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Design and Evaluation of Advanced Virtual Reality Applications in Healthcare

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Gent, juni 2022
Joris Heyse

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List of Acronyms

A

AR Augmented Reality.

AV Augmented Virtuality.

B

BIT Behavioural Inattention Test.

C

CB Contextual Bandit.

CBS Catherine Bergego Scale.

CBT Cognitive Behavioural Therapy.

CGI Computer-Generated Imagery.

CNN Convolutional Neural Network.

CR Conditioned Response.

CS Conditioned Stimulus.

CVS Caloric Vestibular Stimulation.

D

DSS Decision Support System.

E

ET Exposure Therapy.

G

GDPR General Data Protection Regulation.

GPU Graphics Processing Unit.

GVS Galvanic Vestibular Stimulation.

H

HCP Health Care Professional.

HMD Head Mounted Display.

I

ICU intensive care unit.

ISI Insomnia Severity Index.

L

LA Limb Activation.

M

MC Markov Chain.

MILP Mixed Integer Linear Programming.

MINI Mini International Neuropsychiatric Interview.

MINLP Mixed Integer Non-Linear Programming.

ML Machine Learning.

MNT Music Neglect Therapy.

MR Mixed Reality.

N

NMT Neurologic Music Therapy.

NVM Neck-Muscle Vibration.

O

OASIS Overall Anxiety Severity and Impairment Scale.

OKS Optokinetic Stimulation.

OWL Web Ontology Language.

P

PA Prism Adaptation.

PDD Prototype Design Document.

POL Panic Opinion List.

PTSD Post Traumatic Stress Disorder.

Q

QoE Quality of Experience.

R

RDF Resource Description Framework.

RL Reinforcement Learning.

RML RDF Mapping Language.

RW Rescorla-Wagner.

S

SAT Sustained Attention Training.

SUDS Subjective Units of Distress Scale.

SVM Support Vector Machine.

SWRL Semantic Web Rule Language.

T

TAP Test for Attention Performance.

tDCS transcranial Direct Current Stimulation.

TMS Transcranial Magnetic Stimulation.

U

US Unconditioned Stimulus.

USN Unilateral Spatial Neglect.

V

VE Virtual Environment.

VR Virtual Reality.

VRET Virtual Reality Exposure Therapy.

VST Visual Scanning Training.

W

WHO World Health Organisation.

X

XR eXtended Reality.

Y

YLD Year Lived with Disability.

Samenvatting

De gezondheidszorg wordt steeds complexer. Dit heeft te maken met de stijgende vraag naar consultaties, het vaker voorkomen van multimorbiditeit, en de gelijktijdige daling van de zorgcapaciteit. Met andere woorden, casussen worden complexer waardoor ze meer tijd vragen terwijl er steeds minder tijd voorzien kan worden per patiënt. Gelukkig zorgde de digitale evolutie in de gezondheidszorg voor efficiëntere, betere en soms zelfs kostenbesparende zorg. Dit heeft geleid tot de introductie van de term eHealth, of elektronische gezondheidszorg, wat verwijst naar het gebruik van informatietechnologie ter ondersteuning van toepassingen in de gezondheidszorg. Eén van die digitale technologieën is Virtual Reality (VR) waarmee gebruikers een virtuele wereld kunnen ervaren en daarbij het gevoel krijgen zich werkelijk in die wereld te bevinden. Meestal wordt hier een Head Mounted Display (HMD) voor gebruikt, waarbij kleine schermpjes voor de ogen van de gebruiker worden geplaatst zodat die enkel nog de virtuele beelden kan zien. De voordelen van VR zitten voornamelijk in de flexibiliteit van de technologie, een alternatieve wereld kan namelijk gecreëerd worden waarin elk aspect aanpasbaar en aanstuurbaar is. Zo kunnen gebruikers situaties ervaren die in werkelijkheid zeer moeilijk of helemaal onmogelijk te realiseren zijn.

De elektronische gezondheidszorg haalt voordelen uit deze VR technologie door ze toe te passen bij behandelingen of therapieën waarbij de patiënt leert hoe die kan handelen in een zeer specifieke situatie. De vaardigheden die in VR omgevingen worden aangeleerd, kunnen nadien toegepast worden in het dagelijkse leven. Onder andere twee specifieke domeinen in de gezondheidszorg die dit soort therapie gebruiken, zijn de behandelingen van angststoornissen, als onderdeel van de mentale gezondheidszorg, en cognitieve of fysieke revalidatie. Dit zijn tevens de twee domeinen die aan bod komen in dit proefschrift. Maar het toepassen van VR technologie ter bevordering van de efficiëntie en doeltreffendheid van de gezondheidszorg is niet vanzelfsprekend. We moeten er ook op toezien dat we VR technologie niet zomaar gebruiken om technologie te gebruiken, maar dat ze effectief ook meerwaarde biedt. Hiervoor dienen we ons voornamelijk te laten leiden door de kennis en de vraag uit elk specifiek domein van de gezondheidszorg en moeten we weerstaan aan de verleiding om steeds de laatste technologische innovaties toe te passen.

Eén van de uitdagingen bij het creëren van geavanceerde VR toepassingen is de nood aan gepersonaliseerde omgevingen. Het is al langer gekend dat gepersonaliseerde zorg veel efficiënter is omdat ze doelgericht inspeelt op de noden van de specifieke patiënt. Het spreekt voor zich dat een uniforme aanpak (one-size-fits-all) niet altijd als doeltreffend ervaren wordt omdat iedere persoon anders is. De uitdaging zit hem net in het zoeken naar oplossingen om de noden van de patiënt te identificeren en er vervolgens naar te handelen. Daarvoor zijn enerzijds algoritmen nodig, die aan de hand van data kunnen achterhalen hoe de patiënt evolueert, hoe die reageert op de behandeling en hoe die specifieke opdrachten uitvoert. Anderzijds zijn ook systemen nodig die aan de hand van deze inschatting van de patiënt, het vervolg van de behandeling kunnen bijsturen. Voor deze algoritmen is er voldoende data nodig om betrouwbare beslissingen te maken. Met VR technologie is het echter mogelijk om zeer veel data van de gebruiker te verzamelen terwijl die zich in een virtuele wereld bevindt. Dit kan bijvoorbeeld door data van sensoren in de VR hardware op te vangen, door gebeurtenissen in de virtuele omgeving te registeren, of zelfs door externe meetapparatuur te gebruiken. Deze data kan vervolgens gebruikt worden om gedragspatronen van de patiënt te analyseren. De systemen die vervolgens de behandeling personaliseren kunnen gebruik maken van de eerder vermelde eigenschap dat met VR technologie eender welke virtuele omgeving gecreëerd kan worden. Personalisatie kan er bijvoorbeeld voor zorgen dat bepaalde aspecten van die omgeving aangepast worden om de doeltreffendheid van de behandeling te optimaliseren.

Een volgende uitdaging is de ontwikkeling van een platform voor patiëntgerichte zorg waarbij VR centraal wordt geplaatst. Hierbij dient het platform de behandeling van de patiënt te bevorderen en de relatie tussen de patiënt en de zorgverlener te ondersteunen. Dit kan gerealiseerd worden door de patiënt hulpmiddelen aan te reiken ter zelfbekrachtiging van diens behandeling, vooral buiten de consultaties, en door het uitwisselen van informatie te vereenvoudigen. Als het platform de informatie die het ter beschikking heeft kan analyseren, kan die analyse ofwel gebruikt worden in algoritmen, bijvoorbeeld voor personalisatie, ofwel kunnen er inzichten uit gedestilleerd worden voor de zorgverlener. Om dit soort platformen te ontwikkelen, dienen de noden en wensen van alle betrokken partijen voldoende gehoord te worden. De codesign techniek, waarbij iedere stem aan bod komt tijdens de ontwerpfase, is hierbij cruciaal. Daarnaast moet er ook rekening gehouden worden met de technische kennis van de gebruikers. Als een systeem te complex is en het gebruik ervan bijkomende kennis vereist, zal het in praktijk weinig meerwaarde kunnen bieden.

In dit proefschrift wordt antwoord geboden op deze uitdagingen door drie toepassingen van VR technologie te ontwerpen, te ontwikkelen en te testen. Iedere toepassing evalueert een combinatie van technologieën, waarbij VR centraal staat. De eerste toepassing past muziektherapie toe in een VR omgeving ter revalidatie van patiënten met een hemispatieel neglect. De combinatie van meerdere sensorische modaliteiten, visueel en auditief, biedt een voordeel bij de behandeling van deze patiënten. Bovendien wordt sensor data van de VR hardware gebruikt om de graad van het neglect in te schatten. Alle informatie wordt weergegeven aan de zorgverlener via een dashboard-applicatie van waaruit de therapie ook aangestuurd kan worden.De tweede toepassing betreft virtuele omgevingen voor het behandelen van mentale stress in een thuissituatie. De omgevingen worden aan de hand van een initiële vragenlijst opgebouwd volgens de wensen van de gebruiker. Vervolgens zal een personalisatiealgoritme aanpassingen doen aan de omgeving op basis van de emotionele toestand van de gebruiker. Uniek aan deze uitwerking is dat die emotionele toestand berekend wordt aan de hand van een mathematisch model dat het effect van veranderingen in de omgeving berekent. Aanpassingen aan de virtuele omgeving gebeuren automatisch zodat deze toepassing gebruikt kan worden zonder bijstand van een getrainde therapeut. Ten slotte, de derde toepassing bekijkt de toepassing van VR voor de behandeling van angststoornissen. Momenteel is de meest doeltreffende behandeling voor angststoornissen blootstellingstherapie (Exposure Therapy (ET)). Hierbij wordt de patiënt geconfronteerd met het onderwerp van hun angst. Een nieuw gebied in onderzoek is geïnteresseerd in het toepassen van ET via VR, of Virtual Reality Exposure Therapy (VRET), om twee redenen. Kostelijke scenarios kunnen goedkoop gesimuleerd worden en er is zeer fijner controle over de scenarios mogelijk waardoor die beter afgesteld kunnen worden op de noden van de patiënt. Voor deze derde toepassing werd een patiëntgericht platform voor VRET ontwikkeld voor blended care, dat is een combinatie van traditionele zorg tijdens consultaties in persoon en oefeningen voor thuis. Het platform biedt verschillende scenarios aan waarin ET kan gegeven worden die elk tot in detail geconfigureerd moeten worden naar de noden van de patiënt. Ter ondersteuning van de therapeut is een algoritme ontwikkeld dat gepersonaliseerde suggesties kan doen voor nieuwe therapie-oefeningen. Daarnaast is er ook een smartphoneapplicatie verbonden aan het platform waarmee patiënten thuis VR oefeningen kunnen doen en gebeurtenissen kunnen registreren in hun dagelijks leven. Via een dashboardapplicatie kan de therapeut alle informatie over de patiënt raadplegen, en de VR oefeningen configureren.

Deze drie toepassingen van VR technologie, in context van de digitale gezondheidszorg, dragen bij aan het onderzoek naar betere, kostenbesparende en efficiëntere zorg. Door de implementatie van deze casussen werden nieuwe technieken verkend, en nieuwe inzichten vergaard. De elektronische gezondheidszorg kent nog steeds verschillende uitdagingen wat de ingebruikname van innovatie in de praktijk soms bemoeilijkt. Maar met gericht onderzoek kunnen we bijdragen aan een beter toekomst.

Summary

The complexity of healthcare is ever increasing. This can be linked to the rising demand for consultations, the increasing prevalence of multimorbidity, and the simultaneous decreasing capacity of our healthcare capacity. In other words, cases are becoming more complex, causing them to take more time to process and leaving less time per patient. Fortunately, the digital evolution in healthcare has improved efficiency and quality, and in some cases even reduced the cost of healthcare. This lead to the introduction of eHealth which refers to the use of information technology to support applications in healthcare. One of those digital technologies is Virtual Reality (VR), a technology that allows users to experience a virtual world giving them the impression to be truly present in that world. Most commonly, VR uses a Head Mounted Display (HMD), a device that positions miniature displays in front of the user's eyes thus filling their field of view. The main advantage of VR is the flexibility of the technology, allowing an alternative world to be created in which every aspect is adaptable and controllable. This allows the user to experience situations that are difficult or even entirely impossible to recreate in the real world.

eHealth benefits from VR technology by applying it in treatments or therapies that teach patients how to handle very specific situations. The skills learned in the VR environment can then be applied in daily life. Among others, two specific domains in healthcare that apply this kind of therapy are the treatment of anxiety disorders as part of mental healthcare, and cognitive and physical rehabilitation. These are indeed the two domains that are discussed in this dissertation. However, the application of VR technology to improve efficiency and effectiveness of healthcare is not without hurdles. We also have to carefully validate that VR technology is not merely being used for the sake of technology, but indeed has its own added value. To achieve this, we should listen to the expertise and needs of each specific domain of healthcare, and we need to resist the temptation to focus on merely applying the latest technological innovations.

One of the challenges in creating advanced VR applications is the need for personalised environments. It has been proven that personalised care is much more effective because it is tailored to the needs of the specific patient. It is self-explanatory that a one-size-fits-all solution is not always experienced as effective because every person is unique. The challenge lies in finding a way to identify the needs of the patient, and act on this information. On the one hand, this requires algorithms that can, based on data, determine how a patient progresses, how they respond to the treatment and how they execute specific tasks. On the other hand, we need systems that can use this information to adapt and tune the successive treatments. These algorithms require

sufficient amounts of data to be able to make reliable decisions. With VR technology, it is possible to collect a lot of data about the user while they are in a virtual environment. This can be achieved by capturing data from sensors in the VR hardware, by registering events in the virtual environment, or even by using external measurement instruments. This data can subsequently be used to analyse behavioural patterns of the patient. Systems for the personalisation of treatments can use the previously described property of VR which allows the creation of any imaginable virtual environment. Personalisation can entail for instance that certain aspects of the environment are adapted to optimise the effectiveness of the treatment.

A next challenge is the development of VR-enabled patient-centred platforms. The goal of the platform is to improve the patient's treatment and support the relation between patient and caregiver. This can be achieved by supplying the patient with tools that encourage self-empowerment and self-management of their treatment in between consultations, and by facilitating the exchange of information. If the platform can analyse the information at its disposal, these analyses could be used to steer algorithms, e.g. for personalisation, or insights could be extracted from them that can help the caregiver. To successfully develop this kind of platform, the needs and wishes of all stakeholders have to be taken into account. The co-design technique, which involves considering all stakeholders in the design of a system, is essential to achieve this. Moreover, the technological proficiency of the users need to be taken into account. When a system is too complex and its use requires additional training, it will be off little value in practice.

