment: indoors or outdoors? Indoors environments do not contain the fire adaptation, and outdoors environments do not contain the artificial light, light color, and controlled breathing adaptations. Secondly, the optimal adaptation intensities should be selected for all active adaptations. Lastly, the initial emotional state needs to be set. As stated in previous section, the values of the initial emotions are set to one. This leads to the user profiles defined in Table 5.3. The first six profiles are extreme cases used for observing general trends and comparing adaptations objectively. This is because the optimal intensity of all adaptations are the same, and thus they will have the same impact on the model. The six last profiles are average users. User 7 and 8 prefer a dark environment with a fire or blue lights. They also prefer music when relaxing and dislike dogs. User 9 and 10 are the opposite, they like dogs and bright environments but dislike fire, blue light, and music. Lastly, user 11 and 12 are somewhat in between. They are quite neutral towards a dog and darkness, dislike music, and like fire and blue light.

5.3 Heuristic optimizer

In this section, the default heuristic optimizer will be analyzed. The order in which it changes the adaptations is $dg$, $py$, $nl$, $al$, $cb$ on, $cb$ off, $ms$, and $lc$. The twelve user profiles from Section 5.2 are loaded and their behaviour is simulated. The results for users 1 and 2 are given in Table 5.4 and 5.5 respectively. These results are also visualized in Figures 5.1 and 5.2 along with the results for all other users. We observe that the heuristic model achieves maximum relaxation for every outdoors environment, but not for every indoors environment. However, despite not always achieving maximal relaxation, it does get very close. Also, it manages to minimize fear and stress in most cases, for both indoors and outdoors environments. Arousal does not always reach a low value, and in
<table>
<thead>
<tr>
<th>Id</th>
<th>Environment</th>
<th>Optimal intensity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>indoors</td>
<td>dg 0.9 py 0.9 nl 0.9 al 0.9 lc 0.9 ms 0.9</td>
<td>Dog lover; Afraid of darkness; Likes music and blue light.</td>
</tr>
<tr>
<td>User 2</td>
<td>outdoors</td>
<td>dg 0.9 py 0.9 nl 0.9 al 0.9 lc 0.9 ms 0.9</td>
<td>Dog lover; Afraid of darkness; Likes music and fire.</td>
</tr>
<tr>
<td>User 3</td>
<td>indoors</td>
<td>dg 0.5 py 0.5 nl 0.5 al 0.5 lc 0.5 ms 0.5</td>
<td>Neutral towards every adaptation.</td>
</tr>
<tr>
<td>User 4</td>
<td>outdoors</td>
<td>dg 0.5 py 0.5 nl 0.5 al 0.5 lc 0.5 ms 0.5</td>
<td>Neutral towards every adaptation.</td>
</tr>
<tr>
<td>User 5</td>
<td>indoors</td>
<td>dg 0.1 py 0.1 nl 0.1 al 0.1 lc 0.1 ms 0.1</td>
<td>Afraid of dogs; Loves darkness; Dislikes music and blue light.</td>
</tr>
<tr>
<td>User 6</td>
<td>outdoors</td>
<td>dg 0.1 py 0.1 nl 0.1 al 0.1 lc 0.1 ms 0.1</td>
<td>Afraid of dogs and fire; Loves darkness; Dislikes music.</td>
</tr>
<tr>
<td>User 7</td>
<td>indoors</td>
<td>dg 0.0 py 0.1 nl 0.1 al 0.7 lc 0.9 ms 0.9</td>
<td>Afraid of dogs; Loves darkness, music and blue light.</td>
</tr>
<tr>
<td>User 8</td>
<td>outdoors</td>
<td>dg 0.0 py 0.7 nl 0.1 al 0.1 lc 0.9 ms 0.9</td>
<td>Afraid of dogs; Loves darkness, music and fire.</td>
</tr>
<tr>
<td>User 9</td>
<td>indoors</td>
<td>dg 1.0 py 0.8 nl 0.8 al 0.1 lc 0.3 ms 0.3</td>
<td>Dog lover; Afraid of darkness; Dislikes music and blue light.</td>
</tr>
<tr>
<td>User 10</td>
<td>outdoors</td>
<td>dg 1.0 py 0.8 nl 0.8 al 0.1 lc 0.3 ms 0.3</td>
<td>Dog lover; Afraid of darkness and fire; Dislikes music.</td>
</tr>
<tr>
<td>User 11</td>
<td>indoors</td>
<td>dg 0.6 py 0.4 nl 0.4 al 0.8 lc 0.8 ms 0.1</td>
<td>Likes blue light; Dislikes music.</td>
</tr>
<tr>
<td>User 12</td>
<td>outdoors</td>
<td>dg 0.6 py 0.8 nl 0.4 al 0.4 lc 0.8 ms 0.1</td>
<td>Loves fire; Dislikes music.</td>
</tr>
</tbody>
</table>

