Creating Bio-adaptive Visual Cues for a Social Virtual Reality Meditation Environment

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Tiivistelmä — Referat — Abstract

This thesis examines designing and implementing adaptive visual cues for a social virtual reality meditation environment. The system described here adapts into user's bio- and neurofeedback and uses that data in visual cues to convey information of physiological and affective states during meditation exercises supporting two simultaneous users.

The thesis shows the development process of different kinds of visual cues and attempts to pinpoint best practices, design principles and pitfalls regarding the visual cue development in this context. Also examined are the questions regarding criteria for selecting correct visual cues and how to convey information of biophysical synchronization between users.

The visual cues examined here are created especially for a virtual reality environment which differs as a platform from traditional two dimensional content such as user interfaces on a computer display. Points of interests are how to embody the visual cues into the virtual reality environment so that the user experience remains immersive and the visual cues convey information correctly and in an intuitive manner.

Avainsanat — Nyckelord — Keywords

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Contents

1 Introduction

This thesis examines designing and evaluating visual cues that adapt into user biofeedback in a social virtual reality meditation environment. Visual cues should provide user information about current physiological and affective state. The virtual reality environment described here is *social* and supports more than one user simultaneously present in the meditation exercise. Hence the visual cues need to work equally well for both users, for one who is the origin of the feedback data and also for the user perceiving the state of the that user.

Visual cues are sensory stimuli that are processed by the visual system. For humans, as well as for many other species, visual system typically offers a vast source of information about the surrounding world and affects how it is perceived. Some examples of typical and intuitive visual cues associated with everyday life in modern societies could be for example advertising billboards, restroom signs and traffic lights. Visual cues can be symbols, patterns or sequential visual information, like video, and they offer a representation for some expected way of action, or try to provide stimuli for the observer to create a mental association to something particular. Visual cues are often meant to offer intuitive or self-explanatory representation or signal of something, for example traffic lights are visual cues for certain traffic rules and provide guidance without verbal instructions.

Virtual reality, as the name suggests, mimics the dimensions and optics of real world which makes it a potential platform to implement visual cues in a manner that is easy for human to perceive and understand. Because of the simulated reality the traditional design choices with two dimensional systems, such as web pages or heads-up displays in computer games, don't generally work well in virtual reality. Instead of using user interface constisting of traditional layout of objects, embedding visual cues into the virtual reality environment itself might be a better option.

Virtual reality environment might also support multiple users, reminiscent to traditional multiplayer video games for example. Then the visual cues should also offer information regarding the state of the other user in addition to information of one's own state.

This work examines a virtual reality environment where visual cues are based on bio- and neurofeedback assessed from the user with biosensors and in the dyadic condition of two users on the synchrony of two different users' input data. Two main data sources for the visual cues are user's *electroencephalography* (EEG) and respiration rate which are measured by electrodes and a brain-computer interface, and a respiration sensor, respectively. More specifically the EEG values are levels of *motivation approach* that are assessed from frontal asymmetry measured from the brain's frontal lobe and breathing rate measured based on the sensor values measured from the chest area. Visual feedback and cues are then produced based on these measurements.

The purpose of visual cues is to act as an intuitive way for the user to get information about the current affective and physiological state of oneself, and of the other in the dyadic condition. Therefore the visual cues have three functions: to give user information regarding the affective and physiological state 1) of oneself, 2) of the other and 3) combining the information and informing users when their states are in sync.

Visual feedback based on EEG and thus user's empathy-related brain activation is visualized with a changing color in different lights and objects. Breathing rate based on respiration sensor is visualized with motion. When two users are simultaneously present in the virtual reality environment, both have the same initial setup of visual cues but then are altered based on the individual biofeedback adaptation.

The project described in this thesis is part of the *Emotional augmentation in virtual environments for empathic social interaction: Effects and underlying neurophysiological processes* research by University of Helsinki and Aalto University. The purpose of the research is to provide new information on the human capacity of empathical interactions in *immersive social virtual environments* (SVE).

1.1 Research Questions

Research questions of this thesis are as listed in Figure 1.

1. Research question 1: How to design and develop neuro- and biofeedback adaptive visual cues and embody them in an immersive and social virtual reality meditation environment?
2. Research question 2: What are the criteria for selecting the visual cues?
3. Research question 3: How the biophysical measures should be used in visual cues to convey synchronization in a social context?

Figure 1: Research questions of the thesis

First research question asks in what manner should the neuro- and biofeedback be visualized and where the visual cues should be embodied in the environment so that the user has an intuitive sense of current affective and biophysical state and also has a sense of presence. This includes both the software development process and the process of turning somewhat abstract ideas into clearly defined and functional components. As there isn't much explicit results and research done on designing and embodying visual cues in a virtual reality meditation environment, the first research question is also about finding a way to do that.

The visual cues have two use cases - user should gain information of one's own state and also of the other user's state, if someone else is present in the meditation environment. For example, in a single user meditation the user should feel oneself present in the environment and be able to read one's own state from the visual cues. Additionally, as the environment supports two simultaneous user which we refer as the *dyadic condition*, in two user meditation the presence and the state of the other should be clear. Users should be able to read the state of the other user and also compare it to one's own state. The visual cues should enhance the feeling of mutual presence when two users are simultaneously in the environment, which is the reason to call them visual cues with social features.

Things to take into consideration regarding the question are plenty - the general setting, intuitiveness of the system, both expected and unexpected user behaviour and how to deal with that user behavior, for example. Additionally the visual cues should be implemented and embodied into a *social* virtual reality environment, which brings another question - how to design and implement ideas in a manner that they work both for for the user who is the origin of the visual cue data and also for the other user who should be able to perceive and understand those same visual cues.

Research question two examines in a greater depth what are the criteria of selecting the correct visual cues and what makes some particular visual cue appropriate. Visual cues are compared and

Research question three examines the additional feature of the visual cues of conveying information when users' biophysical states are in sync. Both biofeedbacks used in the system have their own definitions of being in-sync. The user should be able to perceive synchronization in either of the biofeedbacks clearly.

The evaluation of the design consisted both from a continuous testing during the development, for example finding justification and support for some idea to proceed into actually implementing and keeping it embodied in the system, and finding out how well the system actually performed based on data gathered from a meditation research experiment user self-review reports.

The underlying thought of the thesis is that virtual reality offers great possibilities to create meaningful and subtle visual cues based on movement and color changes which very effectively affect the user experience. Correctly designed and implemented and combined with biofeedback they offer a tool to convey information to the user an interface between system logic and the user which should help to keep user to gain awareness of one's own affective state, which might otherwise be unclear or perceived poorly. In social context the same visual cues should likewise convey the same information to other users simultaneously present in the environment. Methods to test the findings and answers for the reseach questions include both continuous evaluation during the development process, and the wider experiment results assessed from user self-reports.

1.2 Chapters

This first chapter is the introduction chapter. Next, the chapter two goes forward by looking into background information and addressing the current state of different key areas and going through some related background information. First we go through the main areas and fields of study related to the project examined in this work.

Different areas are 1) virtual reality in general and some of its history and applications today, 2) the definition of visual cues and some examples of their use, different user interface models and also the use of visual cues in graphical user interfaces, 3) affective computing, 4) the meaning of biofeedback and some of its relevant applications, and lastly 5) meditation practice, its benefits and examples of its utilization in a monitored computer-based applications such as the one presented later in this thesis.

Chapter three provides general information and an overview of the developed virtual reality environment where the meditation exercises take place. The chapter three is meant to illustrate and explain how the virtual reality system itself is designed and built and to give some understanding how things work before going to more in-depth explanations of the design of the visual cues.

In chapter three we also briefly examine the architecture of the application, development tools and hardware choices in the project and what type of sensors are used to provide the wanted user measurements used for the visual cues. Lastly the chapter explains some key areas regarding the networking and multiplayer support of the application to provide information about how the social features were implemented.

Chapters four and five examine begin to address the research questions of visual cue creation. These two chapters are very much akin to each other and linked together, yet they examine two sides of the coin - chapter four discusses the visual cues that were selected and found most suitable for the research whereas chapter five discusses the visual cues that weren't seen good enough and the reasons behind discarding them. In the end these chapters provide slighly different insight to the design and development process and were thus separated for clarity's sake.

Chapter four examines the approved visual cues for a research project where the intention was to increase the feelings of empathy in a user by using a combination of virtual reality environment, affective computing and adaptive feedback by the use of visual cues. Different design ideas of affective visual cues are examined and prominent evaluation criteria are presented. In each subchapter look into the details of a different visual cue that was selected in the final product and illustrates the design process of that particual visual cue.

Chapter five examines the design ideas that were considered during the development process but were from some reason decided to be left out or discarded during the development. Examining the reasons behind those decisions sheds new light to the designing process and helps to see the chosen ideas presented in the chapter four from a new perspective and also provides insight into the requirements that were set for the visual cues in the project.

Chapter six addresses first the evaluation of the design and development process and then reflects the created system by examining user self-review results. The self-review reports are analyzed and reflected in comparison with the design ideas, implemented visual cues and the requirements and hypotheses set for their functionalities.

Chapter seven continues from the previous chapter with a more pondering tone and reviews the whole process more from the research questions' point of view. The chapter seven also discusses what should or could have been done otherwise and what should be taken into account in future development. All the three research questions along with the solutions and answers yielded by the previous chapters are presented, examined and analyzed here.

In chapter eight the work is wrapped up and summarized. We go once again through the work in this thesis describing its essential substance. Chapter eight concludes this thesis.

2 Background

Before starting to examine the research questions and the the process of designing the most suitable adaptive visual cues for virtual reality meditation, it's beneficial to have a brief look into the background of all different related fields as the nature of this subject is quite multidisciplinary.

This chapter presents subchapters for each of the distinct fields that can be seen related to the topic of this thesis. This chapter is divided into five parts and each part is meant to provide adequate background information regarding the respective field to understand this thesis.

Virtual reality, a more detailed description of what is meant by a *visual cue* and some examples of their use in different user interfaces, very brief explanation of what is affective computing and especially some theoretical background of empathy as an affective state, what is meant by biofeedback and what is the purpose of its use and lastly the practice of meditation, how it's related to the other things in this chapter and how its already been used in applications that are meaningful for regarding this thesis.

2.1 Virtual Reality

In the recent years, as of first half of 2016 when first generation of consumer version Oculus Rift and HTC Vive were released, virtual and augmented reality have gained popularity and virtual reality games are developed at a more rapid pace [Ste18]. Advances in virtual and augmented reality technology have spawned consumer grade virtual reality products like, in addition to Oculus Rift and HTC Vive, Oculus Gear, Oculus Touch and Microsoft Hololens for augmented reality.

Virtual reality has in some form been around for some time, but it's only after recent years' development, and because the commercial consumer-grade products are now easily available, that the technology has started to achieve wider spread and popularity. The coming of more sophisticated and advanced virtual reality devices and new softwares has also lead to new academic interest and research projects, like many works cited in this thesis.

Although augmented reality isn't part of the subject of this thesis, it's mentioned here for clarity's sake and to clearly separate it from virtual reality. As the name suggest, augmented reality aims to add virtual content on top of the existing reality, for example by showing a virtual Pokémon sleeping on an actual real world street. Virtual reality then again is about showing something that is completely artifically produced, for example a spaceship flying simulator.