In this dissertation, these challenges are tackled through the design, development and testing of three VR-enabled applications. Every application is an evaluation of a combination of technologies, with VR at its centre-point. The first is an application of music therapy in a VR environment for the rehabilitation of patients with spatial neglect. The combination of the visual and auditive modalities is an advantage for treating this type of patient. Additionally, sensor data from the VR hardware is used to estimate the degree of neglect. All this information is presented to the caregiver through a dashboard application that also can be used to control the therapy. The second application concerns a virtual environment for treating mental stress in home situations. The environment is constructed based on an initial questionnaire to determine the preferences of the user. A personalisation algorithm will subsequently modify the environment based on the emotional state of the user. Unique to this solution is how the emotional state is calculated by using a mathematical model that calculates the effects of adaptation in the environment. Changes to the VR environment are automatically applied to allow the application to be used without intervention by a trained therapist. Finally, a third application considers the application of VR to treat anxiety disorders. Currently, the most effective therapy for anxiety disorders is Exposure Therapy (ET). This involves confronting the individual with the subject of their fear. A new area of research is interested in the application of ET through VR, or Virtual Reality Exposure Therapy (VRET), for two reasons. Expensive scenarios can be simulated at low cost and a fine degree of control over the scenarios is possible, allowing them to be better tailored to the needs of the patient. For this third application, a patient-centred platform for VRET was developed for blended care, a combination of face-to-face consults and home exercises. The platform offers a number of scenarios for ET in which each detail needs to be configured to match the needs of the patient. An algorithm was developed to support the psychotherapist in the configuration of new therapy exercises by generating personalised suggestions. Moreover, a smartphone application was created that is connected to the platform to allows patients to do VR exercises at home and register events in their daily lives. The psychotherapist can pull up all information about the patient, and configure VR exercises through a dashboard application.

The above three applications of VR technology, in the context of eHealth, contribute to the research towards better, cheaper and more efficient care. The implementation of these cases allowed new techniques to be explored, and new insights to be gained. eHealth still has many challenges ahead that may hinder the use of these innovations in practice. But through targeted research, we can contribute to a better future.

1

Introduction

"'But what is reality?' asked the gnomelike man. He gestured at the tall banks of buildings that loomed around Central Park, with their countless windows glowing like the cave fires of a city of Cro-Magnon people. 'All is dream, all is illusion; I am your vision, as you are mine'"

–Stanley G. Weinbaum (1902 - 1935)

1.1 Virtual Reality Throughout History

The first to read about the wondrous potential of Virtual Reality (VR) must have been the fans of science fiction author Stanley G. Weinbaum. In 1935, he wrote the short story *Pygmalion's spectacles* (Fig. 1.1) in which the main character meets a professor who invented a pair of goggles that creates an experience described as "a movie that gives one sight and sound [. . .] taste, smell, and touch. [. . .] and instead of being on a screen, the story is all about you, and you are in it" [1]. It only took 27 years for this fiction to turn into science when, in 1962, Morton Heilig invented the Sensorama [2]. As a cinematographer, Heilig wanted to create an experience of being "in" the movie. The Sensorama (Fig. 1.2) was a device that stimulated various senses of the viewer such as sight, sound, touch and even smell. It took until 1987 before the term "Virtual Reality" was coined by Jaron Lanier, a computer scientist, researcher and artist [3]. At that time, many researchers and companies had already designed and manufactured various devices to experience VR. The most promising was a Head Mounted Display (HMD) of which the first was introduced in 1968 by Ivan Sutherland [4]. A HMD

PYGMALION'S SPECTACLES

By STANLEY G. WEINBAUM

Author of "The Black Flame," "A Martian Odyssey," etc.

© 1935 by Continental Publications, Inc.

Unbelieving, still gripping the arms of that unseen chair, Dan was staring at a forest

Figure 1.1: The first reference to a device capable of producing an immersive virtual experience is found in the science fiction short story Pygmalions Spectacles, by Stanley G. Weinbaum from 1935.

significantly increased the sense of immersion as visual images are projected straight onto the eyes of the wearer, no matter which direction they look.

VR has known many definitions and interpretations depending on its context of use. Still, many agreed that it was a new medium, just like the telephone or the television [5]. In this dissertation, we will settle on the definition without reference to any of the hardware involved:

> "A *Virtual Reality* is defined as a real or simulated environment in which a perceiver experiences telepresence." [5]

New ideas and technologies emerged that did not exactly fit with existing definitions. They were so fundamentally different that they were labeled with new names such as Augmented Reality (AR) and Mixed Reality (MR), yet so similar that it warranted the introduction of a spectrum on which they can be placed alongside VR. Milgram and Kishino developed the *reality-virtuality continuum* which they first introduced in 1994 [6] as a theory to explain AR, MR and VR, and their relationship to each other. The continuum, visualised in Figure 1.3, shows two extrema, the real world, where nothing is virtual or augmented and everything is "real", and the virtual world, i.e. VR, where the inverse is true and everything is virtual. In between, they placed Augmented Reality as the real world to which virtual aspects are added, and Augmented Virtuality (AV) as the virtual world to which real aspects are added. Everything between the real world and VR, excluding those, is called MR. This definition states that "VR is not part of MR and AR is only a subset of MR" [7]. These definitions formulated by this continuum have been questioned in other papers [7]. More recently, eXtended Reality

Figure 1.2: The Sensorama, invented by Morton Heilig in 1957, is considered as the first actual device to offer an immersive experience. It was designed to create the sensation of being "in" a movie while watching it.

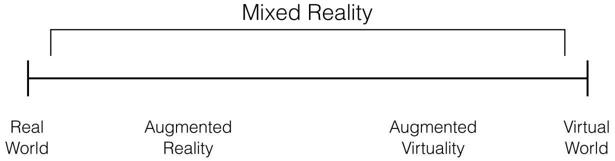

Figure 1.3: The mixed reality continuum, presented by Milgram, provides definition for AR, AV, and MR [6].

(XR) emerged as an umbrella term covering all of these technologies [8].

Currently, VR technology may refer to a wide range technologies that provide a VR experience. A first distinction can be made between the use of dedicated VR goggles (cfr. HMD) or more traditional displays and projectors. A VR CAVE [9] is such an example of VR without goggles in which virtual imagery is projected on the wall of a room, possibly with image transformation to account for the users position. A second distinction is made in the capturing, and delivery of the VR content. The most traditional VR content are Computer-Generated Imagery (CGI), a computer system will render all content in realtime. Another, well established media type is 360 degree video [10]. A special camera which captures images in every direction of its position is used to record video. This video can be viewed using HMDs by projecting the content on the inside of a virtual sphere. Other, more advanced methods, to capture more information from the surrounding in order to provide more realistic representations in VR. For example, 3D-cameras and LIDAR capture volumetric media, often in the form of point clouds [11], which preserve the positional information of objects as

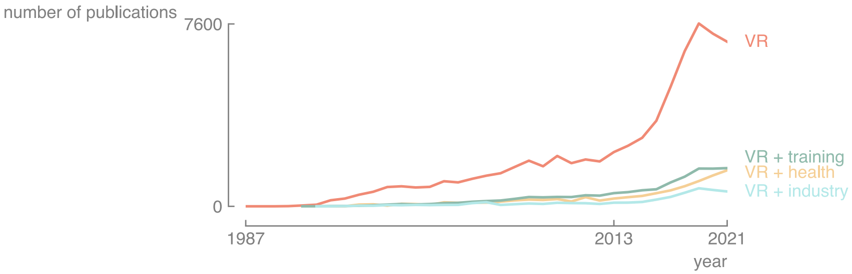

Figure 1.4: The number of publications found on Web of Science on the topics of VR and VR in combination with health, training, or industry, have seen an exponential increase in the last decade.

well, or light field technology [12] which captures light rays in a similar way as they are captured in the human eye.

Throughout the years, it was mainly the entertainment industry that brought the concept of VR to the wider public, with movies such as Tron and The Matrix, and gaming companies like Sega and Nintendo. However, it is clear that even from the beginning of the VR research area, also other industries and sector were interested in the technology. Research was done on military applications [13–15] and healthcare applications [16, 17] and even NASA conducted research with the technology [18].

The interest in VR technology is clearly visible when considering the number of publications on the topic. Since the early 1990s, publication on Virtual Reality have started to appear in increasing numbers. Around 2013, this turned into an exponential trend with the release of the first affordable, consumer grade HMD, the Oculus Rift [19]. These trends are also noticeable in many domains that have tried to incorporate VR such as health, training and industry. The findings are visualised in Figure 1.4 based on the number of publications found on Web of Science for the search query "virtual reality", "virtual reality AND health", "virtual reality AND training", and "virtual reality AND industry". It is assumed that in general this trend is mainly driven by the reduction in cost and the progress in innovation of the hardware.

1.2 Attributes of Virtual Reality

The attention for VR technology is not surprising considering what it has to offer. Its most important attributes are the immersion and sense of presence it provides, the ability to learn in VR environments, the flexibility of and control over the environments, the ability to collect data of the user and the enjoyment it can bring.

The first aspect, is the direct consequence of the technology that VR is build on, namely the *immersion* that it provides. Immersion is rather a technology based term and is defined as: "the use of immersive technologies". In this definition, immersive technologies are anything that stimulates the human sensory system in an artificial manner. The level of immersion is thus influenced by the realism of the stimulation and the range of sensor modalities that are stimulated. The HMD used for VR provides significant immersion focussed on the vision system [20, 21].

A second property of VR that is often falsely interchanged for immersion is *presence*. A *sense of presence* occurs in an immersive VR environment when the brain and nervous system of the user behave in a similar way as in the same situation in the real world. The brain gets tricked just enough into thinking that the environment is real. An extension to this is *telepresence*, in which the user has an experience as if they were in a different location. This ability to virtual transport to different locations is perhaps the essence of VR [20, 21].

Because of the sense of presence, and because the brain reacts in a similar way as in the real world, we can *learn* in VR. Skills can be acquired and refined through repetition of examples, guidance and feedback on their actions just as in real life, and sometimes even better. The aim is of course that skill acquisition in VR can be *transferred* to real world situations, i.e. skills taught in VR can be used and applied in the real world [20, 22].

The environment that a user sees when they enter a VR world is called the Virtual Environment (VE). It is created by the designer of the environment, and VR technology allows the user to see and experience it. The content of a VE is created with modern tools for 3D-modelling, animating and scripting. This offers a great *flexibility* to VR, as anything can be created within the constraints of the tools. This still means that even situations that are not possible in the real world can be created in the virtual world. Additionally, environments do not have to be static, but can be dynamically manipulated while the users are in them. There is, at all times, *full control* over the behaviour and shape of the virtual world [21].

VR technology is very flexible which makes it possible to combine it with a plethora of *(external) instruments* for measuring and recording data of the user. Current VR technology even already includes sensors that can be exploited to record behaviour of the users, e.g. gyroscope, accelerometer and eye tracking in a HMD. By collecting as much data about the users while in a VE, more insigths can be gathered of the users behaviour to better understand and help them [21].

Finally, it cannot be underestimated that VR adds an element of *enjoyment*. Because of the great freedom and flexibility, boring and uninteresting task can be transformed into engaging and enjoyable activities. This eventually leads to increased attention [21, 23].

1.3 Virtual Reality in Healthcare

Many have tried to give one complete and general definition of health [24, 25], none have really succeeded [26]. Each definition has at one point been criticised, including the definition proposed by the World Health Organisation (WHO), or as Daniel Callahan puts it so beautifully, "[...] one of the grandest games is that version of king-of-the-hill where the aim of all players is to upset the WHO definition of *health*" [26]. That definition is: "Health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". The WHO definition does make clear that health is about more than just curing diseases, it encompasses well-being of individuals on physical, mental and social aspects as well. Tools and methods to improve this well-being have been widely researched, and with the increasing popularity of digitalisation the domain of eHealth has emerged from this. eHealth, or electronic healthcare, can be defined as the use of digital innovation and information technology in healthcare application [27].

Electronic healthcare is a very relevant application domain with high societal impact. However, to better understand why it was chosen as the main application domain in this PhD, first its needs and challenges need to be investigated. Next, the characteristics of VR can be discussed in the context of eHealth.

1.3.1 The Needs of eHealth

In 2019, the proportion of people on a waiting lists in the European Union was 19.4% of the people in need of health care [28]. At the same time, studies are reporting an increasing number of medical consultations and a decreasing in clinical capacity [27]. Furthermore, the number of patients presented with multimorbidity is also increasing [29]. It is needless to state that providing qualitative healthcare is getting more complex every year. eHealth solutions are attempting to support Health Care Professionals (HCPs) in more efficient ways than was possible before, for example, by presenting data in ways that makes it easier to interpret. Clearly, new opportunities, challenges and needs arise.

Creating useful and usable applications is not a trivial task, especially in healthcare which is a complex and fragile environment. Some of the challenges involved are the wide range of actors, the complexity of healthcare ecosystems and the cultural background and context in which the eHealth solution needs to operate. Health care is an activity involving multiple stakeholders. The patient is of course at the centre, which is accompanied by a HCP. However, the patient is also surrounded by friends and family, which sometimes take up the role as informal caregiver [30]. Each one is an actor in the envisioned eHealth application and everyone of them serves an important role in the treatment process. Therefore, it is necessary to understand the role and function of each actor and the interactions between them. The functionality of the solution should be tailored to the needs and wished of each actor in the system. This leads to another challenge, an eHealth system entails more than one single application, in most cases it is an ecosystem of multiple applications, for multiple actors, interacting with multiple instance [31]. All of these applications are interconnected by exchanging information. In some cases, an ecosystem already exists for which a new eHealth application needs to be designed and integrated, e.g. when a new digital tool is being designed to support with an existing treatment. In each case, understanding the ecosystem is very important to design appropriate eHealth solutions that can be put in practice. Also cultural and contextual differences, e.g. religion, language, and perception of emotions [32], play an important factor in the design process [33]. What works in one context might not work in another. The organisation of healthcare differs from region to region, therefore, the design of eHealth applications or ecosystems should be appropriately adapted. Identifying this context and understanding what it means for the eHealth solution in necessary.

These challenges indicated that a plethora of knowledge about the domain and context of the system and the needs of the end users is needed to achieve good eHealth solutions. However, this knowledge is seldom readily available to the designers of the system. In some cases, findings from literature can be used but in most cases it are the end users that hold the required knowledge. That is why researchers in the 70s already started investigating the role of end users in the design process [34]. In the United States, *user-centred design* was introduced, which focussed primarily on observing end users in their current activities and asking them for feedback on concepts created by the designer [34]. Simultaneously, researchers in Northern European countries recognised the role of the end user in the early design phases as well and included them in the ideation and conceptualisation of new products along side the designer. This approach is termed *participatory design* and motivates end users to participate in the creation process as opposed to merely being observed by the researchers, i.e. user-centred design [34]. In the last decades, interactions between these two approaches have been explored resulting in a landscape with many design approaches involving the end users. Sanders visualised the landscape of human-centred design research in Figure 1.5 [35]. The characterising factors of each method are the roles of the user, the researcher and the designer, these are projected on two axes. On one end, the user is a subject which is observed by the designer of the researcher. On the other end, the user is actively participating in the process. Approaches driven by researchers rely on techniques and tools introduced from research while approaches driven by designers rely on design techniques from their perspective.