Table 5.3: User profiles used for simulations.
these cases (see user 7 and 11), relaxation tends to not reach its maximum. The heuristic optimizer does a decent job at achieving high relaxation values, especially for outdoors environments. However, it often executes adaptations with higher impact during the later steps. Performing these steps earlier may relax the user sooner, and result in an overall better experience. This will effect will reflect heavily on the average relaxation, as will be illustrated in Section 5.4. These observations indicate that more optimal sequences (i.e. the order in which adaptations are changed) may exist, especially for indoors environments as the current sequence does not always lead to maximal relaxation. The next section will discuss this.

### 5.4 Adaptation order

This section will discuss the sequence in which the heuristic optimizer performs adaptations. Every time interval, exactly one adaptation takes place, which leads to a change of the emotional values. Eight adaptations occur (dg, py, nl, al, cb on, cb off, ms, and lc) as illustrated by Code Fragment 4.5. Therefore, 40320 possible permutations of these adaptations exist, however, as "cb off" should happen after "cb on", only 20160 permutations are valid. Simulating every permutation for a single user takes between four and ten hours, making it infeasible to simulate all twelve users. Luckily, we can make simpli-
Figure 5.1: Visualization of the steps taken by the heuristic optimizer to relax indoors users.
Figure 5.2: Visualization of the steps taken by the heuristic optimizer to relax outdoors users.
Indoors environments do not contain fire ($py$), and outdoors environments do not contain artificial light ($al$), controlled breathing ($cb$), and light color ($lc$). Therefore, indoors environments only have 5040 possible permutations and outdoors environments only have 24. This leads to a runtime of maximum 90 minutes for indoors environments and around 25 seconds for outdoors environments. To further reduce the runtime of indoors environments, the actions "cb on" and "cb off" are combined into one, lowering the amount of valid permutations to 720 and the maximum runtime to about 12 minutes. Simulating the twelve users now takes approximately 45 minutes, which is acceptable. This is illustrated in Figure 5.3. The results of this simulation are thus split into (1) user profiles on indoor environments, and (2) user profiles on outdoors environments. First we consider outdoors environments, afterwards we consider indoors environments.

### 5.4.1 Outdoors environments

The results of the simulation for outdoors environments are given in Table 5.6. The simulated sessions are ranked first according to the final relaxation value (column) and second to their average relaxation during the session. We observe that for outdoors environments, it always is possible to reach the optimal state of relaxation, which is indicated by the fact the the final relaxation value is always 1. This observation makes sense as outdoors environments do not contain certain adaptations, especially controlled breathing, which simplifies the model by a lot. Next, we observe that user 6 has an average relaxation of 1 for all simulated sessions, meaning that the user already started in his most optimal state. Therefore, user 6 will be excluded from simulations from now on. In Table 5.6, the top four sequences for each individual user have been marked in each column.
tion illustrates that the optimal sequences for every user (except user 8), are contained in the overall top five simulated sessions. More importantly, the set of sequences 1, 2, 3, and 5 contains an optimal sequence of every user (except user 8). These are the four sequences in which the first two adaptations are dog and natural light, and the last two are fire and music. This indicates that a good general approach could be to only consider these four sequences for outdoors environments. As stated before, user 8 is an exception to this rule. The reason is that he has an optimal $nl$ intensity of 0.1, which is rather low. Because the $nl$ intensity always starts out at 0.0, it is already close to the optimal intensity, and thus it makes no sense to change it first as other adaptations have a bigger impact.