Virtual reality simulates the three dimensional space where user usually may look and even move around. Interaction with the virtual reality world is done usually by looking at the target or with appropriate controller accessories, like Oculus Touch for Oculus Rift or HTC Vive controller. Traditional joysticks, keyboards and mice are often also supported.

What separates virtual reality from the traditional three dimensional environments presented on a two dimensional display is the immersion that is achieved via the optics of a virtual reality head mounted display and generating stereoscopic view.

Virtual reality environments offer a simulated experience of the three dimensional reality and therefore offer better premise for creating immersive real-life simulations compared to traditional 2D-systems [RCvD97]. This also makes it more interesting platform to exploit the natural traits of human attention that have been shaped by evolution. For example using motion and illumination to capture and guide the user's focus might work better in virtual reality than on traditional display setups. A great initial inspiration for this thesis' subject was an idea of fireflies in a nighttime forest where human visual system is able to catch the subtle movement and light of the fireflies even from the outer ranges of the field of vision, and how that same trait might be taken advantage of when creating visual cues to be used in a virtual reality environment.

Virtual reality as a platform for different sorts of exercises has also been proven to excel in many fields. In healthcare, virtual reality simulation training has been shown to improve operating room performance [SGR+02]. Offering this kind of training and making it possible to practice specific surgeries benefits especially novices and intermediate level surgeons [TBHK+17]. In military use virtual reality is used for combat training, parachute simulation and, overlapping healthcare, post-traumatic stress disorder treatment where patients can be exposed to the triggers of their condition in a safe environment and then gradually adjust and learn to cope with them [BSBGP15].

Psychological treatments, various simulated training sessions and 3D design are some areas where it virtual reality environments become useful. For example, training exercises in medical or military context might be dangerous or expensive to perform in real life. Creating a cost effective and safe virtual environment might offer a justifiable alternatives to the original real life counterparts of those kinds of training exercises.

2.2 Visual Cues and User Interfaces

Visual cues are visual stimuli that are processed by the visual system. Human visual system is part of the central nervous system and is a major source of information regarding the surrounding world. The psychological process of interpreting that information is called visual perception. Visual cues are information that provide guide or further information and insight after being perceived and processed. A red traffic light signals drivers to stop whereas green symbol of a walking person signals to pedestrians that it is allowed to cross the road. First judgements of a person or product rely on visual cues such as color of a product or the clothes of a person. A sign of a crossed-out camera in a museum signals that taking photos is not allowed.

Visual cues can be intentionally used to convey information regarding current state of some system or, as in the case of this work, the affective and physiological state of a human body. Taking into account that we are dealing with a virtual reality system, designing subtle and discreet visual cues to convey information might be a better option than using more straight-forward written instructions, for instance. When building an immersive virtual reality environment, user interface elements traditionally used in a two dimensional display setups are not a preferable option as floating text boxes are not typically present in everyday realworld life and might break the immersion of the virtual reality.

Creating a *head-up display* (HUD) of floating user interface elements is a are a great way to show information in a non-VR system, like computer games where graphical user interface (GUI) is projected into a 2D-monitor display. Such an approach is called non-diegetic, which means that it doesn't exist in the world itself but it's useful in the player's own context - like a film score where the music is usually an added element and not actually played by an orchestra in the film's context, or a HUD-element in a first-person shooter video game where the player's health and ammo might be shown as integers [Uni17d].

Non-diegetic user interface doesn't usually work well in virtual reality because eyes won't comfortably focus as close as where the HUD-elements would be, and even if they did it would cause constant change in focusing to those elements and then back to elsewhere in the virtual reality world. Underlining the futility of this approach in virtual reality context is that for example Unity game engine doesn't even support *screen space-overlay* in virtual reality which is needed to achieve it [Uni17d].

Another approach is a spatial user interface where, as the name suggests, the user interface elements are rendered in world space within a distance that is comfortable for the user. This is a very common approach to build for example user interface menus in virtual reality. This approach might still decrease the immersion as the spatial user interface elements convey something in a way that is not familiar in the real world.

Similar to spatial user interface is diegetic user interface where environment itself is used to display information. Familiar examples taken from everyday life could be a television screen or a clock face, for instance. It might also be something more imaginary as long as it's part of the environment's context. In other words, all the objects showing information are things that are inherently part of the depicted world. Because of that, diegetic user interfaces might feel more realistic and immersive, and give a better sense of presence instead of having an ever-present HUD-element floating in the air [SPR+17]. As immersiveness was a major criteria for the meditation environment during the planning, a diegetic user interface was chosen as a premise for the project from early on.

Game-like environments making use of diegetic user interface design with EEG and meditation have been used before and one such work for example presented temple grounds where meditation progress was visualized with blooming flowers [CM14]. Flowers are part of the diegetic user interface and still as visual cues designed with the intention of informing users of their performance and progress in the environment that they wouldn't otherwise get in a traditional meditation setting.

One other example is a virtual meditative walk -therapy system for chronic pain management where diegetic user interface is also applied by using changes in weather as visual cues for patient's biofeedback [GTC+15].

2.3 Biofeedback

Biofeedback means any kind technique that gives the user greater awareness and information of some physiologic process which is under control of the autonomic nervous system, but which are not perceived clearly or accurately [Gar76]. Biofeedback is meant to help gain awareness of those physiological functions.

Biofeedback can be used as a self-regulation techique to voluntarily control such processes which might have seemed involuntary because of their obscurity. This is done by converting physiological signals into for example visual and auditory cues [FKK+10]. Primarily the instruments used in gaining biofeedback are electrical sensors.

Biofeedback processes that are examined in this work are electroencephalograph (EEG) and respiration. EEG belongs to the field of neurofeedback which can be seen as a subfield of biofeedback, and it's a method of monitoring electrophysiologically the brain's electric activity. Neurofeedback has been used in the treatment of many disorders with succesful results [FKK+10]. EEG-feedback is a good example of making some autonomous process, that isn't perceived consciously or clearly, more fathomable.

2.4 Affective Computing and Empathy

Affective computing was introduced by Rosalind Picard in 1995 [Pic97]. Research in affective computing is motivated by finding ways for a machine to detect and adapt into an emotional state of the user and be able to display emotions.

One of the problems in affective computing is how to define and detect emotion. Detecting emotions begins with gathering data from the user by harnessing user's biofeedback, in other words instrumentating physical or physiological state with sensors. These sensors could include a video camera to record physical states like facial expressions and gestures, or a sensor that directly measures physiological data like heart rate or skin temperature.

Prominent side of the case project in this thesis is the system's need to detect empathy as an affective state, more precisely the affective state is the amount of engagement, and then creating the visual representation of the measured values. Empathy itself is assessed from the EEG by measuring *frontal asymmetry*. Frontal asymmetry is the relative difference of measured activity between right frontal and left frontal hemispheres of the brain. Increased left frontal activity corresponds to higher engagement and approach motivation [ACN04].

One technical focuspoint in the project is on applying the affective feedback information to the graphical user interface of the virtual environment. This is done with the visual cues based on the EEG-data embodied into the environment so that the user is aware of own and, in the dyadic condition, of other user's biophysical state and how it affects the progress of the meditation exercise.

Continuing from the affective computing point of view, the purpose of the meditation experiment is to arouse empathy. One way of measuring the amount of empathy is assessing the level of *perceived affective interdependence* in the users [SJR+18]. Affective interdependence is a sub-component of social presence which means the effect that the someone else's affective state in interaction has on one's own state, and on the other hand what effect one's own state has on the other [HB04]. Social presence is suggested to exist not only in face-to-face interactions but also in mediated interaction, including its different levels [HB04]. In this case the interaction is between the users in the meditation exercise.

Affective contagion is the process of emotions and affective states to converge and become social [HCR93]. Affective contagion might happen for instance through mimicrying facial, vocal and postural expressions of emotions [BG07]. In addition to those, one way of affective or emotional contagion to occur is by empathy [Elf14]. Here empathy means that perceiving or imagining the emotional state of someone else leads to alike emotional state in oneself or merging of affective states. The frontal asymmetry has been previously used in studies on empathy and its used as a premise in this project [SJR+18].

2.5 Meditation and its Applications

Meditation is the basis for the work presented in this thesis. It's present both in the design choices such as serene looking sitting statues reminiscent of buddhist traditions and as an exercise instruction for the research subjects.

Meditation can be thought of as a series of emotional and attentional regulatory exercises. Meditation and mindfulness exercises are shown to have many beneficial effects on human physiology and many of these exercises are derived from the traditional Buddhist practices [LSDD08].

Traditional meditation might be used while seeking beneficial effects on physiology, mental balance and cognition. Meditation and mindfulness exercises are shown to lower blood pressure [CSFP07], reduce heart and vascular disorders and improves memory, information processing, emotion control and decision making. Different meditation techniques differ also on the neural level [TS10].

Emphasis on this work is on compassion and loving-kindness meditation, derived from Buddhism, which endeavor to develop uncondtitional, positive emotional states of compassion and sympathy towards others by directing positive feelings towards oneself, specifically toward others or in all directions to all other beings [HGH11]. This kind of meditation might enhance feeling of social connection, positivity, empathy and decrease stress responses [HGH11].

As pointed out earlier, some virtual reality based meditation experiences and games have already surfaced [CM14] [GTC+15]. The systems share some aspects with the topic of this project as they are meditative virtual reality environments with a diegetic user interface where the visual cues are embodied, and also the visual cues are based on user biofeedback.

It has also been shown that combining virtual reality with meditation exercises and neurofeedback adaptation can yield better results than doing the exercise without virtual reality. The research was done on a neuroadaptive system where user's concentration and relaxation levels are estimated from the EEG and then mapped into the virtual reality environment. Results indicate that using neurofeedback in addition to having the meditation exercise in a virtual reality environment increased the feeling of presence in the users. The research also found out that utiliziting virtual reality environment in combination with neurofeedback produced the highest level of presence and proved more effective than traditional display setup [KSJ+16].

It thus seems that combining biofeedback and meditation exercises in virtual reality is gaining both interest both academically and recreationally.

3 System Overview

To make visual cues work as they are meant to, first we need to consider the environment where they are to be embodied. Visual cues themselves won't be enough if the virtual reality environment lacks immersiveness and isn't seamlessly supporting the user experience. Therefore many things related to immersion and mood of the setting are needed to be done correctly. To achieve this, both the client side visible to the user and also the underlying technical architecture have to be designed correctly. The goal is that the user experience is immersive and gives the user a sense of presence.

This chapter explains the system design and considers the reasons behind the design choices. We go through the research system we created, tentatively named as MindTier and ultimately settling to DYNECOM VR (Dyadic Neuro COMpassion). The high level view of the used architecture choices of hardware is presented and the equipment and development tools are explained in adequate enough way to get a general understanding of the system design. In addition to that, some networking and multiplayer logic used in the project is explained in some detail as it is vital to understand the behavior of the system that is needed when the system is run in the dyadic condition. This was also one of the hardest part to implement as it wasn't preferrable to make compromises in the design vision because of technical issues.