As the eHealth systems become more complex, it is of utmost importance to have a vast understanding of their objective. Participatory design approaches are crucial for this [36]. The co-design method can be of great value, as it engages the end users and other actors, e.g. family and friends, in the design process [37]. By allowing every stakeholder to contribute to the requirements of a system, we can focus on building the system that they would actually use.

Studies have shown that personalised treatments are more effective than one-size-fits-all approaches [38]. Personalisation is aimed at better understanding how an individual responds to treatment and providing a tailored plan based on that understand-

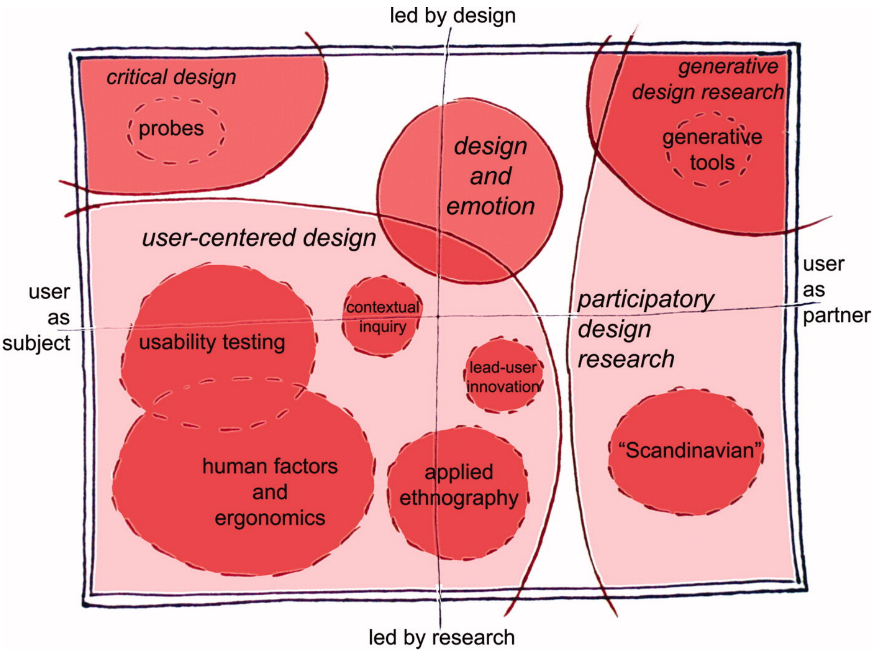

Figure 1.5: The landscape of human-centred design research. Image used from [35]

ing. Important for this approach is to have good models of treatment which often rely on a lot of data and/or knowledge. The application of personalised treatment goes hand in hand with the patient-centred philosophy.

Research has provided evidence that self-management and patient empowerment have a positive impact on care practices [39–41]. This is done by providing patients the tools to make informed decisions about their own treatment and to apply what they have learned in sessions with medical professionals. Therefore, self-management goes well with a blended-care approach, this method combines face-to-face sessions with eHealth tools [42] that can be used at home.

To accomplish personalised treatments and enable patient empowerment, fine grained feedback is required. The HCP should know how the patient is progressing, for example by knowing which aspects are going well and which are not. That way, an individualised approach to the treatment becomes possible. To the patient, detailed feedback is also relevant. They can learn from their own behaviour by understanding what they are doing right. Therefore, it can provide them with the right motivation to stay engaged with their treatment.

To conclude, when creating new eHealth solutions, extra attention should be given to a few aspects. First, new solutions should be created in close collaboration with the end users of the system. They help in generating new ideas that are in line with their expectations and the needs of the context in which they operate. Second, there does not exist a one-size-fits-all approach in healthcare. Therefore, personalised treatments should be explored as much as possible in new eHealth solutions. Third, eHealth should empower patients to invest the required time and effort into their treatment and provide the tools for self-management wherever it is possible. Forth, fine grained feedback of how the patient is doing is required to enable a personalised treatment and provide patients with the insights to self-manage their treatment. eHealth should facilitate this feedback collection as mush as possible.

1.3.2 Virtual Reality in Mental Health and Rehabilitation

Anxiety disorders are ranked 6th on the list of largest contributors to global disability by WHO [43]. Together with depression, it is one of the most prevalent health issues in the world. Anxiety disorders are a collection of mental disorders in which feelings of anxiety and fear are the main characteristics [43]. Mental disorders can, amongst others, be treated with various forms of Cognitive Behavioural Therapy (CBT).

For many other health conditions such as diseases, injuries and traumas, rehabilitation is part of the advised treatment. Rehabilitation aims at reducing disability in patients in interacting with their environment [44]. This can be for disability in, amongst others, mobility, vision or cognition. As stated by the WHO [45], 75% of the Years Lived with Disability (YLDs) of the worldwide population are caused by health conditions which can be treated with rehabilitation. Furthermore, as the population is ageing and the prevalence of noncommunicable diseases increases, the need for rehabilitation close to home will rise [44].

It has been shown that VR technology can be of great value in mental health therapy [46] and rehabilitation [47]. Specifically, many mental disorders rely on therapy that involves cognitive behavioural change. This means that new behaviour needs to be learned by the patient. Also rehabilitation therapy consists of learning and training of sensory-motor skills. It is exactly for learning in specific situations that VR technology shows a lot of potential. The main benefits of VR for mental health treatment and rehabilitation are time and cost efficiency, the possibility for treatment at home, extensive personalisation opportunities and easier feedback collection.

The immersion and sense of presence of VR allows the user to be completely submerged in an environment that is designed for treatment. The immersive technology allows to control which stimuli the user is exposed to, by blocking out reality and simulating a controllable virtual world. Due to the sense of presence, the users can learn in VR, by mimicking real life situations. The user can then transfer the skills they learned in VR to real life situations, e.g. certain motions with their upper limbs or specific behaviour in stressful situations.

The flexibility of VEs allows for situations to be created that are dangerous, expensive, uncommon or even impossible in real life [21]. The configuration of these situations is paramount for the therapy. Without the flexibility to virtually recreate situations, some therapies would be overly expensive, e.g. chartering a plane to overcome a fear of flying, or impossible, e.g. exercising upper limbs by playing a game in which mini dragons are caught. Furthermore, situations that are rare in real life but require to be experienced repeatedly by the patient can easily be created. Because of the flexibility, treatment in VR can be made more time and cost efficient, especially as every treatment scenario can be created at the office of HCP. This aspect also enables treatment at home as the patient can take the VR googles with them and experience the same VE from anywhere.

The full control over the VE at all times, means that the situation can be adapted to the needs of the user. This allows for real-time personalisation of VEs. Personalised treatment is important in mental health, e.g. in the treatment of anxiety disorders [48], as well as for rehabilitation [49]. Personalisation depends on a fine-grained feedback of how the patient is responding to the treatment. Collecting this feedback becomes easier with to VR technology. Information about the users behaviour in VR can be extract from the VR hardware itself. It can also be extended with *external instruments* to collect even more information of the patient's response to the treatment.

1.4 Pitfalls of Virtual Reality

For all the benefits that VR has to offer in eHealth applications, there are also a few risks involved in using the technology. The main pitfalls to look out for are, cybersickness, potential high cost of specialist hardware, and complexity of tools that could required high proficiency with digital technology.

A commonly known side effect of using VR is cybersickness, which is motion sickness induced by VR. Some earlier studies showed that 30-80% of the population was affected by it [50, 51]. More recent results indicate that 25-60% get cybersickness in VR. This led to the conclusion that improvements in hardware already reduce its impact [52]. At the same time much research is going on to reduce cybersickness [53–55]. However, the issue still remains significant, especially in the context of healthcare, where treatment should be safe and effective.

Second, while VR technology has seen a significant reduction in cost in recent years [56], the total cost of a consumer system still cannot be overlooked. In the early 1990s a HMD was commercially available for $49K [57]. Today, high-end HMDs can be bought for prices starting at $599[1]. However, the use of the goggles still requires an investment of approximately $1K for a capable computer system. For home use, this investment is a significant threshold which could prevent the technology from being adopted. The introduction of cheaper, low-end VR hardware has tried tackling

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[1] https://www.theverge.com/a/best-vr-headset-oculus-rift-samsung-gear-htc-vive-virtual-reality, accessed on 01/03/2022

this problem by making a tradeoff between price and the quality of the technology (e.g. smaller field of view, less accurate tracking, or lower display resolutions).

Third, using eHealth applications often requires some degree of proficiency with digital technology [27]. For example, the design and configuration of a VE can be complex without the appropriate tools. Both for patient and HCP it can be a significant threshold to incorporate overly complex eHealth solutions into the treatment. However, reviews suggest that eHealth has the potential to both increase and decrease health inequality [27]. By including the most vulnerable groups in the co-design process, applications can be tailored to their level of proficiency. Likewise, by listening to what HCPs need for their practice, solutions can be developed that actually support them without requiring extensive technical expertise of how to use the system.

These risks warrant extra careful consideration when researching the application of VR technology in healthcare.

1.5 Open Challenges & Overall Goal

From the previous sections, it should be clear that there are still many open challenges in the application of VR in the eHealth domain. Some of these challenges are summarised below:

Challenge 1: Assessment Personalisation depends on a good understanding of how the patient responds to the treatment, regardless of whether the personalisation is provided by the HCP or an intelligent system [58]. Therefore, automatic assessment of tasks and learning can be a very effective first step in reaching personalisation. However, it has not been fully exploited yet in many studies. Automatic assessment has the advantages that it can perform quantitative and standardised tests, it has the possibility of measuring parameters currently left uncollected, and the assessment can be performed on a much higher resolution leading to more fine-grained insights [47].

Challenge 2: Personalisation While the advantages of, and need for personalisation of VEs are well established and agreed upon [38, 48, 49, 59], it has trouble getting adopted in mainstream applications. In part this is due to the high complexity of the situations in which personalisation is most beneficial. Research is needed on personalisation techniques for various applications domains in eHealth, with a focus on complex systems and more robustness.

Challenge 3: Patient-centred platforms There is a need for large scale, patient-centred platforms, providing VR-based treatment in which all stakeholders are included. However, the role of stakeholders, such as the health care providers, also needs to be considered in the design of such platforms. The purpose of such platforms should be to connect the stakeholders (e.g. patient and therapist) without becoming a barrier that separates them. Thus, for VR to be really included in existing protocols and treatment, we need studies of good examples where the platform provides the required support to all stakeholders and assists them in their tasks.

Challenge 4: Expertise driven development Because the VR domain is currently seeing significant technological innovations in terms of hardware and software, many of the recent studies with VR have been driven by the technology [60]. Instead we need to focus more on an expertise driven design for new systems and studies where the VR technology is viewed as the provider of the medium and the tools. This requires co-design processes in which the goals and knowledge of health care domain experts is used as drivers for the design of new system. The focus should be on applying existing, evidence-based treatments in VR environments and exploring new ways of treatment that were not possible before.

Challenge 5: Co-design The collaboration of computer scientists and experts from different domains such as healthcare can only be encouraged. However, the technical expertise and proficiency of HCPs and end users has to be considered as well in order for VR technology to be adopted in large scale studies and mainstream therapy [60]. When the required technical knowledge supersedes the capabilities of the target group, the VR solutions become obsolete. Therefore, the technology should always be easy to use and support the user in their task.

The overall goal of this dissertation is to investigate how VR technology can be applied in eHealth applications, beyond the naive and straightforward translation of existing solutions to VR. The aim is to enhance eHealth solutions by using VR as a tool.

1.6 Main Research Contributions

This PhD dissertation contributes to the research domains of VR technology, eHealth, and personalisation. The use cases in this research are chosen from the mental health and rehabilitation domains. The presented research challenges and goals in Section 1.5 are tackled in the following three contributions:

Contribution 1: The design, development and testing of a new therapy tool for Unilateral Spatial Neglect (USN) with VR. This new approach improves on existing therapy by incorporating multiple sensory modalities. In addition to the visual aspects of CGI VR content, also spatial audio is included. This is done by applying Music Neglect Therapy (MNT), an approach that has seen positive effects in other forms of therapy. This research is the first documented case in which music therapy is used in VR. The use of VR is very important because of its immersive characteristics, it is able to stimulate the patient on the visual and auditory spectrum while blocking them from other external, non-intended, distractions. Furthermore, in this research, continuous automatic assessment is performed by making use of sensor data from internal sensors of the HMD hardware, specifically head movement, and feeding it back to the therapist. This approach allows for a cheap way of extracting new insights on the patients behaviour that would otherwise be much more complicated.

Contribution 2: The design, development and testing of relaxation therapy in VR including automatic adaptations to the emotional state of the user. The use of VR technology and CGI content allows the user to be completely submerge in a tranquil and relaxing environment, away from real world distractions. Additionally, total control of the VE is required in order to adapt it to the current needs of the user. The personalisation of the therapy relies on the emotional state of the user. The challenges of detecting or measuring emotional conditions is mitigated by following a predictive approach through a mathematical model built on theoretical foundations. The model assumes user profile and changes in the environment to update the predictions of the emotional state. Eventually, the VE is adapted using a heuristic optimiser for determining the appropriate environment changes based on the emotional condition. Furthermore, this research aims to empower users by giving them the tools to support their own health through a VR application. The user is put at the centre of the design process and the resulting application by alleviating the need for a trained therapist therapist.

Contribution 3: The design, development and testing of a patient-centred platform for Virtual Reality Exposure Therapy (VRET) with longitudinal follow up and homework exercises through a mobile coaching app. This research was part of an interdisciplinary project, called PATRONUS, involving psychotherapists, computer scientists, communication scientists, VR developers and secure cloud system specialists. The platform developed in the PATRONUS project formed the central support tool for psychotherapists to provide gradual exposure therapy to patients in VR, through CGI content, and in vivo, through real life situations. The support to the therapists was enhanced by incorporating an intelligent system that provided suggestions for personalised configurations of the VE used for the therapy. Specifically, the configurations are adapted to the therapeutic needs of the patients and aim to maximise the learning of the patient in the VE. By providing this support to the therapist, no extended technical proficiency is required to use the VR tool. The knowledge used to power the adaptions is managed through semantic technology.

1.7 Outline

This dissertation is composed of a number of publications that were realised within the scope of this PhD. The selected publications provide an integral and consistent

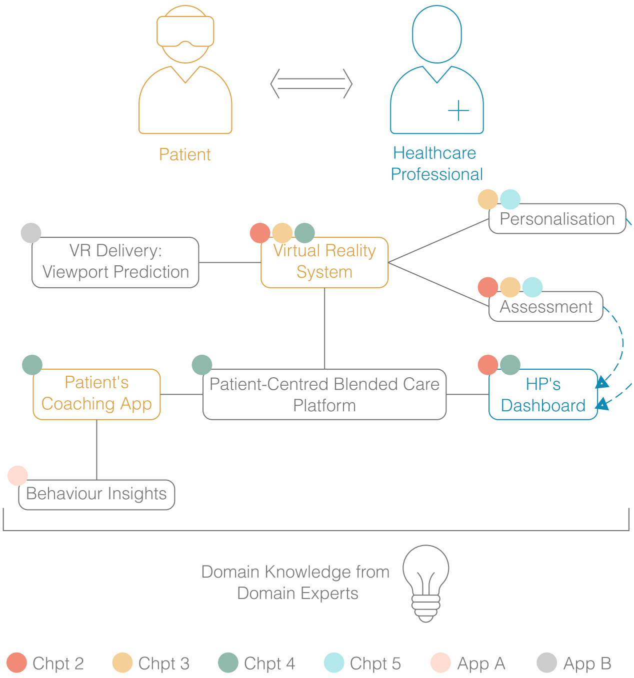

Figure 1.6: Schematic position of the different chapters in this dissertation.

overview of the work performed. The complete list of peer-reviewed publications that resulted from this work is presented in Section 1.8.