To summarize, one can select a subset of sequences and compare these, this is done by computing the final and average relaxation for all of them and selecting the best ones. First, if a user has a low optimal $nl$ intensity, the optimal sequences to consider are (1) $dg, py, ms$, and $nl$; and (2) $dg, ms, py$, and $nl$. Second, if the user does not have this optimal $nl$ intensity, the optimal sequences to consider are (1) $dg, nl, py$, and $ms$; (2) $dg, nl, ms$, and $py$; (3) $nl, dg, py$, and $ms$; and (4) $nl, dg, ms$, and $py$. One of these sequences will be the optimal one, which one depends on the user. In the case of low optimal $nl$ intensity, the simulation runtime is less than two seconds. In the opposite case, this takes less than four seconds. Alternatively, if time is less of an issue, one can simulate all 24 possible sequences. This takes about half a minute. Half a minute is still acceptable during the initialization phase, but not when re-calculating the model during a therapy session. Re-calculation is not done in this thesis and thus, comparing all 24 possible sequences is a valid option. The default sequence used by the heuristic optimizer in the implementation corresponds with sequence 9 in Table 5.6. This is not a bad sequence, but it doesn’t belong to the best set either. We can therefore conclude that it can be improved by applying a strategy as discussed above.

### 5.4.2 Indoors environments

In this section, indoors environments are considered. The simulation results are partially given in Table 5.8 and are again ranked according to the final and average relaxation, in this order. The complete table contains 720 rows, and is therefore not given here. For outdoors environments, generating the whole table at runtime was feasible as it takes less than 30 seconds. For indoors environments however, generating this table takes on average 30 minutes, which is clearly unacceptable. Therefore, a subset of sequences is selected. Table 5.8 illustrates that for every single user that contains $dg$, the top 50%
<table>
<thead>
<tr>
<th>Nr.</th>
<th>Sequence</th>
<th>User 2 average</th>
<th>final</th>
<th>User 4 average</th>
<th>final</th>
<th>User 6 average</th>
<th>final</th>
<th>User 8 average</th>
<th>final</th>
<th>User 10 average</th>
<th>final</th>
<th>User 12 average</th>
<th>final</th>
<th>Average over averages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dg nl ms py</td>
<td>0.844</td>
<td>1</td>
<td>0.938</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.870</td>
<td>1</td>
<td>0.784</td>
<td>1</td>
<td>0.931</td>
<td>1</td>
<td>0.8945</td>
</tr>
<tr>
<td>2</td>
<td>dg nl py ms</td>
<td>0.822</td>
<td>1</td>
<td>0.946</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.857</td>
<td>1</td>
<td>0.784</td>
<td>1</td>
<td>0.931</td>
<td>1</td>
<td>0.8899</td>
</tr>
<tr>
<td>3</td>
<td>nl dg ms py</td>
<td>0.882</td>
<td>1</td>
<td>0.969</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.870</td>
<td>1</td>
<td>0.668</td>
<td>1</td>
<td>0.917</td>
<td>1</td>
<td>0.8844</td>
</tr>
<tr>
<td>4</td>
<td>dg ms nl py</td>
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<td>1</td>
<td>1</td>
<td>0.897</td>
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<td>0.931</td>
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<td>0.668</td>
<td>1</td>
<td>0.917</td>
<td>1</td>
<td>0.8798</td>
</tr>
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<td>6</td>
<td>ms dg nl py</td>
<td>0.746</td>
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<td>1</td>
<td>0.897</td>
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<td>0.784</td>
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<td>0.931</td>
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</tr>
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<td>7</td>
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<td>0.827</td>
<td>1</td>
<td>0.960</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.870</td>
<td>1</td>
<td>0.668</td>
<td>1</td>
<td>0.917</td>
<td>1</td>
<td>0.8737</td>