3.1 Meditation Environment and User Experience Design

The meditation system is divided into four different *scenes*, which in Unity can be thought as an implementation of different abstract game levels or separate stages of the game environment. First scene is the launch screen where session parameters are defined. Second scene is the baseline room where each session starts with a minimalistic room for recording the participant's baseline neurophysiological activation.

The following scene three is the actual meditation environment consisting of six stone statues sitting in a ring on a small shrine-like platform surrounded by a dim nighttime forest. The platform is circled by a short wall and the forest is lit by a cloudy evening sky. In scene four user is shown a floating canvas with self review questions. The answers are selected with Oculus Touch controllers.

The space for the visual cues is a serene virtual reality environment where one or two users perform meditation exercises. The setting is created with a metaphor of "sitting together by the campfire" in mind. Meditation area includes six stone statues sitting in a ring formation on a small round stone platform surrounded by a dim nighttime forest. The platform is circled by a short wall and the forest is lit by a cloudy evening sky.

The participating meditators are sitting in the real life laboratory during the meditation experiment. In the virtual reality they see the environment from a first person view of one of the two statues that are distinctly connected by a bridge object, which is slightly elevated from the rest of the platform. Visual cues are presented in the meditator's field of view in different objects which get their input from the affective feedback. There are four lights pointed to the surface of the meditation circle, an aura above and around the user statue, plane objects layering the bridge and an another set of plane objects in the recesses on both the sides of the bridge.

To guide the participants' attention to focus in the circle, a short wall was added to encircle the meditation platform. The wall limits the field of view only to the essential elements and thus functions as a discouragement for the possible tendency in the users to go exploring the environment further. It also adds to the comfort of the "campfire" metaphor by making the space feel enclosed, safe and intimate when the view to nighttime forest is at least somewhat restricted from the meditation area. Then again the short wall leaves the above open air space visible and that counters possible claustrophobic anxieties by conveying a feeling that there is also an outside world beyond the meditation circle, and also gives the user a sense of the surrounding forest as it can be seen over the wall.

Some static effects were also added into the environment to make it more immersive and to help the users to adapt into it more easily. For example, environmental effects simulating natural phenomenona like a gentle wind waving the branches of the trees and fireflies flying around in the vicinity beneath the trees make the surroundings feel more natural and vibrant.

Additionally an audio track containing pink noise resembling wind rustling through the trees and foliage was also added to the scene. The purpose of the pink noise is, in addition to creating an audio soundscape, to mask the background noises coming through from the laboratory during the experiment which might break the immersion. Also during the testing sessions of the system, the environment without these additional effects felt a little off, unnerving and unnatural. These subtle effects where enough to make the environment feel real while still remaining in the background so that the user doesn't focus on them instead of the meditation exercise.

Depending on the meditation session conditions and parameters, the bridge, the scene lights, the aura-like ring surrounding active statues and the statues themselves show various visual cues of multiple visual effects meant to intuitively guide the user. The visual cues are based on the neuro- and biofeedback and their purpose is to inform the user of their current state. A Unity editor image showing the environment from an outside perspective in shown in Figure 2.

To conclude this setting includes many favorable aspects that work well at increasing the immersiveness and arousing empathy. Nature acts a relaxing background environment and the built-in elements balance the dark wilderness with comfort and familiarity. Also in the dyadic condition the

Figure 2: Overview of the meditation grounds

sense of doing something together while perceiving the visual cues gives a feeling of a shared social activity.

Dusk was chosen as a time of day in the environment because the dim lighting contrasts the illuminated and colored objects. Creating that kind of visual hierarchy contrasting light and dark puts focus on the main objects of priority that are the visual cues and makes it easier for the user to notice, read and understand them.

3.2 Virtual Reality Sickness

One substantial consideration in the design was also how to deal with *virtual reality sickness*. Virtual reality is known to cause discomfort commonly known as virtual reality sickness, or VR sickness in short. Symptoms of VR sickness include nausea, disorientation and headache after being exposed to virtual reality content. One potential cause for the symptoms is the disparity between perceived and real physical motion which causes conflict between sensory inputs [LaV00].

We took this into account by designing a static scene where users' need and even possibilities to move around are kept in minimum. First of all the intended posture while using the system is sitting position. Secondly, as described earlier, the meditation area is circled by a wall which is meant to act as disencouragement to desires to go wandering further. User is still free to look around as they like, but after getting the first glimpse of the surroundings and their few relatively interesting details such as the swarms of fireflies and bustling tree branches, the area of interest lies always in front of the user.

User gets a clear idea of the direction to look at and should easily notice the visual cues representing user's own state as well as the visual of the other user, including the cues of embodiment in the opposite statue belonging to that other user. The user isn't encouraged and doesn't have to look around in a wide angle, which should also remove the excessive changes in the field of view and perspective, which should further reduce the factors leading to virtual reality sickness.

3.3 Development Tools and Architecture

The virtual reality environment was built using Unity3D game engine developed by Unity Technologies which is a very popular game engine with a vast amounts of games produced with it during the last years [Uni17a]. Unity engine is a cross-platform game engine with built-in support for virtual reality [Uni17e].

Microsoft's multi-paradigm object oriented programming language C# was used as the programming language within Unity to implement the system's game logic and scripting. Unity offers a lot of tools out of the box, which eases development. For example basic light objects and particle systems are included in Unity's toolset. A screenshot displaying the basic layout of the Unity editor is shown in Figure 3.

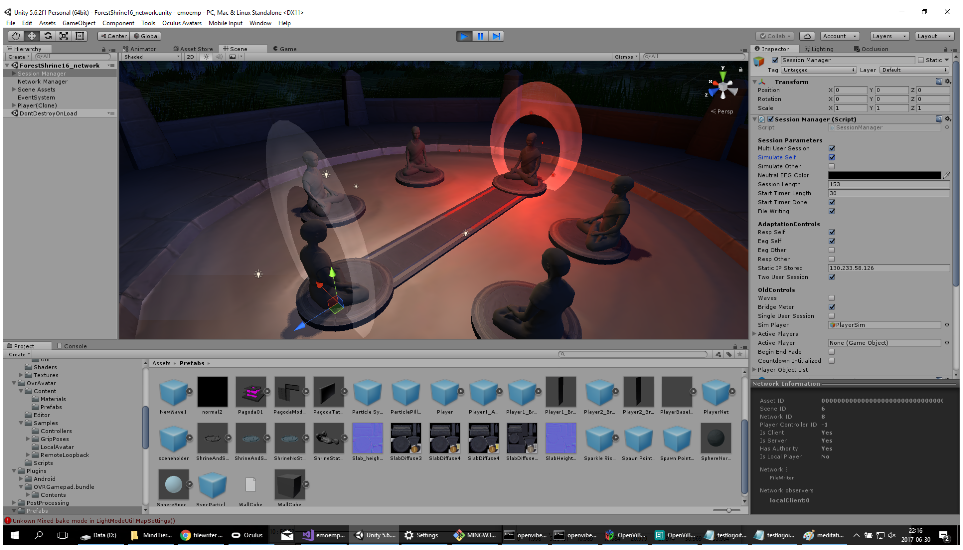


Figure 3: Unity development environment

EEG and frontal asymmetry are measured with 40-channel *QuickAmp* amplifiers produced by Brain Products GmbH. The data consists of two measured alpha channels per user and is then processed with OpenWibe-software before it's sent to Unity via TCP/IP. In Unity a script then calculates the final frontal asymmetry value $\log(alphaRight) - \log(alphaLeft)$, which is a float between 0 and 1, where zero is the initial value.

The measured range of values differs from user to user. That means, when the maximum and the minimum engagement value from frontal asymmetry might be very different from user to user, the values can't be directly used in the visualizations. Instead the values are normalized before passing them on to be used as visual cue inputs in the virtual reality environment.

Full experiment setup consisted of four separate computers. One pair where each computer was running an instance of OpenWibe connected with an electrode-hat and recording psychophysiological data from a user with a BrainVision Recorder software. The recorded psychophysiological data was then streamed onwards to OpenViBE for processing and calculation routines. Connected to both computers were also the respiration sensors that detect chest movements. We used the respiration sensor data to detect exhales and inhales.

In another pair of computers, each was running an individual instance of the meditation system connected to virtual reality headset. The choice for virtual reality devices, which include the head-mounted display and hand sensors, were Oculus Rift and Oculus Touch developed and manufactured by Oculus VR, owned by Facebook Inc. The Oculus Touch handsensors weren't used in the meditation phase of the experiment but were needed in the following user self-review report to select answers provided by the feedback form. The feedback phase was also implemented in the same virtual reality surroundings as the meditation exercise itself.

Figure 4: Self-Report Form with Oculus Touch

3.4 Networking and Multiplayer

While the solo condition in the meditation exercise can be considered straightforwardly as a single player instance, the dyadic condition of two users was a subject of a bit more complex architecture regarding the implementation.

In addition to the extra logic of creating the multiplayer system and implementing the same user experience for simultaneous users, the system must also perform well enough so that both users are in sync and can observe each other's visual cues in realtime in order to create immersive enough social virtual reality experience. As the visual cues are the only way of communicating in the environment, there's all the more reason to stress the importance of the social side of the visual cue design and the architecture behind it so that the experience is as seamless as possible.

The multiplayer logic is done by using Unity's *High Level API*, abbreviated as HLAPI [Uni18c]. Unity's network behavior and its architecture is rather complex and it could easily take the extent of an individual thesis itself to be explained in detail. Because of this only the basic things are covered here to get an understanding of how different values and parameters were communicated between objects in Unity and what factors were essential to take into consideration while designing the framework of the visual cues.

In the dyadic condition of two users the first player is a *host* and acts both as a server and a client creating the multiplayer instance of the environment session, which acts as a server, and joining it as a *local client*. The second player then joins to the session as a remote client. The server/client combination role of the first user is mostly regarded as an ordinary client in the HLAPI code, although it uses the same Unity scene and objects as the server and handles the communication with the server internally using message queues instead of sending messages over the network [Uni17b].

The multiplayer network architecture is done so that both users have a symmetrical set of objects that they own and have authority over, meaning that the objects by default are modifiable by their owner. Once something is modified, for example the lighting color based on EEG, the change is done locally and then the same action is performed on the other user's end by calling Unity's *Remote Procedure Calls*, or RPCs. Unity's network system includes two different RPCs that are *Command*s and *ClientRpc*s [Uni17c].

Commands are sent from a local player object and invoked on server objects, and ClientRpc-calls are sent from objects on the server to objects on clients. It's also important to note that while Command is called and sent by a client, the call itself is executed on the server, and vice versa, ClientRpc is called by the server and then executed on all of the clients that are connected to the server.

As previously mentioned, the first player, although also a client, acts also as a server in this context whereas the second player is a client connecting to the server. This had to be taken into consideration to keep both players always updated and in sync with the current state of the system. So every change in the state had to be executed both on the client and the server. To achieve this the solution was to forward all Commands through ClientRpcs. This way all changes made by a client were reflected to both clients simultaneously.

A typical example of the described multiplayer programming logic is shown in the simplified code snippet in Figure 5. The example is from the actual implementation of changing the colors lighting the user statue and its vicinity. The code illustrates how color changes are done in an update loop function for every frame rendered and how changes are communicated so that the changes are executed on both users.