Within this section we give an overview of the remainder of this dissertation and explain how the different chapters are linked together. Figure 1.6 positions the different contributions that are presented in each chapter (Chpt) and appendix (App).

In **Chapter 2** a VR application is presented for the treatment of spatial neglect through music therapy. The patient, wearing an HMD experiences exercises in the VE developed for this use case. An assessment module performs continuous evaluation of the user by recording head rotation from the internal sensors of the HMD. The information from this assessment is presented on a dashboard application for the HCP providing the therapy. The presented approach provides a tool that aims to improve on existing therapy by using VR and by giving more insights to the health care practitioner.

In **Chapter 3** a VR application is presented focussed on providing relaxation therapy. This application presents a method of personalising the relaxation experience based on the emotional state of the user. To make the personalisation possible, a mathematical model is designed and implemented that makes an assessment of the current emotional state by making prediction based on user profile and changes in the VE. This application provides a self-management tool for the user as the system is semi-autonomous and intended for use at home.

The platform introduced in **Chapter 4** is the result of the PATRONUS project in which a patient-centred blended care solution for VRET is designed, developed and tested. The project was an interdisciplinary endeavour between psychotherapists, computer scientists, communication scientists, VR developers and secure cloud system specialists. In this chapter the architecture of this platform is described, it includes: a VR system for the presentation of two VE scenarios, personalised adaptation to these VEs based on the needs of the patient, a central system for data management and control, a coaching app for the patient through which longitudinal follow-ups and homework exercises are possible, and a dashboard application for the therapist through which they can monitor and manage VR session. The adaptation algorithm that enables the personalisation of the VE for VRET is discussed in detail in **Chapter 5**. The personalisation algorithm provides support to the therapist by presenting suggestions for the next exercise on the dashboard. The therapist can then choose which suggestion of the algorithm to use. The information used by the algorithm is a combination of self-assessments of the patient and domain knowledge. In **Chapter 5**, the use of semantic technology is described for the management of this knowledge and information.

Appendix A presents an extension to the coaching app in the PATRONUS platform. This extensions analyses usage data of the mobile app to gain better understanding of the patient. By identifying patterns, different types of usages were distinguished that help therapists in providing better follow-up treatment.

Finally, **Appendix B** investigates, on a more technical level, how VR experiences can be delivered with higher quality. Specifically, this research focuses on the challenge of viewport prediction for streaming VR content. By predicting the direction a user will look at, streaming protocols can be optimised to provide better Quality of Experience (QoE). Multi-armed bandits were used to learn the behaviour of users and make better predictions.

Every VR application and intelligent component is designed with the input of domain experts and/or domain knowledge. Wherever possible, an inclusive approach was followed where input from patients and HCPs was taken into account.

Table 1.1 shows the challenges that were highlighted in Section 1.5 and indicates which were targeted per chapter.

1.8 Publications

The research results obtained during this PhD research have been published in scientific journals and presented at a series of international conferences. The following list provides an overview of the publications during my PhD research.

Table 1.1: An overview of the challenges tackled per chapter in this dissertation.

	Chpt. 2	Chpt. 3	Chpt. 4	Chpt. 5
Challenge 1	●			
Challenge 2		●		●
Challenge 3			●	
Challenge 4	●	●	●	●
Challenge 5	●	●	●	●

1.8.1 Publications in International Journals (listed in the Science Citation Index [2])

1. **Joris Heyse**, Maria Torres Vega, Thomas De Jonge, Femke De Backere, and Filip De Turck, *A Personalised Emotion-Based Model for Relaxation in Virtual Reality*, Published in Applied Sciences, Volume 10, Issue 17, September 2020.

2. Sam Van Damme, Maria Torres Vega, **Joris Heyse**, Femke De Backere, and Filip De Turck, *A low-complexity psychometric curve-fitting approach for the objective quality assessment of streamed game videos*, Published in Signal Processing: Image Communication, Volume 88, Issue 1, October 2020.

3. **Joris Heyse**[3], Stéphanie Carlier[3], Ewoud Verhelst, Catharine Vander Linden, Femke De Backere, and Filip De Turck, *From Patient to Musician: A Multi-Sensory Virtual Reality Rehabilitation Tool for Spatial Neglect*, Published in Applied Sciences, Volume 12, Issue 3, January 2022.

4. **Joris Heyse**, Barbara Depreeuw, Tom Van Daele, Tine Daeseleire, Femke Ongenae, Femke De Backere, and Filip De Turck, *An Adaptation Algorithm for Personalised Virtual Reality Exposure Therapy*, Revision submitted to Computer Methods and Programs in Biomedicine, March 2022.

5. **Joris Heyse**, Klaas Bombeke, Anissa All, Bernard François, Steven Thys, Pat Van Roey, Michael Van der Vloedt, Barbara Depreeuw, Tom Van Daele, Tine Daeseleire, Femke Ongenae, Femke De Backere, and Filip De Turck, *PATRONUS: Towards an Architecture for Personalised Virtual Reality Exposure Therapy*, Manuscript submitted to Expert Systems with Applications, April 2022.

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[2] The publications listed are recognised as 'A1 publications', according to the following definition used by Ghent University: A1 publications are articles listed in the Science Citation Index Expanded, the Social Science Citation Index or the Arts and Humanities Citation Index of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper.

[3] The first two authors share co-first authorship of this work.

1.8.2 Publications in International Conferences (listed in the Science Citation Index [4])

1. **Joris Heyse**, Maria Torres Vega, Tim Wauters, Femke De Backere, and Filip De Turck, *Effects of Adaptive Streaming Optimizations on the Perception of 360° Virtual Reality Video*, Published in proceedings of the 30th International Teletraffic Congress (ITC 30), IEEE, Vienna, Austria, pages 89–92, September 2018.

2. **Joris Heyse**, *[DC] Self-Adaptive Technologies for Immersive Trainings*, Published in proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces (VR), IEEE, Osaka, Japan, pages 1381–1382, March 2019.

3. **Joris Heyse**, Maria Torres Vega, Femke De Backere, and Filip De Turck, *Contextual Bandit Learning-Based Viewport Prediction for 360 Video*, Published in proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces (VR), IEEE, Osaka, Japan, pages 972–973, March 2019.

4. **Joris Heyse**, Thomas De Jonge, Maria Torres Vega, Femke De Backere, and Filip De Turck, *A personalized Virtual Reality Experience for Relaxation Therapy*, Published in proceedings of the Eleventh International Conference on Quality of Multimedia Experience (QoMEX), IEEE, Berlin, Germany, June 2019.

5. Maria Torres Vega, Jeroen van der Hooft, **Joris Heyse**, Femke De Backere, Tim Wauters, Filip De Turck, and Stefano Petrangeli, *Exploring New York in 8K: an adaptive tile-based virtual reality video streaming experience*, Published in proceedings of the 10th ACM Multimedia Systems Conference, ACM, Amherst, Massachusetts, USA, pages 330–333, June 2019.

6. Sam Van Damme, **Joris Heyse**, Femke De Backere, Maria Torres Vega and Filip De Turck. *Effects of Haptic Feedback on User Perception and Performance in Projected Augmented Reality*, Submitted to the 14th International Conference on Quality of Multimedia Experience (QoMEX), IEEE, Lippstadt, Germany, September 2022.

1.8.3 Publications in other International Conferences

1. **Joris Heyse**, Femke Ongenae, Femke De Backere, and Filip De Turck, *Personalisation of Exercises in VRET*, Published in proceeding of the Artificial Intelligence Applied to Assistive Technologies and Smart Environments Workshop at the

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[4] The publications listed are recognised as 'P1 publications', according to the following definition used by Ghent University: P1 publications are proceedings listed in the Conference Proceedings Citation Index - Science or Conference Proceedings Citation Index - Social Science and Humanities of the ISI Web of Science, restricted to contributions listed as article, review, letter, note or proceedings paper, except for publications that are classified as A1.

Thirty-Second AAAI Conference on Artificial Intelligence, AAAI, New Orleans, USA, pages 141–144, February 2018.

2. **Joris Heyse**, Femke Ongenae, Jolien De Letter, Anissa All, Femke De Backere, and Filip De Turck, *Design of an Ontology for Decision Support in VR Exposure Therapy*, Published in proceedings of the 13th EAI International Conference on Pervasive Computing Technologies for Healthcare - Demos and Posters, EAI, Trento, Italy, May 2019.

3. **Joris Heyse**, Gilles Vandewiele, Femke Ongenae, Femke De Backere, and Filip De Turck, *How do Users interact with Mobile Health Apps?: A Markov Chain Analysis*, Published in proceedings of the 14th EAI International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth), ACM, Atlanta, Georgia, USA, pages 255–258, May 2020.

References

[1] S. G. Weinbaum. *Pygmalion's spectacles.* Start Publishing LLC, Lanham, 2016. OCLC: 953832758. Available from: http://rbdigital.oneclickdigital.com.

[2] M. L. Heilig. *Sensorama simulator*, August 1962.

[3] M. I. Berkman. *History of Virtual Reality.* In N. Lee, editor, Encyclopedia of Computer Graphics and Games, pages 1–9. Springer International Publishing, Cham, 2018. Available from: http://link.springer.com/10.1007/978-3-319-08234-9_169-1, doi:10.1007/978-3-319-08234-9_169-1.

[4] I. E. Sutherland. *A head-mounted three dimensional display.* In Proceedings of the December 9-11, 1968, fall joint computer conference, part I on - AFIPS '68 (Fall, part I), pages 757—764, San Francisco, California, 1968. ACM Press. Available from: http://portal.acm.org/citation.cfm?doid=1476589.1476686, doi:10.1145/1476589.1476686.

[5] J. Steuer. *Defining Virtual Reality: Dimensions Determining Telepresence.* Journal of Communication, 42(4):73–93, December 1992. Available from: https://academic.oup.com/joc/article/42/4/73-93/4210117, doi:10.1111/j.1460-2466.1992.tb00812.x.

[6] P. Milgram and F. Kishino. *A Taxonomy of Mixed Reality Visual Displays.* IEICE TRANSACTIONS on Information and Systems, 77(12):1321–1329, 1994.

[7] M. Speicher, B. D. Hall, and M. Nebeling. *What is Mixed Reality?* In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pages 1–15, Glasgow Scotland Uk, May 2019. ACM. Available from: https://dl.acm.org/doi/10.1145/3290605.3300767, doi:10.1145/3290605.3300767.

[8] S. Mann, T. Furness, Y. Yuan, J. Iorio, and Z. Wang. *All Reality: Virtual, Augmented, Mixed (X), Mediated (X,Y), and Multimediated Reality.* arXiv:1804.08386 [cs], April 2018. arXiv: 1804.08386. Available from: http://arxiv.org/abs/1804.08386.

[9] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti. *Surround-screen projection-based virtual reality: the design and implementation of the CAVE.* In Proceedings of the 20th annual conference on Computer graphics and interactive techniques, pages 135–142, 1993.

[10] W. Lo, C. Fan, J. Lee, C. Huang, K. Chen, and C. Hsu. *360° Video Viewing Dataset in Head-Mounted Virtual Reality.* Technical report, June 2016. Type: dataset. Available from: https://dl.acm.org/do/10.1145/3192927/abs/, doi:10.1145/3192927.

[11] D. Bolkas, J. Chiampi, J. Chapman, and V. F. Pavill. *Creating a virtual reality environment with a fusion of sUAS and TLS point-clouds.* International Journal of Image and Data Fusion, 11(2):136–161, April 2020. Available from: https://www.tandfonline.com/doi/full/10.1080/19479832.2020.1716861, doi:10.1080/19479832.2020.1716861.

[12] J. Yu. *A Light-Field Journey to Virtual Reality.* IEEE MultiMedia, 24(2):104–112, April 2017. Available from: http://ieeexplore.ieee.org/document/7924239/, doi:10.1109/MMUL.2017.24.

[13] T. A. Furness. *The Super Cockpit and its Human Factors Challenges.* Proceedings of the Human Factors Society Annual Meeting, 30(1):48–52, September 1986. Available from: http://journals.sagepub.com/doi/10.1177/154193128603000112, doi:10.1177/154193128603000112.

[14] M. Moshell. *Three views of virtual reality: virtual environments in the US military.* Computer, 26(2):81–82, February 1993. Available from: http://ieeexplore.ieee.org/document/192003/, doi:10.1109/2.192003.

[15] R. M. Satava. *Virtual reality and telepresence for military medicine.* Computers in Biology and Medicine, 25(2):229–236, March 1995. Available from: https://linkinghub.elsevier.com/retrieve/pii/001048259400006C, doi:10.1016/0010-4825(94)00006-C.

[16] D. Ota, B. Loftin, T. Saito, R. Lea, and J. Keller. *Virtual reality in surgical education.* Computers in Biology and Medicine, 25(2):127–137, March 1995. Available from: https://linkinghub.elsevier.com/retrieve/pii/001048259400009F, doi:10.1016/0010-4825(94)00009-F.

[17] K. Stanney. *Realizing the full potential of virtual reality: human factors issues that could stand in the way.* In Proceedings Virtual Reality Annual International Symposium '95, pages 28–34, Research Triangle Park, NC, USA, 1995. IEEE Comput. Soc. Press. Available from: http://ieeexplore.ieee.org/document/512476/, doi:10.1109/VRAIS.1995.512476.

[18] J. P. Hale. *Applied virtual reality research and applications at NASA/Marshall space flight center.* In Advances in Human Factors/Ergonomics, volume 20, pages 523–528. Elsevier, 1995. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0921264706800857, doi:10.1016/S0921-2647(06)80085-7.

[19] P. R. Desai, P. N. Desai, K. D. Ajmera, and K. Mehta. *A Review Paper on Oculus Rift-A Virtual Reality Headset.* arXiv:1408.1173 [cs], August 2014. arXiv: 1408.1173. Available from: http://arxiv.org/abs/1408.1173.

[20] L. Jensen and F. Konradsen. *A review of the use of virtual reality head-mounted displays in education and training.* Education and Information Technologies, 23(4):1515–1529, July 2018. Available from: http://link.springer.com/10.1007/s10639-017-9676-0, doi:10.1007/s10639-017-9676-0.