</tr>
<tr>
<td>8</td>
<td>nl py dg ms</td>
<td>0.809</td>
<td>1</td>
<td>0.976</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.857</td>
<td>1</td>
<td>0.668</td>
<td>1</td>
<td>0.878</td>
<td>1</td>
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<tr>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>0.870</td>
<td>1</td>
<td>0.784</td>
<td>1</td>
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<td>1</td>
<td>0.8640</td>
</tr>
<tr>
<td>10</td>
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<td>0.757</td>
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<td>0.925</td>
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<td>1</td>
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<td>1</td>
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<td>0.863</td>
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<td>1</td>
<td>1</td>
<td>0.910</td>
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<td>0.784</td>
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<td>0.8557</td>
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<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>0.870</td>
<td>1</td>
<td>0.784</td>
<td>1</td>
<td>0.856</td>
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<td>0.8499</td>
</tr>
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<td>ms dg py nl</td>
<td>0.657</td>
<td>1</td>
<td>0.858</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.910</td>
<td>1</td>
<td>0.784</td>
<td>1</td>
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</tr>
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<td>1</td>
<td>1</td>
<td>0.870</td>
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<td>0.668</td>
<td>1</td>
<td>0.859</td>
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</tr>
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<td>0.924</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>0.668</td>
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<td>1</td>
<td>1</td>
<td>0.897</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>0.897</td>
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<td>0.859</td>
<td>1</td>
<td>0.8204</td>
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</table>

Table 5.6: Effect of different adaptation sequences on the final and average relaxation for outdoors environments. Highlighted values are the top values for that user.
Table 5.7: Illustration of the drop in final relaxation between sequence 360 and 361, due to the order in which dg and cb occur. This drop does not happen for user 5 and 7 as they do not contain the dg adaptation.

sequences are sequences in which dg activates before cb. There is a noticeable drop in final relaxation between between the top and bottom half, i.e. sequence 360 and 361, as illustrated by Table 5.7. This drop does not occur for user 5 and 7, as they do not contain the dg adaptation.

Next, out of all 720 sequences, exactly 72 achieve maximal final relaxation for all users. These 72 sequences turn out not to be random, they consist of a first set of 60 and a second set of 12 entries. As indicated earlier, both sets contain only sequences in which dg occurs before cb. Furthermore, the first set consists of all sequences ending with al, resulting in \( \frac{5!}{2} = 60 \) entries. The second set consists of all sequences in which the last adaptation is lc and the last but one adaptations is al, resulting in \( \frac{4!}{2} = 12 \) entries. When inspecting these 72 sequences deeper, we notice that the optimal sequences of the individual users are all present in the first set, with exception of users 5 and 7. Their optimal sequences are not included in the set of 72 at all. The reason is that these users have the combination of a low optimal nl, al, and dg intensity. A low optimal dg intensity deactivates the dg adaptation, and thus "dg occurs before cb" is not valid anymore. Furthermore, the absence of the dg adaptation means that fear and stress need to be decreased by another adaptation before activating cb, i.e., by nl and al.