First can be seen the client-server -separation and which function, Command or ClientRpc, is to be called and invoked. If the function call is made by the server, the ClientRpc containing the color changing logic is called straight away. Otherwise if the caller is from a client, Command is called which is invoked in the server, which in turn calls the ClientRpc for color changes which are invoked in all clients. An example of the light and color change logic is illustrated in Figure 5.

```
public class PlayerFAScript : NetworkBehaviour
{
  ...
  void Update() {
    Color PlayerColor // These two values are precalculated elsewhere
    float PlayerFA    // and FA stands for Frontal Asymmetry
    ...
    if (NetworkServer.active) {
      RpcPlayerLight (PlayerColor, PlayerFA_Display);
    } else if (NetworkClient.active) {
      CmdPlayerLight (PlayerColor, PlayerFA_Display);
    }
  }
  [Command]
  void CmdPlayerLight(Color PlayerColor, float PlayerFA_Display) {
    RpcPlayerLight(PlayerColor, PlayerFA_Display);
  }
  [ClientRpc]
  void RpcPlayerLight(Color PlayerColor, float PlayerFA_Display) {
    try {
      for (int i = 0; i < PlayerLights.Length; i++) {
        Lights[i].GetComponent<Light>().color = PlayerColor;
        Lights[i].GetComponent<Light>().intensity = 0.05f + PlayerFA_Display * 1.1f;
      }
    } catch (Exception e) {
       ...
    }
  }
}
```

Figure 5: Unity Remote Actions

In this case each client or player has a set of lights which are then looped through and changed according to the precalculated color values. Each user or client can change only the colors over which they have authority, in other words the set of lights that belong to their instance. The network logic makes sure that the color changes for those particular lights are invoked also in the other client's instance.

3D-objects can't be directly transferred between clients as raw data by the means of Unity's network because that would be ineffective and heavy. Instead, the parameter values used by the objects were being transferred. The basic logic of changing and updating visual cue values was similar to example in Figure 5 throughout the project in different scripts that altered the objects in the environment.

4 Adaptive Visual Cues for Bio- and Neurofeedback

This chapter examines all the visual cues that were selected to be used in the environment. We go through the visual cues one by one, demonstrating the design principles, how they work and how they are embodied in the virtual reality enviroment.

There are two sources of information measured from the user for the visual cues that create a feedback loop. Feedback loop here means that when an attribute is perceived though a visual cue, for example and exhale, it gives more information to consciously affect the breathing rate and then also affecting the following feedback values. The two sources are 1) respiration/biofeedback and 2) EEG/neurofeedback. These two sources are separated into two distinct domains of biofeedback and neurofeedback with a different sets of rules that define the design so that they are easier to distinguish between each other.

The approach in the visual cue design was the use of diegetic visuals based on bio- and neurofeedback. Information and cognitive overload are well known phenomenons in user interface design and are acknowledged as things to be considered for example in the traditional user interface design [NSK11]. To keep things as simple and intuitive as possible, the amount of different visual cue categories were kept to a minimum. Otherwise the visual cues may feel ambiguous to the user and it would be hard for to reach an intuitive understanding of the visual cues because of the information overload, which in turn would hinder the sense of presence.

Many different visual cue alternatives where designed and even implemented and tested out prior to settling to the ones found the most suitable. In this chapter we go through the design and explain those visual cue choices that were kept in the final version.

4.1 Respiration and EEG

Biofeedback from respiration uses motion as the design principle for the visual cues whereas neurofeedback from the EEG utilizes colors and different kinds of light effects. Additionally a social dimension was brought into the setting and the visual cues posses capabilities of visualizing special cases of shared activities. When the environment is shared by two users in the dyadic condition of two players, some of the visual cues react not only to the input got from the respective user's neuro- and biofeedback, but also to the other user's visual cues and their values. For example breathing in sync and closely equal EEG-measurements are visualized with certain kind of light and color effects that extend the behaviour of the existing visual cues.

Visual cues for biofeedback, and more specifically respiration, were decided to make use of motion. Breathing intervals are paced with two distinct events, an inhale and an exhale. In the environment, objects assigned with movement properties are *the aura ring* seen around the statue and *the breathing bar* on the bridge. The respiration visual cue was designed to be simple and unambigously visualize the breathing rate.

In contrast for the biofeedback motion visualization, visual cues for EEG and neurofeedback exploit color and illumination. In the environment color is used in multiple occasions and it changes based on neurofeedback. EEG-visual cue might seem somewhat ambiguous, but using the correlating visual cue in multiple places in the environment should make it feel more reliable [Jac02].

Different colors, spectrum from somewhat cold shades from green to yellow and warmer shades from purple to red, are used to represent empathy which is the assessed level of *approach motivation* measured from EEG frontal asymmetry. In addition to change in color, the intensity of light is taken into account as well. When users reach high level of frontal asymmetry engagement and are closely in sync, the colors start to glow and pulse. The choice of having night as a time of day in the environment offers a great canvas to toy and exploit with subtle changes both in color hue, brightness and saturation.

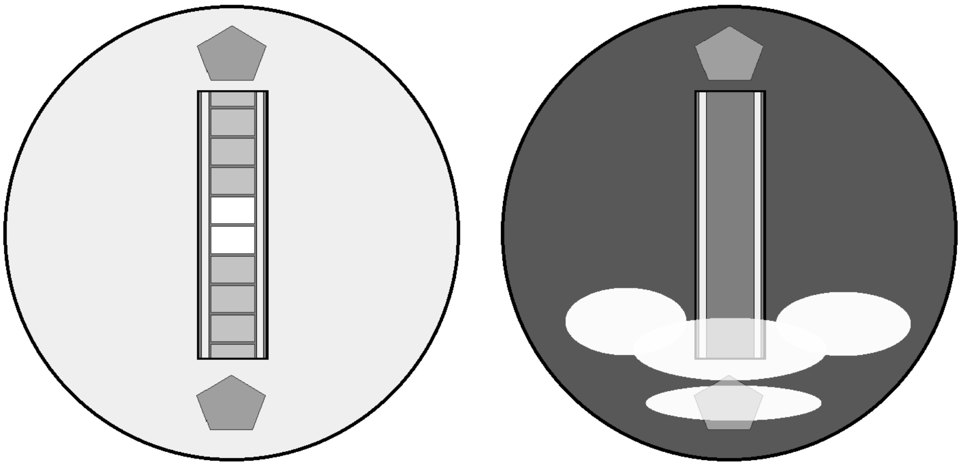
From a practical point of view it became a requirement for the visual cues to be observable from one point of view as users are not meant to look around much during the meditation. This had to be taken also into account while considering proper locations to embody the visual cues. Luckily the symmetrical design helped to achieve this. An abstraction of the visual cue objects and their locations are displayed in the diagram seen in Figure 6.

4.2 Frontal Asymmetry Color

In the environment the different colors are used to represent the amount of measured approach motivation, which is linked to empathy, measured with the EEG. In other words frontal asymmetry values, or the affective states, are color encoded which acts as a visual cue of the progress and current state in meditation. The colors are altered in a continuous manner to keep the changes subtle. The colors are calculated from the float-values harnessed from the EEG-neurofeedback.

While developing and going through ideas we chose the color range from green through yellow to purple and finally to bright and intensive red which would represent the EEG-values from lowest to highest, respectively. The idea behind this choice was that the mellowness of green would indicate a low engagement in the meditation exercise and thus lower measured frontal asymmetry which would then grow gradually towards more intense colors representing higher engagement in meditation.

Based on user feedback after the experiments it was clear that this wasn't the best option as the color range was misunderstood in an opposite manner



(a) Layout for the visual cues for respiration and breathing in-sync embodied in the bridge.

(b) Layout of the EEG visual cue light sources where light areas are marked in white.

Figure 6: Locations of the EEG-color and respiration's Breathing Bar visual cues in the meditation circle.

by some users. Green was thought as a desirable color when it was meant to represent the lowest point, in other words the baseline, of a user's frontal asymmetry values. Furthermore red was seen as a warning-type of color that should be avoidedm, whereas it was meant to signal passion and empathy. This might be due to the fact that in real-life visual cues, such as traffic lights and safety guides, green is the color of good and things being alright and red means danger and is noticed clearly because of its intensiveness.

Different colors and changes in their intensity as visual cues were decided to be implemented in multiple parts of the environment rather than in just one specific place or game object in the meditation circle. This was in part to add correlated cues for the same source of information, which should increase the reliability of the whole visual cue for EEG [Jac02].

One design idea was also that different lights and colors should provide a certain ethereal and even dreamlike aesthetics which should support the meditation experience and immersion when embedded into the nighttime meditation setting. The *bloom* effect with *HDR-rendering* was applied to the intensive light sources to make them seem more surreal and even psychedelic, but also to make them feel more realistic with such property.

Bloom is an effect where light seems to leak outside the actual light source. HDR-rendering is short from High Dynamic Range rendering, which basically helps to capture colors in particularly bright or dark settings [Uni18a]. Essentially in standard rendering pixel intensity is presented by a float in the range 0..1 whereas HDR-rendering allows values outside that range. HDR-rendering then allows effects like bloom to use that information in post-processing to create more vivid visual effects [Uni18b]. An example of bloom glow with HDR-rendering can be seen in Figure 8.

The color is present in two separate functionalities on the bridge, in four light sources and in statue auras around the meditating statues. Distributing, or even duplicating, the feature in such a way has many favorable outcomes. Firstly, user is kept informed of the state of one's progress more steadily and persistently. When the color cue can be observated in multiple different locations, the user doesn't have to focus attention long distances back and forth between one specific visual cue location and elsewhere while looking around in the virtual reality world.

Secondly, using multiple light sources saturates the meditation circle vicinity with a soft diffuse glow. This works towards the previously mentioned goal of gathering around a proverbial campfire as it creates a separation between dark nighttime forest and a haven where meditation exercise takes place. The layout of the light sources is shown in Figure 6b.

The soft lighting also gives a certain kind of ethereal feeling to the visual appearance of the meditation grounds, especially when the measured EEG-feedback values begin to rise and correspondingly the EEG-cue color changes and gets more intense. The reflecting soft glow on the area surfaces also adds to the visual cue being present in multiple locations and making it easy to read. Thirdly, duplicating and repeating the action underlines its importance.

When the visual cue of the EEG-feedback is ever-present the user should get an intuitive feeling that it holds a significant meaning and represents the state of the meditation exercise. Also the color of EEG-values cumulates with multiple light sources emitting it and when the measured EEG-values are high, it's supposed the give a powerful feeling that the user's engagement in the meditation actually has an effect in the virtual reality.

Figure 7: Example of the color range of the visual cue for the EEG-feedback

4.3 Bridge Recesses and Synchronization Cue

During the exercise user has a focus towards the other meditator's statue in the other end of the connecting bridge. The bridge is therefore usually in user's line of view which makes it a good area to embed visual cues. Although EEG-color cues are already present in a few places, as described in the previous subsection, the recesses on the sides of the bridge are meant to work as more obvious and in-your-face presentation of those color cues with some features unique to them only.