[21] G. Tieri, G. Morone, S. Paolucci, and M. Iosa. *Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies.* Expert Review of Medical Devices, 15(2):107–117, February 2018. Available from: https://www.tandfonline.com/doi/full/10.1080/17434440.2018.1425613, doi:10.1080/17434440.2018.1425613.

[22] B. Xie, H. Liu, R. Alghofaili, Y. Zhang, Y. Jiang, F. D. Lobo, C. Li, W. Li, H. Huang, M. Akdere, C. Mousas, and L.-F. Yu. *A Review on Virtual Reality Skill Training Applications.* Frontiers in Virtual Reality, 2:645153, April 2021. Available from: https://www.frontiersin.org/articles/10.3389/frvir.2021.645153/full, doi:10.3389/frvir.2021.645153.

[23] D. Cano Porras, P. Siemonsma, R. Inzelberg, G. Zeilig, and M. Plotnik. *Advantages of virtual reality in the rehabilitation of balance and gait: Systematic review.* Neurology, 90(22):1017–1025, May 2018. Available from: https://www.neurology.org/lookup/doi/10.1212/WNL.0000000000005603, doi:10.1212/WNL.0000000000005603.

[24] F. Leonardi. *The Definition of Health: Towards New Perspectives.* International Journal of Health Services, 48(4):735–748, October 2018. Available from: http://journals.sagepub.com/doi/10.1177/0020731418782653, doi:10.1177/0020731418782653.

[25] H. Lerner. *A critical analysis of definitions of health as balance in a One Health perspective.* Medicine, Health Care and Philosophy, 22(3):453–461, September 2019. Available from: http://link.springer.com/10.1007/s11019-018-09884-1, doi:10.1007/s11019-018-09884-1.

[26] D. Callahan. *The WHO Definition of 'Health'.* The Hastings Center Studies, 1(3):77–87, 1973. Publisher: The Hastings Center. Available from: http://www.jstor.org/stable/3527467, doi:10.2307/3527467.

[27] R. M. van der Kleij, M. J. Kasteleyn, E. Meijer, T. N. Bonten, E. J. Houwink, M. Teichert, S. van Luenen, R. Vedanthan, A. Evers, J. Car, H. Pinnock, and N. H. Chavannes. *SERIES: eHealth in primary care. Part 1: Concepts, conditions and challenges.* European Journal of General Practice, 25(4):179–189, October 2019. Available from: https://www.tandfonline.com/doi/full/10.1080/13814788.2019.1658190, doi:10.1080/13814788.2019.1658190.

[28] Eurostat. *Self-reported unmet needs for health care by sex, age, specific reasons and educational attainment level.* Technical report, 2019. Available from: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hlth_ehis_un1e&lang=en.

[29] A. Cassell, D. Edwards, A. Harshfield, K. Rhodes, J. Brimicombe, R. Payne, and S. Griffin. *The epidemiology of multimorbidity in primary care: a retrospective cohort study.* British Journal of General Practice, 68(669):e245–e251, April 2018. Available from: https://bjgp.org/lookup/doi/10.3399/bjgp18X695465, doi:10.3399/bjgp18X695465.

[30] H. Deek, S. Hamilton, N. Brown, S. C. Inglis, M. Digiacomo, P. J. Newton, S. Noureddine, P. S. MacDonald, P. M. Davidson, and the FAMILY Project Investigators. *Family-centred approaches to healthcare interventions in chronic diseases in adults: a quantitative systematic review.* Journal of Advanced Nursing, 72(5):968–979, May 2016. Available from: https://onlinelibrary.wiley.com/doi/10.1111/jan.12885, doi:10.1111/jan.12885.

[31] E. C. Schiza, T. C. Kyprianou, N. Petkov, and C. N. Schizas. *Proposal for an eHealth Based Ecosystem Serving National Healthcare.* IEEE Journal of Biomedical and Health Informatics, 23(3):1346–1357, May 2019. Available from: https://ieeexplore.ieee.org/document/8358757/, doi:10.1109/JBHI.2018.2834230.

[32] K. Oatley, D. Keltner, and J. M. Jenkins. *Understanding emotions.* Blackwell publishing, 2006.

[33] G. L. Kreps and L. Neuhauser. *New directions in eHealth communication: Opportunities and challenges.* Patient Education and Counseling, 78(3):329–336, March 2010. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0738399110000224, doi:10.1016/j.pec.2010.01.013.

[34] E. B. Sanders. *Design research in 2006.* Design research quarterly, 1(1):1–8, 2006.

[35] E. B.-N. Sanders and P. J. Stappers. *Co-creation and the new landscapes of design.* CoDesign, 4(1):5–18, March 2008. Available from: http://www.tandfonline.com/doi/abs/10.1080/15710880701875068, doi:10.1080/15710880701875068.

[36] D. Yun and J. Choi. *Person-centered rehabilitation care and outcomes: A systematic literature review.* International Journal of Nursing Studies, 93:74–83, May 2019. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0020748919300537, doi:10.1016/j.ijnurstu.2019.02.012.

[37] M. van Limburg, J. Wentzel, R. Sanderman, and L. van Gemert-Pijnen. *Business Modeling to Implement an eHealth Portal for Infection Control: A Reflection on Co-Creation*

With Stakeholders. JMIR Research Protocols, 4(3):e104, August 2015. Available from: http://www.researchprotocols.org/2015/3/e104/, doi:10.2196/resprot.4519.

[38] M. Kaptein, P. Markopoulos, B. de Ruyter, and E. Aarts. *Personalizing persuasive technologies: Explicit and implicit personalization using persuasion profiles.* International Journal of Human-Computer Studies, 77:38–51, May 2015. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1071581915000075, doi:10.1016/j.ijhcs.2015.01.004.

[39] R. L. Bashshur, J. D. Howell, E. A. Krupinski, K. M. Harms, N. Bashshur, and C. R. Doarn. *The Empirical Foundations of Telemedicine Interventions in Primary Care.* Telemedicine and e-Health, 22(5):342–375, May 2016. Available from: https://www.liebertpub.com/doi/10.1089/tmj.2016.0045, doi:10.1089/tmj.2016.0045.

[40] H. Pinnock, L. Steed, and R. Jordan. *Supported self-management for COPD: making progress, but there are still challenges.* European Respiratory Journal, 48(1):6–9, July 2016. Available from: http://erj.ersjournals.com/lookup/doi/10.1183/13993003.00576-2016, doi:10.1183/13993003.00576-2016.

[41] R. W. Lam. *Challenges in the treatment of anxiety disorders: beyond guidelines.* International Journal of Psychiatry in Clinical Practice, 10(sup3):18–24, January 2006. Available from: http://www.tandfonline.com/doi/full/10.1080/13651500600933851, doi:10.1080/13651500600933851.

[42] J. Wentzel, R. van der Vaart, E. T. Bohlmeijer, and J. E. W. C. van Gemert-Pijnen. *Mixing Online and Face-to-Face Therapy: How to Benefit From Blended Care in Mental Health Care.* JMIR Mental Health, 3(1):e9, February 2016. Available from: http://mental.jmir.org/2016/1/e9/, doi:10.2196/mental.4534.

[43] WHO. *Depression and Other Common Mental Disorders: Global Health Estimates.* Technical report, World Health Organization, 2017. Available from: https://apps.who.int/iris/bitstream/handle/10665/254610/WHO-MSD-MER-2017.2-eng.pdf.

[44] WHO. *Access to rehabilitation in primary health care: an ongoing challenge.* Technical report, World Health Organization, 2018. Available from: https://apps.who.int/iris/bitstream/handle/10665/325522/WHO-HIS-SDS-2018.40-eng.pdf.

[45] WHO. *The need to scale up rehabilitation.* Technical report, World Health Organization, 2017. Available from: https://apps.who.int/iris/bitstream/handle/10665/331210/WHO-NMH-NVI-17.1-eng.pdf?sequence=1&isAllowed=y.

[46] P. M. Emmelkamp and K. Meyerbröker. *Virtual Reality Therapy in Mental Health.* Annual Review of Clinical Psychology, 17(1):495–519, May 2021. Available

from: https://www.annualreviews.org/doi/10.1146/annurev-clinpsy-081219-115923, doi:10.1146/annurev-clinpsy-081219-115923.

[47] E. Wade and C. J. Winstein. *Virtual Reality and Robotics for Stroke Rehabilitation: Where Do We Go from Here?* Topics in Stroke Rehabilitation, 18(6):685–700, November 2011. Available from: http://www.tandfonline.com/doi/full/10.1310/tsr1806-685, doi:10.1310/tsr1806-685.

[48] D. J. Stein, M. G. Craske, B. O. Rothbaum, S. R. Chamberlain, N. A. Fineberg, K. W. Choi, P. Jonge, D. S. Baldwin, and M. Maj. *The clinical characterization of the adult patient with an anxiety or related disorder aimed at personalization of management.* World Psychiatry, 20(3):336–356, October 2021. Available from: https://onlinelibrary.wiley.com/doi/10.1002/wps.20919, doi:10.1002/wps.20919.

[49] A. L. Faria, M. S. Pinho, and S. Bermúdez i Badia. *A comparison of two personalization and adaptive cognitive rehabilitation approaches: a randomized controlled trial with chronic stroke patients.* Journal of NeuroEngineering and Rehabilitation, 17(1):78, December 2020. Available from: https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-020-00691-5, doi:10.1186/s12984-020-00691-5.

[50] Y.-C. Chen, X. Dong, J. Hagstrom, and T. A. Stoffregen. *Control of a virtual ambulation influences body movement and motion sickness.* BIO Web of Conferences, 1, 2011. Available from: http://www.bio-conferences.org/10.1051/bioconf/20110100016, doi:10.1051/bioconf/20110100016.

[51] Y. Y. Kim, H. J. Kim, E. N. Kim, H. D. Ko, and H. T. Kim. *Characteristic changes in the physiological components of cybersickness.* Psychophysiology, 0(0):050826083901001–???, August 2005. Available from: https://onlinelibrary.wiley.com/doi/10.1111/j.1469-8986.2005.00349.x, doi:10.1111/j.1469-8986.2005.00349.x.

[52] L. Rebenitsch and C. Owen. *Estimating cybersickness from virtual reality applications.* Virtual Reality, 25(1):165–174, March 2021. Available from: https://link.springer.com/10.1007/s10055-020-00446-6, doi:10.1007/s10055-020-00446-6.

[53] C.-Y. Chen, C.-H. Chuang, T.-L. Tsai, H.-W. Chen, and P.-J. Wu. *Reducing cybersickness by implementing texture blur in the virtual reality content.* Virtual Reality, October 2021. Available from: https://link.springer.com/10.1007/s10055-021-00587-2, doi:10.1007/s10055-021-00587-2.

[54] Y. Farmani and R. J. Teather. *Evaluating discrete viewpoint control to reduce cybersickness in virtual reality.* Virtual Reality, 24(4):645–664, December 2020. Available from: http://link.springer.com/10.1007/s10055-020-00425-x, doi:10.1007/s10055-020-00425-x.

[55] J.-R. Chardonnet, M. A. Mirzaei, and F. Merienne. *Influence of navigation parameters on cybersickness in virtual reality.* Virtual Reality, 25(3):565–574, September 2021. Available from: https://link.springer.com/10.1007/s10055-020-00474-2, doi:10.1007/s10055-020-00474-2.

[56] J. Martín-Gutiérrez, C. E. Mora, B. Añorbe-Díaz, and A. González-Marrero. *Virtual Technologies Trends in Education.* EURASIA Journal of Mathematics, Science and Technology Education, 13(2), January 2017. Available from: https://www.ejmste.com/article/virtual-technologies-trends-in-education-4674, doi:10.12973/eurasia.2017.00626a.

[57] A. Borrego, J. Latorre, R. Llorens, E. Noe, and E. A. Keshner. *Low-cost, room-size, and highly immersive virtual reality system for virtual and mixed reality applications.* In 2015 International Conference on Virtual Rehabilitation (ICVR), pages 273–277, Valencia, Spain, June 2015. IEEE. Available from: http://ieeexplore.ieee.org/document/7358587/, doi:10.1109/ICVR.2015.7358587.

[58] P. Spicker. *Personalisation Falls Short.* British Journal of Social Work, 43(7):1259–1275, October 2013. Available from: https://academic.oup.com/bjsw/article-lookup/doi/10.1093/bjsw/bcs063, doi:10.1093/bjsw/bcs063.

[59] J. Hayhurst. *How Augmented Reality and Virtual Reality is Being Used to Support People Living with Dementia—Design Challenges and Future Directions.* In T. Jung and M. C. tom Dieck, editors, Augmented Reality and Virtual Reality, pages 295–305. Springer International Publishing, Cham, 2018. Series Title: Progress in IS. Available from: http://link.springer.com/10.1007/978-3-319-64027-3_20, doi:10.1007/978-3-319-64027-3_20.

[60] B. Garrett, T. Taverner, D. Gromala, G. Tao, E. Cordingley, and C. Sun. *Virtual Reality Clinical Research: Promises and Challenges.* JMIR Serious Games, 6(4):e10839, October 2018. Available from: http://games.jmir.org/2018/4/e10839/, doi:10.2196/10839.

2

From Patient to Musician: A Multi-Sensory Virtual Reality Rehabilitation Tool for Spatial Neglect

The first advanced virtual reality application of this dissertation is a rehabilitation tool for the treatment of patients with spatial neglect. The main advancements in this application are the use of music therapy as a multi-modal treatment together with vision stimuli, and the use of internal sensors of the head mounted display for automated assessment. In this chapter, three of the challenges presented in Section 1.5 are tackled. Specifically, the following challenges: (i) the use of automated assessment to extract insights of the patient's behaviour that is presented to the health care professional on a dashboard, (ii) the need for expertise-driven instead of technology-driven applications, and (iii) application design that takes into account the technical proficiency of the users.

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Abstract Unilateral Spatial Neglect (USN) commonly results from a stroke or acquired brain injury. USN affects multiple modalities and results in failure to respond to stimuli on the contralesional side of space. Although USN is a heterogeneous syndrome, present-day therapy methods often fail to consider multiple modalities. Music Neglect Therapy (MNT) is a therapy method that succeeds in incorporating multiple modalities by asking patients to make music. This research aimed to exploit the immersive and modifiable aspect of Virtual Reality (VR) to translate MNT to a VR therapy tool. The tool was evaluated in a 2-week pilot study with four clinical users. These results are compared to a control group of four non-clinical users. Results indicated that patients responded to triggers in their entire environment and performance results could be clearly differentiated between clinical and non-clinical users. Moreover, patients increasingly corrected their head direction towards their neglected side. Patients stated that the use of VR increased their enjoyment of the therapy. This study contributes to the current research on rehabilitation for USN by proposing the first system to apply MNT in a VR environment. The tool shows promise as an addition to currently used rehabilitation methods. However, results are limited to a small sample size and performance metrics. Future work will focus on validating these results with a larger sample over a longer period. Moreover, future efforts should explore personalisation and gamification to tailor to the heterogeneity of the condition.