To summarize, if the user has a low optimal nl, al, and dg intensity, only sequences where cb is last should be considered. It is important to notice that due to the construction of the model, nl and al will always be equal. This results in 24 possible sequences and it takes less than 30 seconds to compare these. For any other user, all sequences ending with al in which dg occurs before cb should be considered. This results in 60 possible sequences, it takes less than one minute to compare these. If this runtime is considered
too long, one could simply pick a random sequence out of the set of 72 top sequences as all of these sequences lead to an maximal final relaxation. However, this may result in the average relaxation being non-optimal. When comparing the above approach to the default sequence used by the heuristic optimizer, we observe that the default sequence performs poorly. It does not even guarantee optimal relaxation for all users and is ranked 114th for user 1, 101st for user 3, 55th for user 5, 646th for user 7, 114th for user 9, and 334th for user 11. This results in an overall ranking of 226 out of 720. Therefore, it is advised to change this default sequence.

Figure 5.4 provides a summary of this section about adaptation orders in form of a decision tree. In this figure, $S(X)$ is the set that contains all permutations of $X$, and $S(X)_i$ is the $i_{th}$ entry from this set. Furthermore, $S^*(X)$ is the set that contains all permutations of $X$ where $dg$ occurs before $cb$, and $S^*(X)_i$ is the $i_{th}$ entry from this set.

5.5 Splitting adaptations

In order to assess if it influences the optimal relaxation sequence, this section will analyze the effects of splitting one adaptation into two adaptations. This means that instead of
<table>
<thead>
<tr>
<th>Nr.</th>
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<th>User 1 avg</th>
<th>User 1 fin</th>
<th>User 3 avg</th>
<th>User 3 fin</th>
<th>User 5 avg</th>
<th>User 5 fin</th>
<th>User 7 avg</th>
<th>User 7 fin</th>
<th>User 9 avg</th>
<th>User 9 fin</th>
<th>User 11 avg</th>
<th>User 11 fin</th>
<th>Average over avg</th>
<th>Average over fin</th>
</tr>
</thead>
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<td>0.925</td>
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<td>0.753</td>
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<td>0.754</td>
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<td>0.698</td>
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<td>0.754</td>
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<td>0.681</td>
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<td>0.778</td>
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<td>0.778</td>
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</tr>
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<td>0.736</td>
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<td>0.684</td>
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<td>0.741</td>
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<td>0.774</td>
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... 221 dg nl al cb ms lc ...

... 716 al cb ms dg nl lc ...

... 717 al cb nl ms lc dg ...

... 718 al cb ms nl lc dg ...

... 719 al cb nl ms dg lc ...

... 720 al cb ms nl dg lc ...

Table 5.8: Effect of different adaptation sequences on the final and average relaxation for indoors environments.
making an adaptation advance to its most optimal state in one go, it first goes to an intermediate state and at a later point in time, it advances to its optimal. E.g., an adaptation "A" is split into adaptations "A_1" and "A_2", creating a whole new set of possible sequences. This is illustrated by an example in Figure 5.5. As we will be comparing different adaptation orders again, we will consider both indoors and outdoors environments separately. Furthermore, to speed up simulation times, we will only consider those sequences that performed best in Section 5.4.

5.5.1 Outdoors environments

First we will consider outdoors environments. Outdoors environments have four adaptations: dg, ms, nl and py. As ms is a discrete adaptation with only two states, it is impossible to split. Similarly, dg is a discrete adaptation with three states, splitting these is possible but will always lead to an inferior solution. Thus, two possible adaptations to split remain: nl and py. First, we will perform a split on nl and evaluate all possible sequences. This results in a set of 60 possible sequences. As with the regular outdoors environment, every possible sequence reaches maximal relaxation and thus, we will order them based on average relaxation. The 24 top sequences have been summarized in Table 5.9. The gray entries in this table represent sequences that are the same as their original, i.e. the two parts of the split appear subsequently in the sequence. The red entries in this table represent sequences of which the original (grey) sequence is higher ranked. Therefore, these are sequences that do not benefit from a split. Lastly, the green entries represent sequences that do benefit from the split, and are thus higher ranked as their original (grey) sequence. From this table we can conclude that splitting nl is not beneficial at all. Out of the 24 top sequences only one benefits from its split, however, it
is only ranked 21. Without showing the results, we now do the same for \textit{py} and conclude that the results are the same as for \textit{nl}. In other words, outdoors environments do not benefit from splitting the adaptations into multiple steps.