Colors are shown in two recesses on the bridge, a little similar to an aqueduct, and to achieve this cavities were added to the sides of the bridge 3d-model. Both users are allocated a half on their side of the bridge length.

The functionality of the color recesses can be separated into three phases. First, most important and obvious is adapting into the EEG-color and showing the same color hue as all the other color cues elsewhere in the environment. Second phase is activated in the dyadic condition when two users' EEG-values are in sync. The colors on both side of the recesses are given a boost in intensity which work in conjunction with the bloom effect and HDR-rendering of Unity. This makes the colors glow more intensively and gives a certain kind of magical feeling to the environment. The glowing effect is seen in Figure 8.

Third phase is a special case of the second which is required for the third phase to become active. When users' EEG-values are both in-sync and in the top end of the scale, meaning that the empathy meditation is going well and engagement value is high giving the visual cue a reddish color, the glowing recesses also start to flicker. This is done by increasing and decreasing color brightness and saturation which gives a pulsating feel to the color recesses and indicates a special progress in the exercise.

4.4 Breathing Bar

Breathing bars replaced the previous breathing wave as a visual cue for respiration. The breathing bars consists of five consecutive layers that are enabled and illuminated with a fade in and a fade out effects based on exhaling intervals. The layers stay illuminated for a short while after the fade-in phase is completed, and then fade-out. New exhales simply launch the fade-in phase again. If a new exhale occurs before the fade-out phase after the previous exhale is finished, the new fade-in overrides it and illuminates again the already faded-out layers.

The idea behind the breathing bar visualization was to integrate the visual cue closely to the sensor values and show them reminiscent to a beating and pulsating frequency bar in graphic equalizers. The visual cue extends responsively based on exhales and then quickly retracts back to invisible. An abstraction of this is shown in Figure 6a.

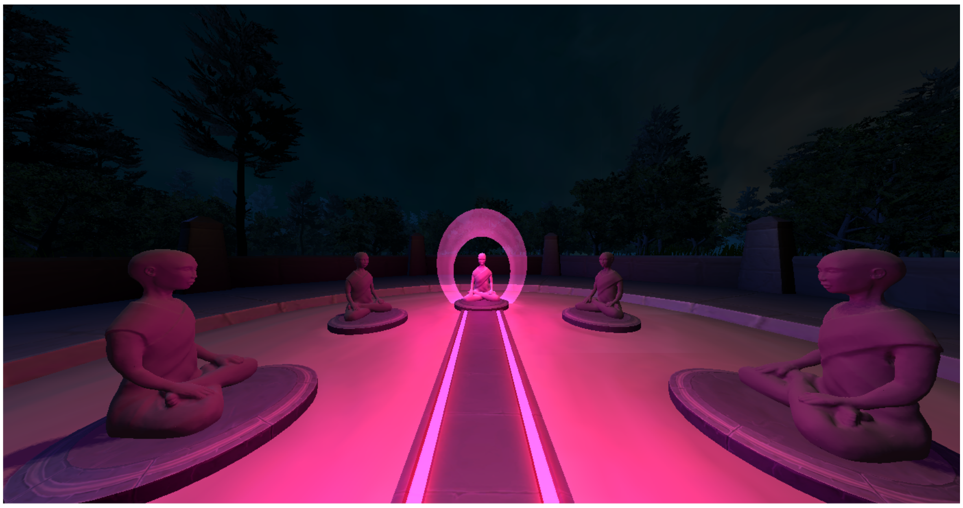


Figure 8: Glowing sides in same color when in sync

Visual cue reliability from user's point of view is a concern here too as visual cues that are ambiguous are also estimated unreliable [Jac02]. To counter this, the motion cue was designed to be simple but powerful which already should make it a little more reliable. Additionally, like with the visual cues for EEG, other visual cues that are correlated with respiration were also added.

The bar visualization is launched when an exhale is detected. Then each of the bars is illuminated one by one by fading in from invisible object into a bright colored one. Figure 9 shows the breathing bar visual cue in solo condition. The image shows the inhale phase of breathing where the furthermost layer has already disappeared and the next one is fading out. Noteworthy is also the color of the layers which takes it hue from the EEG color cue which can be seen in the ambient lighting and in the bridge recesses.

4.5 Breathing In-sync Blink

The design goal for the Breathing bar was to get users try to sync their breathing rates. To encourage and guide the users toward this, a gamification element was added to the visual cue in a form of *sync blink*. The condition for the sync effect is that when either of the breathing bars complete the fade-in phase, the other set of breathing bars has not yet faded out any layer completely. An abstraction of this is shown in Figure 6a.

After fade-in is complete, the visualization has a 1.5 seconds waiting period before the fade-out phase begins. In practice this means that users' breathing is considered to be in sync if the moments of exhale differ rougly 1.8 seconds. As the time needed for the fade-out is somewhat dependent on the rendering speed of the hardware that's running the virtual reality

Figure 9: Breathing bars

system, the duration of the fade-out phase might slightly vary.

Human exhales approximately a few dozen times in a minute, which meant designwise that the visual cue has to be quick and clearly noticeable. When users breathe in sync, the layers of the breathing bar are launched and illuminated simultaneously or nearly at the same time, which seems like the bars would collide the middle of the bridge. The collision is visualized with the two layers nearest the center of the bridge on both sides give a quick flashing blink effect. This is achieved by increasing the alpha values of the layers that control the opacity to the maximum before starting the usual fade off visual cue. The blinking effect in action is shown in Figure 10

4.6 Breathing Aura with EEG-color

Breathing aura is a visual cue whose main functionality is to represent user's breathing but it also acts as a visual cue for EEG. Aura is shown as a curved, colored and pulsating plane object around user's statue. It is mainly used to give user's affective state information for the other user on the opposite side since it's located slighty behind to the point where user's point of view while looking forward towards the center of the meditation circle in the environment. Naturally user can look around and be able to see it, but this isn't a use it was designed for.

The aura ring expands and contracts creating a pulsating effect based on the phases of breathing - expanding on inhales and contracting on exhales. Whereas the Breathing Bar detects only exhale, the inhale detection of the Breathing Aura gives the visual cue an additional dimension of information as the pulse and rhythm of the breathing rate is a bit more distinguishable.

Additionally the breathing aura also adapts to the measured frontal

Figure 10: Breathing in-sync effect. When users exhale simultaneously enough, the breathing bars collide in the middle producing a blinking effect.

asymmetry feedback. While the aura movement guides the sync of breathing, breathing aura is also colored based on the same feedback as all other color cues in the environment. The breathing aura thus combines visual cues for both respiration and EEG, which is a bit different from the other visual cues as it was purposefully designed to embody both visual cues in the same object. Both visual cues still remain in their own visulization domains of color and motion.

One's own aura itself isn't usually visible to the user as it is positioned slightly behind the statue embodying the user. The aura therefore acts mostly as a source of information for the other user which separates it purposewise from the other visual cues. As the opposite statues and auras are in the center of the user's field of vision, the colored and pulsating aura offers a lot of information on a quick glimpse.

4.7 Statue Breathing Animation

Statue breathing is an animation embodied in the 3D-model statue and meant to act solely as a visual cue for other user's breathing and also make the statue seem more living giving the intuition that the user is actually embodied in the statue.

The visual cue was created by using the same data as other respiration visual cues. Unity's animation controller detects the start and end of exhale which act as the starting points of two different animations that are exhaling and inhaling. Statue breathing animation is enabled only if the respiration sensors are being used.

We found three reasons for the statue's breathing animation. First thing is that in contrast to other effects in the environment the breathing clearly gives the otherwise static statue a sense of life and thus should increase the sense of the opposite statue embodying a user. Although the effect is subtle from the user's point of view, it still creates a sense of someone else being present. Secondly when both frontal asymmetry and respiration measuring are enabled, the statue animation is the only effect that's visualizing only breathing. Thirdly it seemed to function properly together with the Aura animation and the Breathing Bar visualization to represent breathing.

5 Discarded Visual Cue Designs

Whereas the previous chapter described the visual cues that fulfilled the requirements, in this chapter we now examine the rest of the ideas that didn't make it to the final version of the system for some reason. We go through the visual cue designs and ideas in detail that were considered at some point for promising ideas but were eventually left out as not qualified. The reasons behind the decisions that lead to discarding the visual cues from the project were various and differed between cases.

By examining the discarded designs, and finding the reasons why they ended up being failures in this context, should bring some information on it's own right regarding what makes a working visual cue. Seeing the contrast between failures and succesful designs illuminates the pitfalls there might be to designing a visual cue for this kind of rather particular system, but it also helps to see more clearly the decisions and design choices done with the visual cues described in the previous chapter.

In few occasions the requirements for the system design changed a little during the development process, which is one reason for multiple and differing ideas. Other reasons included the nature of the development process where different things were brainstormed, implemented and tested. Naturally, some ideas were better than others and it wasn't possible to include all the ideas in the project, but the task also included picking the best ones among multiple ideas.

5.1 Breathing Wave

First requirement for the respiration visualization was to give user visual feedback of the moment of user's exhale. Another requirement was to provide the user with a certain sense of the rhythm of breathing. Therefore in addition to visualizing the moment of exhale, the effect should also linger on for a short while and thus have an appropriate decay time. Initial design idea for implementation this was called the *breath wave*.

The design of the breath wave is a curved and a semi-transparent 3D-object. when an exhale is detected, the breathing wave is spawned and sent moving forward from the height of the user statue's torso area towards the other user at a constant speed. Wave objects are loaded with Unity-engine provided *colliders* which are used to trigger a collision event when two waves moving in opposing directions run into each other.

On collision a few scenarios were considered. Breathe wave's lifetime was set so that the wave travels approximately three quarters of the bridge length so that it visibly passes a little over halfway of the bridge. If the waves collided, the visual cue to convey information of the collision would have been that the waves were given coloring based on the current EEG-feedback values and corresponding EEG-color of the users. If no collision was detected the wave object would have gradually faded invisible and then removed from the scene.

In the first implementation of the design had issues with the wave's course of movement being too high above the ground and after it was launched towards the other user the 3d-object was on an eye-level. This lead to a situation where it became difficult to clearly distinguish own wave from the wave of the opposite user as one of the waves would be hidden behind the other if more than one wave was present. This was fixed simply by positioning the breathing wave object to never be at the height of the expected viewing angle but rather somewhere below.

In the second iteration the simple curved plane was replaced by a more complex particle system cloud which was vertically shorter and also positioned lower than the first wave implementation. This solved the problem of distinguishing two different waves as they no longer got to positions where they could cover and obscure each other from the user's point of view. The more animated and cloudy wave was also more pleasing aesthetically and it certainly seemed to fit better into the meditation setting than the first iteration. But still it somehow felt out of placed. The breathing wave in its cloudy form during the second iteration is presented in Figure 11.

Figure 11: Breathing Wave

The breathing wave was probably one of the most discussed visual cue ideas during the project but in the end the wave wasn't seen as optimal and intuitive representation of breathing. Additionally the visual cue had a requirement to be able to convey information when the users breath in sync. One idea was to calculate the overlapping parts of the colliding waves when breathing rates are in sync and color them in different colors based on the EEG-values, but the idea felt cumbersome as it would be hard to read and understand and it would be technically rather challenging to produce.