2.1 Introduction

Approximately 25 to 30% of all stroke individuals suffer from Unilateral Spatial Neglect (USN) [1]. Moreover, USN is a syndrome that is systematically under-diagnosed due to a lack of sensitivity in the used assessment methods [2]. Stroke is the leading cause of disability according to the World Health Organisation (WHO), and neglect predicts poor outcomes in functional recovery, leading to longer hospitalisations, functional dependency or long-term disability in everyday activities. Therefore, USN is an important syndrome that requires careful diagnosis and treatment [1, 3].

USN is a syndrome that is commonly caused by unilateral brain injury, most often a stroke [4]. It is defined as the failure to report, respond or orient to meaningful or novel stimuli that occur on the side contralateral to the hemispheric lesion, where this failure cannot be attributed to either an elemental sensory or motor deficit [5]. The different modalities in which this lack of awareness manifests itself are manifold, and its presence severely hinders functional recovery after brain injury [6].

Moreover, USN is considered to be a heterogeneous syndrome, which means that the disorder can affect various modalities [7]. The most prevalent ones are the visual, auditory and motor modality [8]. Although it is crucial for a rehabilitation method to include all the affected modalities, more often than not, solely the visual modality receives attention in current treatments [9]. Visual Scanning Training (VST), for example, is a technique that enjoys a high adoption rate in clinical practice but fails to incorporate other sensory modalities [10]. However, Music Neglect Therapy (MNT) is a therapy method based on active music-making that shows potential for the multisensory rehabilitation of USN [11].

The aim of this paper is to research the feasibility of translating MNT to a Virtual Reality (VR) environment for the rehabilitation of patients with USN, exploiting the immersive power and versatility of VR to provide a multi-sensory experience. For the design of this VR therapy tool, an interdisciplinary approach is taken in close cooperation with experts from the Ghent University Hospital. The resulting proof of concept is evaluated in a pilot study with four individuals suffering from USN and four non-neglect individuals.

The remainder of this paper is structured as follows. First, relevant related research is discussed in Section 2.2, followed by the vision of the therapy tool for USN in Section 2.3. Hereafter, the materials and methods will be discussed, subdivided into Section 2.4, which elaborates on the design of the proposed therapy tool, and Section 2.5, which discusses the implementation of the system. Next, Section 2.6 presents the setup of the performed pilot study. We follow with Sections 2.7 and 2.8, which present and discuss the findings of the pilot study. Finally, a concise conclusion will be given in Section 2.9.

2.2 Background

This section will discuss relevant background information and related work concerning the classification of spatial neglect, followed by the assessment and existing rehabilitation techniques for USN. Finally, musical therapy and the use of VR for patients with USN will be covered in depth.

2.2.1 Classification of Spatial Neglect

USN is relatively common and has many causes, including neurodegenerative diseases, neoplasm, aneurysm, traumatic brain injury after the surgical resection of a brain tumour and stroke, where stroke is by far the most prevalent cause [4, 12–14]. Left-sided neglect is more common than right-sided neglect, as it is mostly linked to damage to the right hemisphere of the brain [15, 16]. The brain has an asymmetric attention mechanism, where the left hemisphere is responsible for processing input originating from the right side of space, whereas the right hemisphere is responsible for stimuli from both the left and partly the right. When damage occurs at the left hemisphere, the right hemisphere can partially compensate for it. However, when the right hemisphere is damaged, no compensation is possible.

Although the existing literature is not consistent on the classification of the types of USN, two categories exist. The first categorises neglect based on the affected modality, including sensory, motor or representation neglect. Patients with sensory

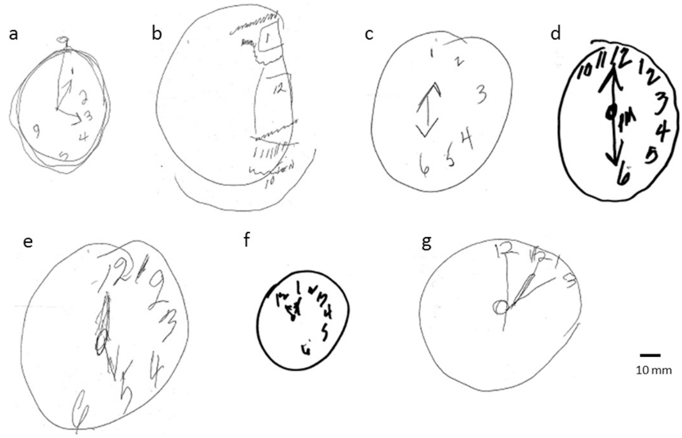

Figure 2.1: When patients with representational neglect are asked to draw an analogue clock from memory, the numbers are placed in their non-neglected side of the clock (a-g). Image used from [21].

neglect experience a disordered awareness of sensory inputs originating from their contralesional side of space. They lack the ability to bring their attention to this side of space in the presence of external stimuli [12, 15]. This type of neglect can be further specified by the sensory modality in which it manifests itself, such as visual, auditory and tactile neglect [8]. An example of sensory neglect is when the patient only eats half the plate of food, despite still being hungry [17]. Next, motor neglect is defined as a failure to generate the desired movement in response to observed stimuli, where this failure cannot be ascribed to a primary sensor or motor deficit [8, 18]. Multiple sub-types of this type of neglect exist, such as the under-utilisation of a limb opposite to the brain lesion [19]. A final type of modality-based neglect is representation neglect or imagery neglect, where a person ignores the contralesional side of images that were internally generated, such as mental representations of a task, action or movement [8, 20]. An example of this type of neglect can be seen when a patient is asked to draw an analogue clock from memory, in which the patient places all the numbers on their non-neglected side of the clock [21]. An example of this experiment is shown in Figure 2.1.

The second method classifies neglect according to the distribution of abnormal behaviour in space, e.g. personal and spatial neglect [22]. Personal neglect is the lack of exploration of half of the body contralateral to the damaged hemisphere [23]. An example of personal neglect is only shaving half of their face, or putting on only one shoe. Personal neglect differs from sensory neglect as it is characterised by an unawareness of the body part itself, whereas sensory neglect refers to an unawareness of external stimuli, e.g. vision or touch [8]. Spatial neglect is defined as neglect where the abnormal behaviour is not located in personal space; this thus refers to failure to acknowledge stimuli on the contralesional side of space [23]. Spatial neglect is often used as a synonym for the neglect syndrome as a whole. Two sub-types of spatial neglect can be discerned. Peripersonal or near-space neglect is when symptoms manifest in the reaching distance of the patient, e.g. the example of eating half a plate of food. When symptoms occur in the space beyond reaching distance, e.g. inadvertently bumping into obstacles while walking, it is classified as extrapersonal or far-space neglect.

Although these categories exist, USN remains an inherently heterogeneous syndrome, meaning that patients often experience multiple types of neglect simultaneously [7].

2.2.2 Assessment of USN

To assess the degree and nature of the spatial neglect, several assessment methods are available today that try to measure a potential bias towards the non-neglected side of space. These assessment tests can be categorised into the so-called paper-and-pencil tests, which are often tools for quickly screening patients, and the behavioural tests, which aspire to assess spatial neglect based on everyday tasks [8, 24, 25].

Examples of paper-and-pencil tests are the line bisection test and the cancellation test. During the line bisection test[2], patients are asked to indicate the horizontal centre of a simple straight line. A bias towards the right or left can then indicate USN, as shown in Figure 2.2 [26–28]. For the cancellation test, the patient has to cross out certain symbols on a sheet of paper, often ignoring other distraction symbols. One example of such a cancellation test is the star cancellation test[3], shown in Figure 2.3, in which all small stars need to be indicated, ignoring the random distraction words. The quantification of USN is then the difference between the missed stars on the left versus the right side [28–31]. An example of a digital paper-and-pencil test is the neglect test of the Test for Attention Performance (TAP). The neglect test is a subtest of the TAP test suite[4], during which the patient needs to respond to a flickering stimulus on the screen by pressing a button [32]. These paper-and-pencil tests are simple and quick to set up. However, they should only be used for initial screening and not for clinical diagnosis as they cannot discriminate between sensory and motor neglect.

Examples of behavioural tests are the Behavioural Inattention Test (BIT), the Semi-Structured Scale for Functional Evaluation of Hemi-Inattention and the Catherine Bergego Scale (CBS). The BIT consists of conventional pen-and-paper tests as well as practical tests such as reading a menu or sorting coins [8, 28, 33]. Similarly, for the Semi-Structured Scale for Functional Evaluation of Hemi-Inattention[5], the patient

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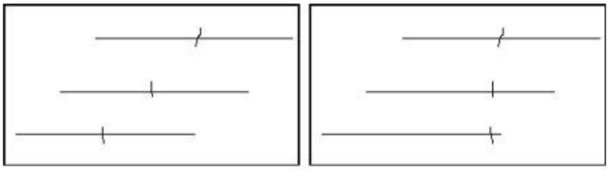
[2] https://www.strokengine.ca/en/assessments/line-bisection-test, accessed on 21/01/2022

[3] https://strokengine.ca/en/assessments/star-cancellation-test, accessed on 21/01/2022

[4] https://www.psytest.net/en/test-batteries/tap/subtests#visual_field_examination, accessed on 21/01/2022

[5] https://strokengine.ca/en/assessments/semi-structured-scale-for-the-functional-evaluation-of-hemi-inattention, accessed on 21/01/2022



A. Normal line bisection B. Highly impaired line bisection

Figure 2.2: For the line bisection test, the middle of the line has to be indicated (**A**). A bias towards one of the extremities of the line can be an indication of USN (**B**).

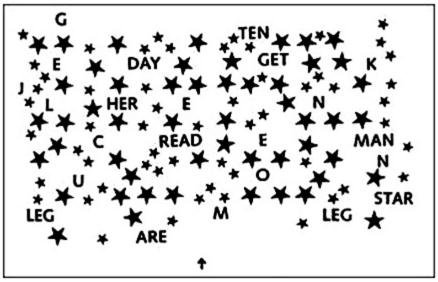


Figure 2.3: For the star cancellation test, all the stars have to be indicated. The difference in missed stars between the left and right side indicates potential USN.

has to perform functional tasks such as combing their hair or serving tea [8, 28, 34]. Finally, the CBS[6] is a standardised checklist for the detection and degree of unilateral neglect during the observation of everyday life situations. Moreover, the scale also measures the self-awareness of behavioural neglect. Examples are grooming and paying attention to people talking to the patient from one side of their field of view. The disadvantage of these behavioural tests is that they often focus on visually based functional tasks and do not differentiate between sensory and motor neglect [8, 28].

2.2.3 Rehabilitation Techniques for USN

Many interventions for the rehabilitation of spatial neglect have been proposed; however, there is a need for more evidence regarding their effectiveness. Consequently, no standardised set of rehabilitation methods for USN exists [30]. The existing approaches can be categorised into top-down methods, bottom-up methods, modulation of inhibitory processes and increasing arousal.

Top-down methods aim to stimulate the voluntary attention gaze of the patient towards the neglected side of space. This stimulation consists of cues and instructions from the therapist. VST is the most used form of top-down rehabilitation technique. VST aims to orientate the visual scanning of the patient back towards the neglected

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[6] https://strokengine.ca/en/assessments/catherine-bergego-scale-cbs, accessed on 21/01/2022

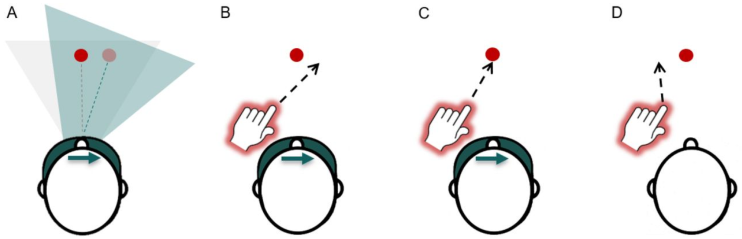


Figure 2.4: The four phases of the Prism Adaptation rehabilitation method. (**A**) Pre-test, (**B**) the perception of visual error signal, (**C**) the adaptation and (**D**) the after-effect. Image used from [41].

side by giving explicit instructions on where to look, e.g. asking them to locate the left-hand margin of the page before reading the next line [10]. Top-down methods are often criticised for their lack of specificity, as not all neglect symptoms seem to improve and non-visual sensory neglect is not addressed [35, 36]. Nevertheless, top-down approaches, and specifically VST, are still mainly used in clinical practice [37].

In an attempt to address the shortcomings of top-down methods, bottom-up methods were developed. A deficit in processing the sensory information of one side of space creates an unbalance in the patient's representation of space. Bottom-up methods aim to restore this balance by manipulating the patient's sensory environment [25, 38]. Sensory Stimulation is an example of such a method, which uses sensory input from different modalities, thereby addressing the multi-sensory aspect of USN, to eliminate this orientation bias towards the neglected side. The most well-known implementations of Sensory Stimulation are Optokinetic Stimulation (OKS), Neck-Muscle Vibration (NVM), Caloric Vestibular Stimulation (CVS) and Galvanic Vestibular Stimulation (GVS) [35]. Another well-known bottom-up technique is Prism Adaptation (PA), where patients wear prisms that shift their vision towards their non-neglected side. For left-sided neglect, the prism introduces an optical shift of several degrees to the right. At the start of the adaptation process, this leads to a right-sided error signal, as shown in Figure 2.4. After several iterations, compensation of the behaviour kicks in, and this error is corrected. When these prisms are then removed, a consistent deviation to the left occurs when pointing to a visual target, called the after-effect [39, 40].

A final example of a bottom-up technique is Limb Activation (LA), where patients are asked to make voluntary contralesional limb movements in their affected side of space. This, in turn, activates the corresponding areas of the brain dealing with extra- and peripersonal space [42]. Studies regarding LA show interesting results; however, long-term functional effectiveness has yet to be determined [36].

The next category are methods that address the modulation of inhibitory processes, such as Transcranial Magnetic Stimulation (TMS) and transcranial Direct Current Stimulation (tDCS). These techniques use non-invasive brain stimulation to reduce the activity of the contralesional hemisphere or increase the activity of the ipsilesional hemisphere [43].

The final category of techniques for the rehabilitation of USN includes methods that focus on the stimulation of arousal, such as Sustained Attention Training (SAT) [7]. USN has been linked with a non-lateralised attention deficit, i.e. patients often struggle to keep their attention focused for a longer time period, even in their non-affected side of space [44]. These techniques aim to stimulate sustained attention to improve associated neglect symptoms. SAT does this by first pointing out the spatial errors that the patients makes during the executing of a certain task. The patient then has to repeat this task, while the trainer provides a reminder, every 20 to 40 s, to remain attentive, teaching the patient to "self-alert" while completing this task on their own [7].

2.2.4 Music Therapy and USN

Music therapy has shown great potential as a therapy method for multiple syndromes [45–47]. The act of playing an instrument provides a patient with the opportunity to train multiple sensory modalities simultaneously, such as hearing, vision, touch, motor and cognitive skills [48, 49]. Moreover, music-making taps into the emotion and reward system of the human brain, making a music therapy intervention intrinsically rewarding and engaging [50].