\subsection*{5.5.2 Indoors environments}

We will now consider indoors environments. Indoors environments have six adaptations: \textit{dg}, \textit{ms}, \textit{nl}, \textit{al}, \textit{lc}, and \textit{cb}. Again, \textit{dg} and \textit{ms} are excluded. Splitting any of these adaptations would result in \(\frac{7!}{2} = 2520\) permutations, i.e. possible sequences, to compare. This however is not feasible as simulation runtimes are too high. Section 5.4 discussed how only 72 of the 720 initial sequences should be considered, this leads to lower simulation times and is assumed in the rest of this section. In the introduction of Section 5.4, "\textit{cb on}" and "\textit{cb off}" were combined into one adaptation. We now will split this adaptation again and discuss its impact. This results in 140 sequences of which the top 24 are visualized by Table 5.10. The same observation as with \textit{py} and \textit{nl} for outdoors environments can be made: splitting \textit{cb} does not lead to better final or average relaxation. The same goes for \textit{lc}, this is illustrated by Table 5.11. This table already has more green entries, but they are not the best entries. Furthermore, observing the tables for \textit{nl} and \textit{al} leads to a similar observation. Therefore, we conclude that indoors environments do not benefit from splitting the adaptations.
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</thead>
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</tr>
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<td>dg nl1 nl2 ms py</td>
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</tr>
<tr>
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<td>dg nl1 nl2 py ms</td>
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</table>

Table 5.9: Effect of different adaptation sequences on the average relaxation for outdoors environments, when nl is split. Gray entries represent sequences that equal a non-split sequence, i.e. the two parts of the split appear subsequently in the sequence. Red and green entries represent sequences of which the original (grey) sequence is respectively higher or lower ranked.
<table>
<thead>
<tr>
<th>Nr.</th>
<th>Sequence</th>
<th>User 1</th>
<th>User 3</th>
<th>User 5</th>
<th>User 7</th>
<th>User 9</th>
<th>User 11</th>
<th>Average</th>
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Table 5.10: Effect of different adaptation sequences on the average relaxation for indoors environments, when cb is split. Gray entries represent sequences that equal a non-split sequence, i.e. the two parts of the split appear subsequently in the sequence. Red entries represent sequences of which the original (grey) sequence is higher ranked.
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<td>240</td>
<td>ms nl lc1 dg cb lc2 al</td>
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Table 5.11: Effect of different adaptation sequences on the average relaxation for indoors environments, when lc is split. Gray entries represent sequences that equal a non-split sequence, i.e. the two parts of the split appear subsequently in the sequence. Red and green entries represent sequences of which the original (grey) sequence is respectively higher or lower ranked.
Chapter 6

Conclusion and future work

This master’s thesis presents a system that provides a personalized VR experience for relaxation therapy. The chosen architecture and setup, as illustrated by Figure 4.2, is an effective approach. As the environment generation is split into two parts (environment generator and adaptor), the environment has a basic design that is present during the whole session. Only the details get re-calculated every iteration. As a result, the environment does not go through drastic changes that could disturb the immersiveness, improving the overall VR experience. Furthermore, not having to generate the whole environment at every iteration is beneficial as this takes less time, which is important for any real-time application.

The environment generator component consists of a set of binary variables, used in a decision tree. This is a simple yet effective model that does not need more complication as only a limited set of basic environments are possible. When using more raw environments (and thus more decision variables), this simple approach may not be sufficient anymore. In this case, more complicated models such as BBNs, can be used. Designing such a model is not necessarily hard, however, it needs data generated by actual users, which tends to be a very time consuming task.