For these reason the breathing wave was dropped after being part of the development for the longest time of the discarded design presented here.

5.2 Particle Pillar

Particle pillar was an idea to inform user of state of close EEG-synchronization when both frontal asymmetry measurements are nearing their maximum value of 1.0, that is when value is greater than or equal to the 0.9 of the normalized value. In such a state a particle system shooting particles towards the sky in the form of a pillar is started. The placements of the particle pillar was to be behind the user statue, a little further away from the other visual cue objects in the scene. The high towards the sky reaching effect is easily spotted among the other visual cues.

Pillar's state is toggled by the frontal asymmetry values, in other words once fired the particle system stays on until either the synchronization between frontal asymmetry measurements is lost or if either user's frontal asymmetry decreases below the level of being extremely engaged. Pillar was included in the system for a long time because it was a powerful, showy effect and unique in the sense that it wasn't placed in the immediate vicinity of the user statues.

When evaluating the particle pillar's accordance with the environment and the other visual cues, it became clear that the effect was too aggressive compared to rest of the visualizations and the general relaxed feeling of the environment. The rapid stream of particles bursting towards the sky broke the serenity and peacefulnes so it was decided not to be used in this case. Also it combined both motion and color although being a visual cue for EEG only, which violated the principle of two distinct design patterns, motion for respiration and colors and light for EEG. Particle pillar in action is seen in Figure 12.

5.3 InSync Particle Burst

InSync Particle Burst was an idea to add a visually striking gamification element for respiration which would also act as a visual cue for breathing in sync. The visual cue implementation was made by spawning a single burst of glowing bright particles, an effect done by utilizing Unity's particle system tools, in an event of synced breathing. When both users exhale simultaneously, or very nearly as the system allows approximately 1.5 second offset in exhales, a bright burst of particles appears from the air in the middle of the bridge. This was done by utilizing Unity's particle system and configuring it to burst *rigid body* particles that are affected by Unity's physics simulation and fall onto the surface of the meditation grounds because of gravity.

This was the most aggressive of the visual cue ideas and it was meant to

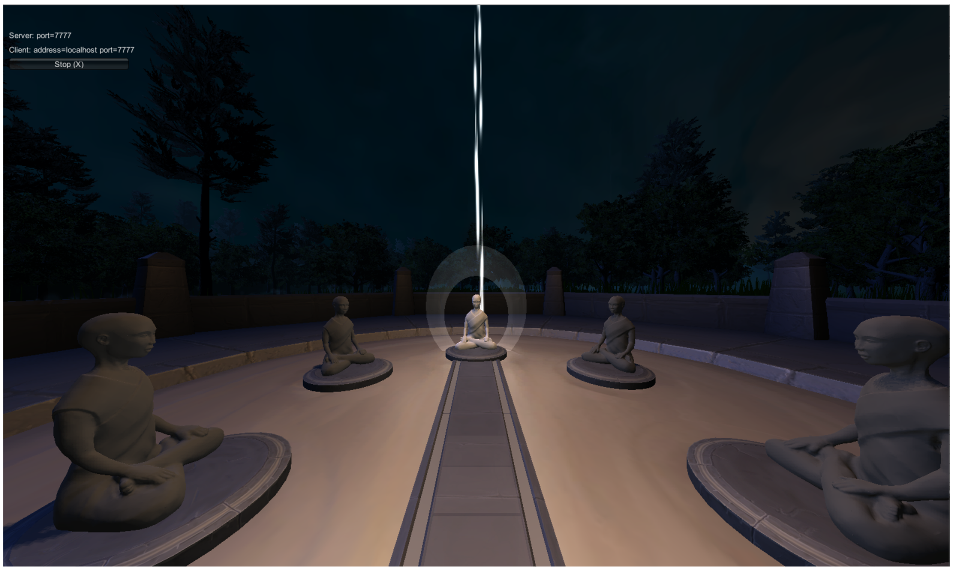


Figure 12: Particle Pillar

appeal to users through gamification and creating an instant gratification when respiration is in sync with the other meditator. Even a sound effect played during the moment of particle burst was considered to make the gratifying element even stronger, but the design was discarded before that idea reached implementation. Of all the visual cue designs, the InSync Particle Burst was the only one obeying the simulated laws of physics provided by the Unity's physics engine.

In the end this visual cue idea was deemed not fitting among the other visual cues and the setting of the environment in general. Firstly, while all the rest of the environment is rather serene and peaceful, the sync particles created an unwanted turbulence in the environment with momentary bright particle bursts. Secondly, considering that when users breathe in sync this effect would be activated constantly following the rhythm of users' exhales which would make the visual cue to lose its charm and striking appearance rather fast and thus rendering the wanted gamification property ineffective. It was decided that particle burst cannot be utilized in this context.

5.4 Stair of Pillars

Stair of pillars was an implementation of the idea of two users building a mutual connecting structure between them based on the frontal asymmetry levels. Once the users reach a certain levels of synchronization between their EEG-feedbacks, the pillars start to grow. The higher the frontal asymmetry level in the EEG-feedback is, the more pillars are shown. Both users have their own set of light pillars where first pillar is closest to the user's statue and also lowest. The fifth and last pillar is halfway along the bridge and also the tallest. This visualization is seen in Figure 13.

Figure 13: A Stair of Pillars

When frontal asymmetry value is mapped between 0 and 1, the pillars represent every 0.2 change in the value. For example when both users are in synchronization with 0.6 frontal asymmetry, three pillars are lit on both player sides.

While the pillars worked as an implementation of the mutual structure idea, one issue was that they added even more light to the scene where many things were already using light and color as visual cues. Additionally by adding gradually increasing and decreasing objects user might also get distracted when respiration is already being visualized by back and forth moving effect.

In conclusion, the stair of pillars was discarded because it was too ambigious and confusing. It used both light and movement, or rather different distances but still conceivable as motion, as visual cues, which violated the two distinct domains principle.

5.5 Focusbeam

In the early drafts and versions of the meditation environment, the exercises that user had to perform were supposed to be about concentrating on different objects with different meditation exercise for each. Different objects were meant to represent a friend, a neutral person or a person towards whom the user has negative feelings. Then by practicing loving-kindness meditation toward the respective object, user's engagement, that is frontal asymmetry, was to be measured.

Focusbeam was an implementation of an adaptive visualization where user sees a flowing stream, or *beam*, of particles towards the focused object. The color and the size of the beam were to be determined by the measured value engagement.

Visualization was designed so that the stream follows a sine wave which helped the user to get a sense of perspective from the first person view camera. If the stream was a straight line, then user would be unable to see anything but the new particles which would then block the view from the earlier ones that have already moved further away.

The visualization design seemed to work in the tests performed during development but after the change of requirements on the system design, and the particular user case dismissed, there was no longer demand for such visual cue. Thus the focusbeam was discarded from the visual cue collection.

6 Evaluation and User Feedback

This chapter discusses in more detail the development process regarding how different adaptive visual cues were designed and evaluated in the project. Examined here is the evaluation process during and after the project and is divided into two main parts.

Firstly under inspection is the development process itself and how different design choices were evaluated on-the-go to decide which are to be implemented and which are not. The flow of the development process is illustrated starting from the beginning. Some examples are also presented to give a view of how the decisions were made and on what basis.

In the second part of the chapter the user self-reports of the users, who took part in the experience the system was created for, are examined. This is to bring outside evaluation to the project and see how the decisions and implementations worked.

6.1 Development Process and Evaluation

The nature of the development project was that of an agile project where the system was developed incrementally based on the wishes of a product owner, in this case the leaders of the research group. This kind of process guided the development so that changes and new design ideas were possible to be rapidly created and brought into the system at least in some preliminary form. This also enabled the discarding of most unusable designs from early on and not wasting development time trying making them to work.

A common flow or development pattern was for example that first an idea was proposed for a visual cue design which then was evaluated based on rough sketches and verbal description. After that if the visual cue design seemed to fulfil its purpose it was created and afterwards evaluted again if the new feature met the requirements and worked adequately in a way that everyone in the research group was happy with.

The development process of the system started with first deciding the main setting. First we proposed a Japanese-style pagoda on a cliff by the sea on an island during daytime. FocusBeam, mentioned in Discarded Visual Cue Designs -chapter, was one visual cue idea that was supposed to be used during the meditation experiment to guide user's attention toward an object where the meditation is focused to. At this point the meditation experiment and the requirements for the setting weren't yet completely decided and clear and along the development new ideas popped up.

For example instead of doing meditation alone and receiving feedback according solely to user's own actions, an idea of doing something more social with a sense of building toward something mutual, for example a structure, was proposed. This was first tried to be implemented by creating another separate island for the other user and representing the progress in meditation exercises by building a connecting bridge between the islands, starting from both ends. Problems with this approach were that the island would have to be too far away from each other to have a personal feeling to the environment. Other idea for the mutual building was some sort of effect where user's progress would incrementally build a double helix structure.

Ultimately the island environment was discarded. As a follow up we first brainstormed a pagoda interior, as we had used the pagoda-theme earlier, or a somewhat similar Japanese-style room with paperwalls. This was a short-lived idea and wasn't implemented because we found that the interior-type design might feel distressing and cramped.

In the third design idea the outdoors and an open sky were taken from the first implementation, but the time of day was decided to be changed from day to night. Night and dark background supported the visual cue design needs better too, as subtle color and brightness changes were easier to spot and gave more room to perform subtle changes that still remain noticeable. Also at this point we settled to the idea of two opposite statues which would also embody some characteristic of presence, like statue's chest movement while the user is breathing.

Although the setting had changed from the earlier designs, the idea of a connecting bridge was brought along to the new design as it seemed like an intuitive and quickly adoptable idea of mutual action between users and their statues. This is an example of an early design brought again to the system. In the end the bridge between user statues remained as one of the major objects in the environment as it hosted both EEG and respiration visual cues.

To summarize when the meditation exercise and all the other requirements were getting refined, the overall design evolved which meant that some of the earlier designs were scrapped to make room for more suitable ones in the new environment, but then again some ideas were usable in some form even when the work progressed. The work on the selected visual cues was based both on previous academic research and own ideas. All decisions were in the end evaluated and approved together with the rest of the research group.

6.2 User Self-Reports

After each meditation exercise session user was launched into a self-report questionnaire form, which was also implemented into the virtual reality environment in order to avoid breaking the immersion between sessions by removing the Oculus Rift head-mounted display. The questionnaire was to evaluate through self reporting if the created meditation environment and visual cue implementations for biofeedback worked towards evoking empathy in the users.

The hypothesis of the experiment was that the use of biofeedback would increase synchronization of the affective and physiological states between the users. The users were instructed before the experiment to evoke feelings of empathy towards the other which would lead to affective interdependence [SJR+18]. These experiment results can also be applied here to evaluate the effectiveness and quality of the visual cues.

In order to create a sense of continuation and familiarity between the meditation sessions and the self-report questionnaire, the questionnaire takes place in the same nighttime forest -setting as the preceding meditation exercise, just a little further to the forest from the meditation circle. The Oculus Touch -controllers and and users hands have visual representations in the virtual reality environment as 3D-objects.