Neurologic Music Therapy (NMT) is a neuroscientifically motivated model of music practice and consists of 20 research-based music therapy techniques. One of these techniques is MNT, a music-making spatial neglect therapy. In this model, MNT is described as a technique that "includes active performance exercises on musical instruments that are structured in time, tempo and rhythm, and is in appropriate spatial configurations, to focus the attention to a neglected or unattended visual field" [11].

The use of music in spatial neglect therapy has additional benefits, such as the Mozart effect. This effect states that one has better spatial–temporal reasoning when listening to a certain Mozart sonata [51], indicating that music and space are closely linked. It has been shown that, for people with spatial neglect, listening to classical music, or pleasant music in general, increases their spatial awareness and boosts arousal [52, 53]. Second, people have a tendency to spatially represent ordinal sequences, such as numbers or tones. Even non-musicians have a so-called "piano in the head", where notes are arranged from left to right, low to high, on a horizontal axis. This neurological trick can thus be applied in a spatial neglect intervention method [54, 55].

For these aforementioned reasons, musical practice is considered a promising tool for the rehabilitation of USN [49]. However, to date, only a few studies exist on the use of MNT [17, 56–58]. These studies use a horizontally aligned instrument, such as a piano, with the objective to increase the active exploration towards the neglected side of the patient. Overall, results were positive, observing significant improvements in the visual exploration of patients, with both short- and long-term effects. One case studied the influence of the congruence of the sound feedback design on the performance of the patient, by comparing multiple sound feedback options, such as congruent sound feedback, i.e. the pitches of the notes are horizontally aligned similar to the keys on a piano, random sound feedback and no feedback, i.e. silence [17]. The researchers observed that the spatial exploration of patients with left-sided neglect was superior in the case of congruent sound feedback and that the use of a musical scale may trigger the preserved auditory and spatial multi-sensory representation of successive sounds.

2.2.5 VR for Rehabilitation

In Virtual Reality, the user is placed in a completely computer-generated three-dimensional simulation, where they can look around and interact with their environment using devices such as a Head Mounted Display (HMD) and gloves or controllers, to create an immersive experience. VR has long since found its place in the world of gaming and entertainment. Nevertheless, VR is increasing in popularity in a clinical setting. A tool for the rehabilitation of children with dystonic cerebral palsy [59], limb pain alleviation [60] and VR exposure therapy for anxiety disorders [61] are just a few examples of the clinical applications of VR [62–67]. Other mixed reality tools, such as Augmented Reality (AR), have also found their way into clinical applications, e.g. neurosurgery [68, 69]

VR has many advantages over traditional rehabilitation techniques. First, VR systems can augment and manipulate the interaction of the user with the environment and can quantitatively monitor it, promoting the functional recovery of the patient [70]. Second, opposed to traditional treatment options, VR is modular, enabling the tailoring of the treatment to the patient's needs and physical or cognitive capabilities. Third, there is no need for a clinician as the system can monitor the performance of the patient and quantify how well a task is being performed and give feedback accordingly. This consequently increases the potential for at-home rehabilitation. Lastly, the virtual environment is often more immersive and enjoyable than conventional treatments, which leads to the patient more actively participating and an increased positive attitude towards the treatment, which increases the overall quality of life of the patient [71].

However, the use of VR introduces several disadvantages as well. First, the immersion aspect can provoke cyber sickness in some, leading to the incompletion of the treatment or an unenjoyable experience. Nevertheless, a large portion of these side effects can be managed by taking appropriate precautions, such as excluding patients prone to motion sickness and following post-immersion procedures [72]. Second, there are studies investigating the spatial perception of distance [73, 74] and orientation [75] in VR environments. These studies have found that subjects perceive distances differently in VR than in real life, while the perception of orientation remains the same in VR. This should be carefully considered in therapy use cases where the perception of the user is important. Third, the design of a new VR tool for a clinical setting should always be based on an informed theoretical foundation [76]. Finally, although the cost of VR devices has decreased in recent years, the initial equipment cost is still far greater than traditional pen-and-paper tools, which can be a barrier to their adaption in a clinical setting, especially in lower-income countries [77, 78].

As mentioned, VR is becoming more and more present in healthcare applications. On of these applications is the rehabilitation of spatial neglect [79–83]. As there is currently no gold standard for the rehabilitation of USN, new VR interventions can flourish. Moreover, VR provides the opportunity to address and support the multi-sensory characteristics of the syndrome as it incorporates not only visual but also other sensory stimuli. Tactile feedback can be provided using haptic feedback through controllers, and the headphones integrated in a HMD provide auditory stimuli. Moreover, three-dimensional sound can be simulated such that sound is linked to a certain location in space. The use of VR in rehabilitation for USN can hereby accommodate the demand for multi-sensory intervention techniques. Next, clear visual and auditory progress markers motivate the user and help the rehabilitation process. Furthermore, the use of VR provides more enjoyment of the therapy and increases overall motivation. Patients that have suffered from a stroke experience often suffer from post-stroke depressions, originating from the feeling of loss of independence [37]. Self-administering rehabilitation can restore the sense of self-ownership by enabling patients to carry out the rehabilitation independently. Finally, the option for at-home rehabilitation is beneficial for those with mobility issues, often the case for post-stroke patients [84, 85].

A variety of studies regarding the use of VR for the rehabilitation of USN exist, such as the grabbing and placing of sushi on a virtual sushi bar [79], following a virtual moving ball with their eyes [80], a rehabilitation tool that offers extra-personal and peripersonal training by performing several tasks in the VR environment [81], a virtual translation of the CBS [82] and a virtual environment based on the PA method, where the HMD emulates the prism [83]. However, no studies have been found that combine music therapy and VR into a rehabilitation tool for USN. Nonetheless, studies combining musical therapy and VR exist, such as a VR system to train everyday hand movements using musical exercises for post-stroke patients [86] or a virtual musical theatre for people suffering from Alzheimer's disease, where patients are immersed in a musical experience among the audience [87].

2.3 Vision and Objectives

The previous section indicates a lack of therapy tools for USN that include multiple modalities, despite the consideration of USN as a multi-sensory deficit. MNT exploits these multiple modalities and is therefore considered to be a promising tool for the rehabilitation of USN patients [49]. The use of VR for the rehabilitation of USN offers the advantage of not limiting the therapy to visual stimuli due to the easy integration of auditory, tactile and motor stimuli. A VR environment facilitates the creation of an immersive experience that can be adapted to the needs of the patient. Moreover, the use of a digital tool, as opposed to manual assessment, provides the opportunity for more unbiased data collection during therapy. Information, such as head direction or responses to stimuli in the VR environment, can be tracked to evaluate progression over time.

The objective of this research is to investigate whether MNT for USN can be successfully translated to an immersive VR environment and whether the data collected during the immersive training can be used for the assessment and thus evaluation of the progress of patients affected by USN. To achieve this, a digital tool has been designed that includes an immersive VR environment in which the patient has to perform several musical exercises, tracking and displaying session data on a therapist dashboard.

To ensure that this tool achieves its objective, expert knowledge about the needs of the target audience and offered therapy is necessary. An iterative participatory design approach has been taken, involving experts and patients in the design process. This research has been established in close co-operation with specialists and therapists from the Rehabilitation Department of the Ghent University Hospital. To evaluate the resulting system, a pilot study, approved by the ethics committee, has been conducted involving several patients who were currently undergoing treatment for USN at the Rehabilitation Department of the Ghent University Hospital.

Three research questions have been investigated:

1. Can MNT be effectively translated into a VR environment?
2. Can the newly designed VR system be used for the treatment of adults with USN with an acquired brain injury?
3. Will the spatial performance of the patient with an acquired brain injury evolve positively after treatment with the VR system?

2.4 Design of the VR Therapy for USN

The multi-sensory VR rehabilitation tool enables the user to perform several musical exercises on a virtual xylophone, while incorporating three sensory modalities, namely

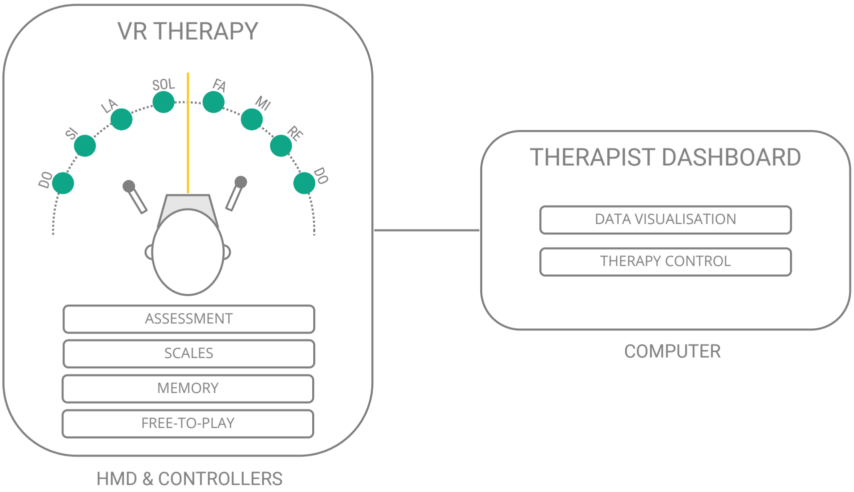


Figure 2.5: The designed VR therapy tool for USN consists of two modules: the VR therapy module, for the patient, who has to wear a HMD and use controllers, and the dashboard, accessible on a computer, where the therapist can control and oversee the session.

auditory, visual and motor. During these exercises, patients are triggered to explore their neglected side.

To ensure that a therapist can guide and follow an ongoing session, the designed platform consists of two modules, one for the patient and one for the therapist, as shown in Figure 2.5. For the therapist, there is a dashboard, accessible on a computer, to oversee and control the therapy as it is in progress. For the second module, the VR therapy, the patient has to wear a HMD and use two controllers, representing mallets, to stroke the keys of the virtual xylophone.

The following sections will first elaborate on the designed VR therapy module and its four tasks, followed by an explanation of the designed therapist dashboard.

2.4.1 VR Therapy Module

During a VR therapy session, the patient will see an arrangement of several musical keys, similar to a xylophone, aligned in a semi-circle around them, as shown in Figure 2.5. Using the controllers, notes can be played by hitting a key with a percussion mallet, i.e. the motor modality of the therapy. The notes produced by the keystrokes are spatial sounds, i.e. originating from their location in space, where its pitch also depends on its location in the virtual environment, i.e. the auditory modality. Finally, when hit, the keys light up in a different colour for approximately 1 s before turning back to their original colour, corresponding to the visual modality.

The VR therapy module contains four tasks, called Assessment, Scales, Memory

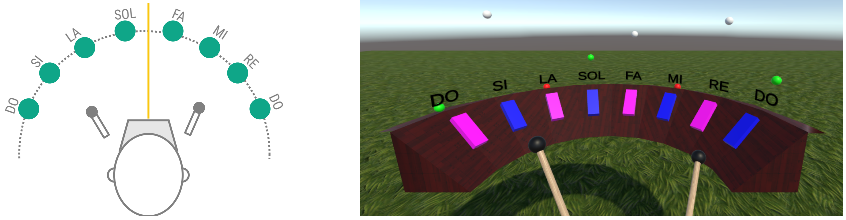


Figure 2.6: General setup of the symmetrical setup of the Assessment task in schematic (**left**) and virtual environment (**right**).

and Free-to-Play. The Assessment task aims to assess the severity of the spatial neglect of the patient and their progress in the rehabilitation process. The other three tasks aim to change the behaviour of the patient by training them to respond to triggers in their environment, a top-down approach.

The use of a VR environment enables us to adapt the setup of the xylophone to the current task and difficulty level. More specifically, the number of keys of the instrument and their location in space can instantly be changed to meet therapy needs. The location of the keys changes based on the objective of the task. Since the *Assessment* task aims to assess progress, the keys will be symmetrically spaced on the semi-circle, as shown in Figure 2.6. However, for the three training tasks, the keys will be located off-centre towards the neglected side of the patients' environment, as shown in Figure 2.7, a bottom-up approach. More specifically, two keys will always be located on the ipsilesional side, while the other keys are situated in the neglected side of the environment. In this setup, the key at the extremity of the instrument is an extra key, producing a special sound. This modification is necessary as people with USN benefit from these anchor points in their neglected side of space. Moreover, a red target will occasionally appear during these training tasks. The users are required to look directly at this target for a few seconds, before continuing with the task. This addition is necessary to keep the patient aware of the location of their mid-line. Finally, the difficulty level of each task is reflected in the number of keys shown, namely difficulty 1 to 4, which corresponds to 6 to 9 keys, respectively. Each task, except the *Assessment*, consists of several of these levels, and thus a different number of keys based on the set difficulty level, as shown in Figure 2.8.

Next, each task will be discussed in more detail.

2.4.1.1 Assessment Task

The *Assessment* task is the only task that does not use difficulty levels and should not be played each session. The objective of this task is to assess the progress of the patient during their rehabilitation and can be performed whenever the therapist deems it necessary. For this task, the instrument keys are set up symmetrically (cf. Figure 2.6),

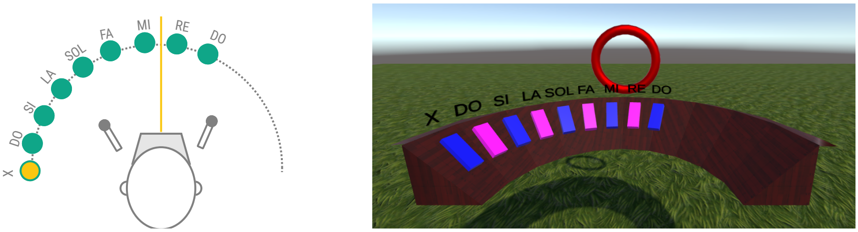


Figure 2.7: General setup of the asymmetrical setup of the three rehabilitation tasks in schematic (**left**) and virtual environment (**right**).

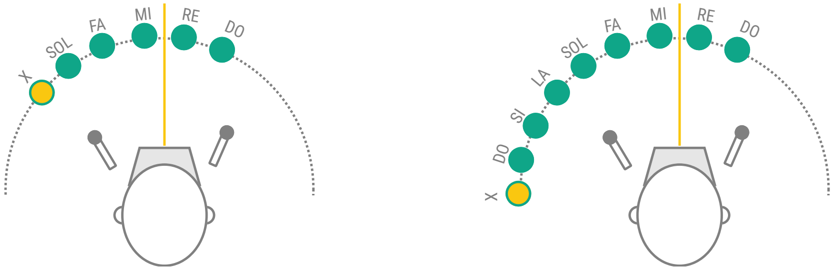


Figure 2.8: Setup of instrument during the rehabilitation tasks. Difficulty One (**left**) and difficulty Four (**right**).

regardless of their neglected side, assuming that the head direction of a patient with USN will indicate a bias towards their non-neglected side.