The principle the adaptor component is based on (generating the final environment based on the basic environment and emotional data) has shown to be effective as well. However, the optimization algorithm used, i.e. the heuristic optimizer, did show some flaws. The analysis shows that better optimized adaptation sequences exist and that, at the price of a few seconds, a sequence closer to the optimal can mostly be found. The term mostly is used because in fact, the heuristic approach can not guarantee an optimal outcome. An approach that can achieve this is the **linear optimization** approach introduced in
Chapter 6. Conclusion and future work

In future work, it may be interesting to try and implement this in real-time. It should be noted that the linear optimizer works because it knows the emotional model. If any other model is used, this optimizer has to be changed or it may make no sense. The same goes for the heuristic optimizer.

The emotional model component is used to simulate the behaviour of users. The model does fulfill its purpose, however, it does not measure the emotions of the actual user in any way. This means that if the model’s prediction does not equal the user’s feelings, it will not correct itself. As all humans behave differently, defining a model that predicts how users feel without actually measuring any emotions is not an easy, not to say impossible, task. A more accurate approach would be to use biofeedback. This means to measure the user’s physiological data and define an emotional model that transforms this data into emotions. Doing this is a hard, but interesting topic to be considered in future work.

If the environments change, the environment model should be re-defined as it is directly dependent on the adaptations. This obviously is not ideal. When using biofeedback, the emotional model is independent of the environment as it is based on physiological data and not adaptations. Therefore, different environments or adaptations do not require a different model, resulting in a more flexible application.

The used hardware in this master’s thesis is an HTC Vive connected to a computer with a i7-6700K processor, 16GB memory and a GTX 980ti Graphics card. However, not everyone has access to this hardware as it is quite expensive. Therefore, cheaper alternatives should be looked into. An interesting alternative could be mobile. The headset for a mobile approach (e.g. the Samsung Gear VR) is considerably cheaper and most of today’s people already have a smartphone. It does require a high-end smartphone and even then, the quality of the VE will probably suffer. Alternatively, a less powerful computer and cheaper HMD can be chosen. Doing so means that people can use their home desktop or laptop, and they only should buy the HMD. It will result in a lower VE quality, but it will still be better than the quality of mobile devices.

As we are working with real humans, the application has to react sufficiently fast to a change in a user’s emotions. This real-time behavior is a limiting factor, as it restricts how much calculations the optimizer can make every iteration. Increasing this amount can be achieved by requiring stronger hardware. This may cause problems when using mobile devices as the dashboard application has to be transformed to mobile as well, which typically results in less computation power available. If the device has not enough...
computational power, the dashboard application could be moved to a third-party server. Doing so will result in an increase of computational power, however, this does require a stable internet connection.

This work has been presented at the 11th International Conference on Quality of Multimedia Experience (Qomex 2019) in Berlin [121]. Visitors could enter their personality data onto the dashboard and start a therapy session fit to their profile. Overall, the reactions were positive. A notable observation was that the vast majority of people tend to choose an outdoors environment. This indicates that in future work, expanding on outdoors environments is advised. This is especially true because, compared to indoors environments, outdoors environments contain less possible adaptations. Introducing methods such as controlled breathing into these environments should therefore be considered.

We conclude this master’s thesis by stating that it is definitely possible to create a system that provides a personalized VR experience for relaxation therapy. However, these kind of systems are still in their infancy stage and require more research. Most importantly, there is a need for a biofeedback model that uses physiological data to define how a user feels, i.e. his emotions. Furthermore, hardware capable of running these applications in real-time should become more widely available in order to fully exploit the strengths of VR. The proposed architecture of such a system is illustrated by Figure 6.1. This architecture is based on this master’s thesis, and is augmented with the components that have been discussed for future work.
References


[91] Early Intervention Center, Cardiac Rehabilitation Center, and Physical Fitness Center. Music therapy, 2014.


References