The self-report questionnaire followed immediately after each meditation session in the experiment. Same set of statements or propositions were shown each time after each meditation session with different parameters and conditions. The parameters were divided between solo and dyadic condition, and both having the settings of both visual cues disabled, only EEG enabled, only respiration enabled and both EEG and respiration enabled. Thus in total the amount of different sessions was eight.

First part of the questionnaire consisted of non-verbal self evaluation of six image series. Each series of images showed nine pictures forming a scale representing different states of feeling. After the images users were asked various question regarding their own affective state and the affective state of the other.

The statements presented were for example about how sympathetic, empathetic and warm the user feels and how well user thought one could read the affective state of the other and how well one's own affective state was readable by the other. Some questions evaluated how clearly the user think their feelings and states of mind were conveyed between each other. To each question user had to select one from 7 values on scale between *completely disagee (1), doesn't disagree or agree (4)* and *completely agree (7)*. The results examined here are based on the analysis of averages and medians of the user answers.

The first six propositions started with a prefix "I feel" and the suffixes were sympathetic, compassionate, warm-hearted, warm, tender and moved. On average in all these six statements the dyadic condition with both EEG and respiration visual cues enabled yielded the most agreeing results, closely followed by the dyadic condition with only EEG enabled. The I feel -statements are shown in Figure 14.

Next user had to provide an answer to statements regarding both the user and the user's pair during the meditation. The meditation sessions in the single player solo condition without the visual cues for the other user, which obviously wasn't present to be visualized, weren't ranked as high as the meditation sessions in the dyadic condition, which is a rather natural and expected result. The statements regarding different kinds of interaction during the experiment are presented in Figure 15.

1. I feel sympathetic
2. I feel compassionate
3. I feel warm-hearted
4. I feel warm
5. I feel tender
6. I feel moved

Figure 14: I feel -statements

With these the best results were also yielded from the dyadic condition with both visual cues enabled. Interestingly from the statements shown in 15, the first three statements pairs yielded the second best results from the dyadic condition with respiration visual cue enabled. Those six statements are distinctly assessing the sense of presence and attention, so the more instantly reactive and real-time visual cue of breathing seems to work slightly better in that context than using the more ambiguous and prevalent EEG visual cue only. All the next statements that followed returned to the previous trend in where better results were yielded by the EEG-visual cue only enabled than with the respiration-visual cue only enabled. In the rest of the statements the most agreeing results were in almost all cases yielded by both visual cues enabled.

The negative proposition described in Figure 15 item 5 stating that the feelings were not clear yielded the lowest score in the dyadic condition and both visual cues enabled, followed by only EEG enabled. In other words the mutual feelings were clearest when both EEG and respiration visual cue were enabled. On an interesting side note, the most agreeing results to the statement *My pair's feelings were not clear to me* were yielded by the combination of both visual cues enabled in the solo condition instead of having both visual cues disabled, which followed closely yielding second largest agreement.

The last six statements evaluated how the users' mood was perceived to affect the interaction. Out of the answers for these six question five questions yielded the best results with only EEG visual cue enabled. Only EEG-visual cue being conceived better option, although only slightly, might be due to the nature of the last six statements as they asked how mood, sentiments and attitutes affected the interaction whereas the previous ones had an emphasis on how the affective states were conveyed between users. When the context of those questions underlined how user's own affective state affected the

1. a) I noticed my pair; b) my pair noticed me
2. a) Presence of my pair was obvious to me; b) my presence was obvious to my pair
3. a) My pair got my attention; b) I got my pair's attention
4. a) I knew how my pair felt; b) My pair knew how I felt
5. a) My pair's feelings were not clear to me; b) My feelings were not clear to my pair
6. I could clearly describe my pair's sentiments; My pair could clearly describe my sentiments
7. My pair's mood had an effect on me; My mood had an effect on my pair
8. My pair's sentiments affected the mood of our interaction; My sentiments affected the mood of our interaction
9. My pair's attitudes affected how I felt; My attitudes affected how my pair felt

Figure 15: Statements

interaction or the affective state of the other user, it might be that EEG somewhat superseded the respiration as being part of the domain of mood and interaction.

Based on the user results it's clear that the perceived affective interdependence was higher in the dyadic condition than in the solo condition where there was no visual feedback. In the dyadic condition the exercises with EEG or both EEG and respiration visual cues enabled evoked higher rates of perceived affective interdependence than with only respiration visual cues enabled. All visual cue combinations, meaning EEG or respiration or both, lead to higher perceived affective interdependence than none of them enabled.

Based on the mean and averages on the questions regarding how easily the visual cues were readable and how easy it was to understand and read own and the other's affective state, in most cases the combination of both EEG and breathing visual cues produced the best results, followed by the use of EEG only.

Results implicate that the combination of two different visual cues for two distinct biofeedback sources provide the best results. Comparing the two visual cues used individually, although the visual cue for the EEG and the state of engagement assessed from the frontal asymmetry, was more ambiguous in its visual representation, it seemed to provide the best results of perceived affective interdependence and a sense of presence than the visual cue for respiration. This might be in part that although the visual cue for respiration gave a direct visual feedback of the user's breathing rate, the intensive saturating light and color of the EEG visual cue might have been more powerful in creating a sense of presence and a feeling that the user is affecting the environment with one's own affective state.

Also the design idea of dreamlike colors and lights might have boosted the level of engagement. The difference between plain meditation circle with the biofeedback visual cues disabled and visual cues enabled is prominent, which is further enhanced by the color changes of the EEG visual cue.

6.3 Summary of the Evaluation Results

In this chapter we found out that in the post-meditation session user self-review report the best results were yielded by having both EEG and respiration visual cues enabled in the dyadic condition. The self-reviews were part of the research experiment and had a goal of assessing the perceived presence of self and other, and the sense of sharing the affective state, feelings or sentiments between each other, that is the perceived affective interdependence.

Results were analyzed as answer averages and medians from self-reviews in which users had answered statements with numbers from one to seven, which encoded a scale from completely disagree to completely agree. All top three results were achieved in the dyadic condition with the best overall scores with the combination of EEG and respirations visual cues, followed by EEG-visual cue only as the second best option, and respiration only visual cues as the third best option. All users had sessions with all visual cue combinations, including both of them disabled, in both the dyadic and solo conditions.

The visual cues were the way to convey information in the experiment and meditation session parameters altered the different combinations of the visual cues and the option of either solo or dyadic condition. Although the self-report statements didn't directly address the visual cues themselves, the self-reports still evaluated their functionality as the visual cues were the tools to convey the information which was assessed in the user self-reports. In general we examine how to design and develop the kinds of visual cues that would suit the needs of this particular setting of immersive virtual reality meditation with a social aspect in mind.

7 Discussion

In this chapter we go through the research questions introduced in the beginning of this thesis and examine the findings regarding each of the questions. In the end of this chapter we discuss some future ideas in the light of the other observations made in this chapter.

7.1 Research Question 1: Visual Cue Design and Development

The goal was to design and implement intuitive visual cues that are easy for a user to understand and which increase the sense of presence and understanding of one's own and affective and biophysical state. Based on the user feedback results the goal was achieved. The combination of EEG and respiration visual cues simultanously enabled yielded the best results throughout the experiment. Both EEG- and respiration visual cues had purposefully their own unique way to visualize and represent user's physiological data. These were colors and lighting for the EEG-feedback and motion for respiration feedback.

Development process was iterative and more or less fail-fast which means that potential ideas were tried out and implemented quickly to some extent to evaluate whether they work at all, and if not, discarded. The criteria for the approved visual cues are examined in more detail in the next subchapter.

Because the system was created to be social environment of two users, the visual cues had to have same rules for both users. The visual cues had to be designed in such a way that both users could be able to perceive their own and the other's biohpysical state and compare them. Good approach to accomplish this seemed to be a symmetrical design of visual cues where both users have the same set of visual cues with same rules.

Part of the visual cue design is the question of how and where to embody them. The attributes of a virtual reality environment certainly play a role in this, for example how the virtual surroundings are designed and how user is supposed to interact or perceive the environment. In this case user's point of view was practically fixed since partakers in the research experiment were advised to sit during the meditation.

The system itself was designed in such a way that the user is encouraged to observe a certain direction as very quickly after beginning the meditation session there isn't much new information coming elsewhere other than from the visual cues. Also the sitting posture towards the visual cues makes observing them a natural choice even when the user is able to look around freely in the virtual reality environment.

As the visual cues of both biophysical feedbacks, and for both the visual cue of being in-sync, has to fit in the same scene both feedbacks were given their own domain of visualization methods. Light and color changes for the EEG and motion for the respiration, with the addition of a gentle light visual cue for the respiration synchronization with the in-sync blink -cue. By separating the visual cues into different visual effect categories it was possible to keep the information in the scene in control and decrease ambiguity of the visual cues.

As the visual cues were designed for an immersive system, it was not desirable to use traditional non-diegetic approach of two dimensional user interfaces when embodying the cues. Instead the cues were embodied into the environment surroundings themselves, following a diegetic approach where visual cues are made part of the perceived environment.

Another, maybe even obvious, finding to take into consideration in the visual cue design process is that the visual cues should be embodied in different parts of the environment in order to keep them clearly perceivable and distinguishing them from each other. In this case the locations of the visual cues were meticulously tested to keep them unambiguous but also all of them always within sight from the user's assumed point of view.

In addition to conveying information of the user's biophysical state, one design objective was that the two different visual cues used together simultaneously would increase the amount of perceived sense of presence, which they seemed to accomplish. Interestingly though when it comes to affecting the mood, interaction and feelings, users mainly regarded the EEG-only condition higher than having both EEG- and respiration visual cues enabled.

This might be due to the nature of different biofeedbacks where respiration could be seen as somewhat simple physiological process, whereas EEG-neurofeedback is more ambiguous and more distinctly linked to feelings in this case. Be that as it may, the previous notion also suggests on its own part that the EEG-visual cue design was succesful in representing neurofeedback clearly, allthemore when it had such an impact that it yielded the best results regarding effects on the affective relations.

7.2 Research Question 2: Criteria for Selecting the Visual Cues

Visual cues had to be intuitive and unambiguously display the information present in their own context. As visual cues were used for both different biophysical measures, EEG and respiration, they had to convey information in a way that feels reliable and that user doesn't confuse different information sources between each other. Thus to importance rose the criterion that every visual cue should act on a basis of some principle which is set on the respective biophysical feedback that needs to be visualized. In this case changing colors were chosen for the EEG-feedback and motion for the respiration feedback.

As mentioned before, the visual cues were designed in a way that they can be embodied in the environment so that they don't feel out of place.

This includes the setting both aesthetically and regarding the general mood as well. Meditation can be seen as a tranquil exercise so many aggressive visual cues didn't work quite well as they broke the peaceful mood that was wanted from the immersive environment.

The EEG and respiration feedbacks were separated by how they visually conveyed information. The reason to set this rule was to decrease ambiguity when the visual cues are perceived, and this was a reason for many visual cue ideas to be discarded when they didn't work well in a context where visual rules were already fedined for the respective feedbacks. For example, some visual cue ideas, that might have worked very well on their own as visual cues in some other context, combined aggressively both motion and bright lights which made it difficult to clearly connect them to the biophysical values they were trying to represent.

In contrast, the aura object embodied both EEG and respiration visual cues in the same element while still keeping the visual cues coherent and not creating ambiguity as they still conveyed the information of both feedbacks with the defined rules.

The in-sync visual cues were somewhat an odd case as they were in a way child visual cues within parent visual cues. Main criterion for them was that they have to be clearly part of the parent visual cue, for example bridge sides were showing colors conveying EEG-feedback information, which made them an adequate place to embody EEG-synchronization representation as well.

Being embodied in the bridge recesses, the in-sync visual cue was also equally easy to perceive for both of the users. The visual cues representing synchronization had to connected to the underlying biofeedback visualization and not bee too overwhelming to be perceived as a wholly distinct visual cue separated from the parent feedback's visual cue.

Although generally the visual cues functioned as intended, there were things that were perceived in a way that weren't the intention. Some users reported after the experiment that the color scale of the EEG-visual cue was counter-intuitive as the red color was seen as something bad and green as something to be achieved, much like the color coding with traffic lights.

This was the opposite of the original design intention where green was thought as a mellow color and thus supposed to hint the initial state of low engagement, and intensive red as something which would represent level of high engagement and affection as it does in certain well known symbols. One example of such is as a red heart that typically signals deep affection. One conclusion from this observation could be that the ways on conveying information would have to be assessed from a broader perspective, in this case for example from a wider cultural context.

In conclusion the criteria in general seemed to follow the pattern that one visual cue domain should implement one certain kind of visualization type. Also the outside conditions and requirements of the environment where the visual cue is to be embodied should be taken into consideration. For example is the lighting of the virtual reality surroundings bright or dark, which affects how the visual cue colors and brightness is perceived, or is the user's point of view stationary or moving, which might affect how well motion may be perceived and tracked.

The biggest pitfall of the design presented here was the color coding of EEG-visual cue, which was sometimes seen counter-intuitive to what it was meant to represent.

7.3 Research Question 3: Conveying Synchronization

In addition to the visual cues' task of making biophysical attributes perceivable in the virtual reality, the users were supposed to use that information from the biofeedback to reach synchronization, or be *in sync*, with the other user. The question is how to use the biophysical measures, in this case EEG and respiration, of the two users to convey the state of synchronization.

Both biofeedbacks, and thus both visual cues domains, were given separate definition of being in sync. EEG is defined to be in sync when the frontal asymmetry values differ up to 0.1 between each other on a range from 0 to 1. Additionally the in-sync effect gains more brightness and a subtle flickering effect when the frontal asymmetry values increase while still being in synchronization.

Respiration then again is seen to be in sync if the exhales differ up to rougly 1.8 seconds. This time limit was mainly an approximation of the average breathing rate of an adult human respiration rate while staying in a sitting posture. One way to improve would be to create a dynamic time limit which is calculated in realtime from users' breathing rate, a sophisticated approach that wasn't necessary or even possible in timeframe of this project.

In both EEG and respiration in-sync visualizations the main idea was to give the existing visual cues a certain kind of boost which would represent the current state as a certain kind of achievement. The EEG-feedback conveys synchronization by giving the bridge sides a glowing visualization using a bloom light effect.

When the progress of both users increases, calculated from their frontal asymmetry measurements, the visual cue increases in brightness and starts to flicker subtly. This kind of visual cue design should help users to perceive that they are in sync and further represent advancements in the exercise if both have progressed far enough.

Respiration feedback's definition of being in-sync is not continuous in the same way as it is with the EEG-feedback as it is evaluated again with every exhale. Because of the rapidness of this biophysical function and that user is able to respond to the feedback information relatively quickly by controlling one's own breathing, the in-sync effect was given a somewhat gratifying visual cue.

As the users are able to monitor both their own and the other user's breathing rate from the pulsating breath bars, synchronization is conveyed as a quick blinking effect in the Breathing Bar -layers in the middle of the bridge and furthest from the users. This should clearly guide users to synchronize their breathing rates with each other and thus increase the perceived interdependence.

7.4 Discussion and Future Research

In the future in order to gain better feedback and to understand the user experience related to the visual cues it might be worthwhile, in addition to the experiment research like the one explained in this work, to assess the functionality of the visual cues more accurately by conducting a questionnaire, or some other type of measurement, limited to the user experience aspect of the visual cues only.

Although such wasn't possible in the research project described here, opinions regarding the functionality of the visual cues and intuitiveness of the chosen colors, for instance, and to gather general feelings if something is awry in during the experience could provide valuable information in further development, fine tuning of the design and implementing the principles examined in this work.

Also to be noted is that while the sessions that used visual cues yielded the best scores, usually the scores weren't as high as they could have been. For the dyadic condition with visual cues for both biofeedbacks enabled the self-report answer averages ranged roughly between 4.33 and 5.99 on a scale from one to seven. Although the best self-report scores were yielded by the use of visual cues in sessions, there's still room for improvement.

One possible deduction from this observation about the scores is that although the current design seemed to work as intended and the use of combined set of EEG and respiration visual cues worked more effectively than using a subset of them or not having the visual cues enabled at all, there's still things to consider regarding the designs. For example how to convey the neurofeedback and EEG even more clearly.

In this experiment the results are based on self-reports by users. In the future, to gain more precise and unabiguous mapping between the virtual reality and the users' affective states it would be necessary to put even more emphasis on physiological state and define more accurately the brain activity during the meditation. Increasing granularity on neurofeedback makes more detailed visual cue response possible, which could help users to perceive their affective states better and, for example, perform meditation exercises more efficiently.

It would also be of interest to increase maximum simultaneous users from two to three or even more and observe the behavior and response to the visual cues presented here in that kind of a more complex setting. Designwise the visual cues presented in this thesis might work just as they are because they were already designed to work symmetrically between two users.

8 Conclusion

This thesis has examined the creation, including designing, developing and implementing, of biofeedback adaptive visual cues for a social virtual reality meditation environment. The points of interest were how to design and implement visual cues for different types of simultaneous biofeedbacks and how to embody them into the virtual reality environment in a way that the they convey information clearly and intuitively. Additionally this thesis examined more specifically the criteria for selecting the visual cues that are the best fit into this context, and how to visually convey information regarding the state of synchronization between users' biophysical states.

The visual cues in this work were created for an immersive virtual reality meditation system that had two sources of biofeedback data: EEG-based neurofeedback and respiration rate for biophysical feedback. Colors, lights and altering their hue, brightness and saturation based on feedback data was chosen as a basis for the EEG-feedback visual cue. For respiration, motion was chosen as the basis of the visual cue based on breathing intervals. The reason of separating the two different biofeedbacks into two distinct domains was to make the visual cues easier for the user to perceive, distinguish and associate with the corresponding biofeedback.

Design of the visual cues took actions with both approaches to battle ambiguity. The color and light visual cues of EEG were embodied in multiple locations that correlated with each other to make them feel more reliable. Motion cue for respiration was designed to be simple and manifest the breathing rate as obviously and accurately as possible to decrease ambiguity and make the visual cue feel reliable, in addition to being embodied in two places.

The virtual reality meditation system in this work was designed to be social which means that in addition to doing the exercises alone, the system supports the dyadic condition of two simultaneous user reminiscent to a multiplayer-setting familiar from computer games. Each of the users in the meditation environment has an identical set of visual cues which then adapt to the user's bio- and neurofeedback.

The purpose of the visual cues is to convey affective state information to both user simultaneously present in the meditation environment. Firstly information regarding one's own affective and biophysical state, that is for the user who is the origin of the biofeedback data, and secondly allowing the second user to observe the state of the other. In other words the visual cues are meant to offer information both of one's own and also of the other's affective and biophysical state, and thus to convey affective states between users and allow emotional contagion through empathy evoked by meditation exercises.

The designing process consisted of a combination of ideas based on previous research, general experience and know-how as well as trying new things out through trial-and-error. The ideas for the visual cues were also proposed to the research team to get some broader feedback during the development and also to evaluate the ideas on the go.

After brainstorming ideas and assuring they are good enough to be accepted, the idea was implemented. All the visual cue ideas had a certain beforehand set hypothesis how it should look and feel. Also the surrounding setting of the virtual reality environment was taken constantly into account in order to be able to embody the visual cues into the environment correctly.

Of the many visual cue design ideas that got implemented some needed more altering and honing before reaching the final form, and some worked as intended starting from the first spark of an idea. Some visual cue ideas were also noticed as inadequate and discarded in different stages of the development process, sometimes right from the start after coming up with an idea and sometimes after a long period of time of trying to find a way to get an idea to work.

This was in some degree due to changing requirements during the development process and also because of the incremental and agile style of development. With this kind of work methodology it was important to continuously evaluate the state of current implementations and ideas whether they still worked as intended.

The design requirement was that the implemented visual cues should satisfy the requirements that were set to them. The requirements included responding correctly and as expected to the real feedback got from the respiration sensor and assessed EEG-values, conveying the information according to the design plan, having the correct look and feel according to our wishes as a research group and being embodied in the enclosing virtual meditation environment in such a way that all the aforementioned conditions still apply. This requirement guided the design and development process of the visual cues.

Regarding the results got from self-reports it was interesting from the evaluation point of view whether the users who took part in the research experiment meditation itself would perceive the visual cues in the way as they were designed to convey the information. The self-reports assessed the functionality of different visual cue combinations in different sessions with both solo and dyadic conditions. The ideal expected outcome was that the best results would be yielded by having both EEG and respiration visual cues enabled in the social dyadic condition of two simultaenous users. The self-reports indicated that this target was fulfilled and that in its own right gives justification for the principles presented here by the three research questions.

The visual cue implementations were implemented accordingly to the designs which were also approved by the research group in the project. Implementations worked in most part as planned which is seen in the self-review reports as the dyadic condition with a combination of EEG and respiration visual cues yielding the best results. As the nature of these visual cues is a little ambiguous as the information isn't explicitly conveyed, some room for tweaking always remains. In this case the color choices of different EEG-intensity levels might be something worth reconsidering or adjusting as it seemed to confuse at least some users partaking in the research experiment.

To conclude, this thesis has examined of the process of designing and implementing visual cues for biofeedbacks in a social virtual reality environment. Virtual reality and its different applications probably continue to gain even more popularity in the future. Next generation of devices are expected to offer support for even more detailed environments which in turn would allow greater possibilities to increase immersion. Virtual reality meditation among other therapeutical purposes based on biofeedback are expected to be increased when the amount of different kinds of biophysical sensors increase in the consumer markets.

Most virtual reality experiences are still supporting single player modes only. In the future with already existing social virtual reality applications such as Facebook Spaces and Oculus Rooms, the social and multiplayer side of virtual reality is very probable to become more common. Different kinds of sensors for measuring EEG, for example, are also becoming more readily available for consumers. Combining these areas, as done in the project examined in this thesis, is probably something that we are going to see a lot more in the future, and that also offers a near endless playground for different visual cue designs as well. This thesis has provided some principles that help create feedback adaptive visual cues that work rather well in a social virtual reality environment.

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