During this task, the patient is asked to freely play the instrument. However, test runs and feedback from the experts indicated the need to incentivize patients to continue playing different notes. Therefore, each key is supported by a small ball, that starts up in the air and slowly falls towards the keys. Patients are instructed to avoid letting the balls touch the keys. When a ball is close to the surface of a key, it turns green, indicating that the patient can then hit the corresponding key to send the ball back up into the air. When the ball touches the key, it turns red (cf. Figure 2.6 right). This gamified element triggers the active exploration of their entire environment during the *Assessment*.

2.4.1.2 Scales Task

The *Scales* task is the first training task. In this task, the patient has to play scales on the xylophone, i.e. the patient has to sequentially hit each key in order, starting from their non-neglected side towards their neglected side. For left-sided neglect, this corresponds to playing the keys from right to left. This task familiarises the user with the off-centre layout of the instrument (cf. Figure 2.7) and explores whether the patient has a certain threshold for which they believe it is the last key on the instrument.

2.4.1.3 Memory Task

The *Memory* task asks the patient to memorise a sequence of notes that is shown to them and then repeat this sequence. This task starts from the lowest difficulty level, showing a sequence of one note, each time increasing the difficulty, i.e. the length of the sequence or the number of keys on the virtual xylophone. When the patient plays an incorrect key, the sequence is shown again; when they play the correct key, positive feedback is given. This process is repeated with increasing difficulty until the patient errs too often.

The cues that are given to indicate the sequence to be memorised are the same as when a key is hit, i.e. the key changes colour and an animation is played, accompanied by the spatial sound of the note.

The *Memory* task urges the patient to actively explore their entire environment and respond to both visual and auditory stimuli. Since the entire instrument is not visible in one glance, the patient has to move their head to locate and react to the spatial audio. This thus aims to improve the ability to respond to external multi-sensory triggers, located in the contralesional side of space.

2.4.1.4 Free-to-Play Task

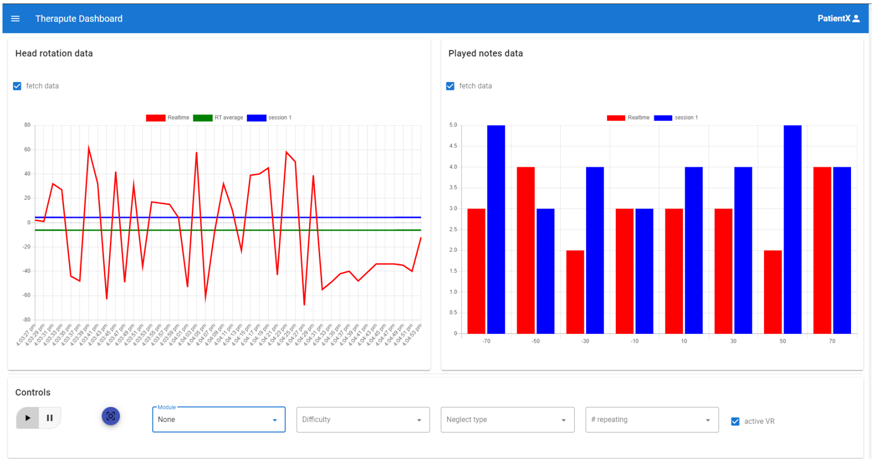
The final task is the *Free-to-play* task. In this task, the objective was to provide the patient with some ‘cognitive downtime´ by letting them play freely. However, similar to the *Assessment* task, to motivate the patients to keep on playing during this task, the same game mechanics have been included. The use of small balls falling to the surface of the keys again triggers the active exploration of the patient, urging them to explore their entire environment to avoid any balls hitting the keys.

2.4.2 Therapist Dashboard

The second module is the therapist dashboard, aimed to oversee and control the ongoing session. The dashboard shows the head direction of the patient over time and the keys that are played during a session, as shown in Figure 2.9. Using the head direction information of previous sessions, the therapist can see if improvements are noticeable and the patient gives more attention to their neglected side. Via the dashboard, the therapist can start or pause the therapy and select which task at which difficulty level is started next.

2.5 Implementation Details

Based on the functional requirements presented in Section 2.4, a working prototype has been developed for the pilot study. However, as the resulting system is used in a research track, some additional non-functional requirements need to be considered.



Module: None

Figure 2.9: Therapist dashboard to control and oversee the therapy.

Specifically, the modifiability of the system is quite essential. Firstly, the system's dashboard needs to be interchangeable with different implementations. Future research might focus on different dashboard designs and their usability, which requires new implementations. Secondly, the system's data storage needs to be as flexible as possible. Legal, ethical or General Data Protection Regulation (GDPR)-related issues might require changes to the data storage deployment, for which it might be necessary to opt for either a local or server-based solution. Furthermore, future research will consider integrating the system with existing data stores—for example, for patient data records.

The remainder of this section discusses the decomposition of the system into individual components connected by interfaces between them. This is followed by an overview of the technologies used and, finally, a discussion of the deployment of the test setup.

2.5.1 Design Overview

Based on the functional and non-functional requirements, the system is decomposed into three separate components. Figure 2.10 shows the system's decomposition into a *VR system*, a *data storage* and a *dashboard*. The *VR system* is responsible for managing and displaying the VR environments to the patient and collecting the data from the therapy sessions and the HMD. The *data storage* component stores and delivers the data displayed on the dashboard. The *dashboard* component is a stand-alone dashboard application that requests the data from the *data storage* to display them in graphs on the screen. The *dashboard* also issues control requests to the *VR system* to control the therapy and configure the exercise.

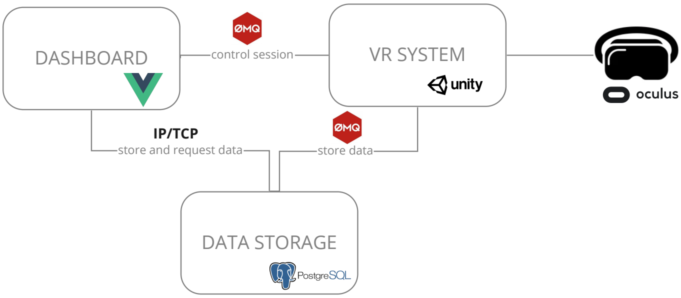


Figure 2.10: The architecture of the designed VR platform.

2.5.2 Interfaces

In order to allow easy modifiability with little constraint on the *data storage* and *dashboard* components, the technologies for the interfaces between the components are based on the TCP/IP protocol stack. Figure 2.10 shows the interfaces between the identified components. Both interfaces between the *VR system* and the *dashboard* and the *VR system* and the *data storage* use a network-based message queue. The communication between the *dashboard* and the *data storage* happens over the database's TCP/IP communication protocol.

2.5.3 Technologies

The *VR system* component was entirely developed in Unity3D[7]. This is a game engine with broad support for VR development. The data store is a PostgreSQL[8] database with a Python script to handle the communication with the *VR system*. The *dashboard* is a vue.js application. For the message bus, ZeroMQ[9] is used. It is an open-source universal messaging library with support for TCP transport. Finally, the HMD is an Oculus Quest 2[10] connected with a link cable to a gaming laptop featuring an off-the-shelf VR-ready Graphics Processing Unit (GPU). The technologies used in each component are indicted in Figure 2.10.

2.5.4 Deployment

For the implementation of the proof of concept used in this study, all components are deployed on a single machine. There are two primary motivators for this. Firstly, security is needed due to the sensitive nature of the data. Secondly, the availability of

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[7] https://www.unity.com, accessed on 21/01/2022
[8] https://www.postgresql.org, accessed on 21/01/2022
[9] https://zeromq.org, accessed on 21/01/2022
[10] https://www.oculus.com/quest-2, accessed on 21/01/2022

the system is required due to the sensitive nature of the therapy. The most affordable tactic to achieve both is restricting the entire software stack to one system and eliminating all external communication. Therefore, the implementation also needs no internet connection. The only external hardware required is the HMD and the controllers connected to the PC, which directly communicate with the *VR system*.

2.6 Evaluation Set-Up

This research aimed to evaluate the proposed VR therapy in practice. Therefore, therapy sessions were performed with diagnosed USN patients. A control group of users without USN also performed the therapy exercises using the VR system. This study was performed at the Ghent University Hospital with clinical patients and in the offices of the IDLab researchers of this work with non-clinical users. Ethical approval was obtained for the study and all participants signed an informed consent form before participating. The study was approved by the Medical Ethics Committee of Ghent University Hospital on 19 March 2021 [B6702021000166].

This section will discuss the test methodology that was adopted, and the timeline of the pilot study. An overview of the participating individuals and the recruitment process is given. Finally, the data collection during the study is discussed.

2.6.1 Method

The clinically diagnosed patients with USN received VR-based therapy for two weeks as part of their rehabilitation program at the hospital. During the two-week period, sessions took place on Monday, Wednesday and Friday in the presence of a therapist. Each session had a duration of approximately 30 min, in which, first, the *Assessment* took place, followed by the *Scales, Memory* and *Free-to-Play* tasks. On four occasions during these two weeks, the *Assessment* task of the therapy tool was performed. During each session, all other VR rehabilitation tasks were performed. Figure 2.11 shows a timeline of the two-week test period, on which the tasks for each session are indicated. At the end of the two-week period, an interview with the patients collected additional feedback and impressions.

As a baseline to compare the performance of the clinical patients with, the same therapy sessions were performed with test users without USN. These test users would each perform a single therapy session of around 20 min. The test conditions mimicked as closely as possible the pilot study with the patients. However, these tests were performed at our computer science lab instead of the hospital.

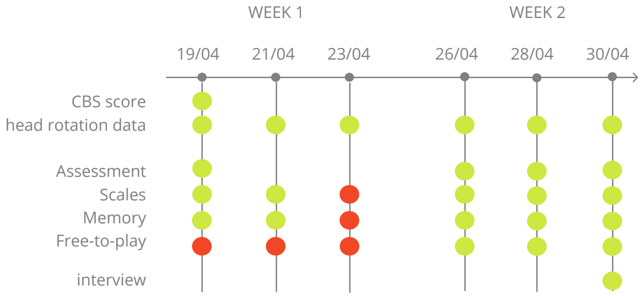

Figure 2.11: The timeline of the clinical study with patients indicates 6 sessions during 2 weeks. Each session consisted of a few tasks and data collection. Green markers indicate the available data; red markers indicate unavailable data.

2.6.2 Recruitment and Participants

The Rehabilitation Centre of the Ghent University Hospital selected four participants for this study. These 4 patients were undergoing rehabilitation therapy for USN at the moment of recruitment and all patients received their first VR therapy session on 19th April 2021 and their last session on 30th April 2021. The participants were all older than 12 years, suffered from an acquired brain injury with USN and were at least six months post-injury. Of the four participating patients, three had left-sided neglect, and one had right-sided neglect. Furthermore, every patient was assessed with standardised USN assessment tests prior to the study. These assessments showed that Patients 1 and 3 had significantly more severe neglect than Patients 2 and 4. Moreover, Patient 4 had Apraxia, i.e. a neurological disorder characterised by the inability to perform familiar movements on command, and a language disorder.

The leading researchers recruited the non-diagnosed test users of this study themselves. In total, four test users participated. Each user was also assessed using the CBS to confirm that they did not have USN. The TAP neglect test was not performed on these test users.

The information for each participant is summarised in Table 2.1. The first column is the pseudonym of the individual used in this paper. The second column indicates the participant's side of the neglect. The third and fourth columns present the CBS and TAP score. For Patient 4 and all test users, the results of the TAP assessment are not available.

2.6.3 Data Collection

The CBS and TAP scores, as discussed above, were collected at the start of the study. During the VR therapy, data about the user's interactions with the system were recorded. Specifically, the head direction of the user and the played notes were

Table 2.1: A table summarising the neglect assessments executed by the clinic. A higher CBS score indicates more severe neglect. More omissions and a higher reaction time on one side in the TAP test indicate neglect towards that same side.

Users	Neglect	CBS Score	TAP	
			Left	Right
Patient 1	left	19/30	reaction: 481 ms omissions: 15/22	reaction: 719 ms omissions: 2/22
Patient 2	left	8/30	reaction: 1074 ms omissions: 5/22	reaction: 834 ms omissions: 1/22
Patient 3	left	19/30	reaction: 1234 ms omissions: 18/22	reaction: 799 ms omissions: 2/22
Patient 4	right	7/30	–	–
Test user 5	none	0/30	–	–
Test user 6	none	0/30	–	–
Test user 7	none	0/30	–	–
Test user 8	none	0/30	–	–

registered in the VR application. Additionally, the time between each played note was also measured during the *Scales* task. For the *Memory* task, the instruction sequence, each played key and whether the key was correct were saved. The *Free-to-Play* task also recorded how long each ball rested on the surface of the key before it was hit. Finally, after all the VR therapy sessions were finished, the patients were interviewed to collect their impressions of the system. The medical experts were also interviewed to learn their findings of the proposed system and therapy. Figure 2.11 indicates the collected data for each session in the clinical pilot study. The green markers indicate the performed tasks for which data were available. The red markers show for which performed tasks data were not available. During the tests with test users, all the above mentioned data were collected for each user.

2.7 Results

The following section presents all results of the two-week pilot study with patients and the tests with non-clinical test users. All data that include a Euclidean angle have been standardised as follows. A positive angle means a rotation towards the neglected side of the patient, regardless of the neglect type of the patient. This allows the comparison of patients with left and right neglect in an equal manner. Furthermore, whenever applicable, the names of the keys and their positions are indicated on the axis of the graph, i.e. the angle between the note and the centre of the VR environment. However, the name of the key is less significant than the position with respect to its impact on USN.

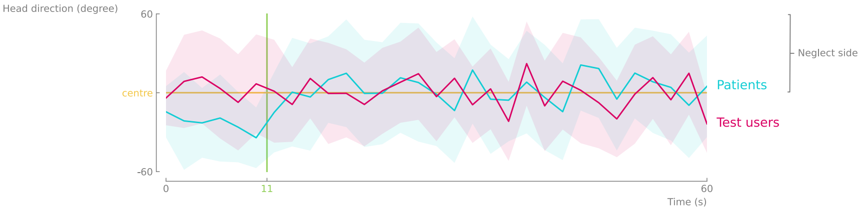

Figure 2.12: The average head direction of the first 60 s of all the Assessment tasks is aggregated and plotted for the clinical patients (blue) and the non-clinical test users (pink). The patients indicate a bias of around 20 degrees towards their non-neglected side for the first 11 s, the average time until the first key is played (green). This bias is corrected after this first stimulus, resulting in an average head direction fluctuating around the middle for the remainder of the 60 s.

2.7.1 Assessment Task

During the *Assessment*, the head direction of the users is recorded, resulting in traces for each user of each session. The average of all traces is calculated and compared for patients and test users. Figure 2.12 shows the first 60 s of the aggregations. The patients show a consistent bias of 20 to 30 degrees towards the non-neglected side during the first 11 s of each *Assessment*. After these 11 s, it appears that the average resides much closer to the centre of the playing area, albeit with a more significant standard deviation. This means that there is a large consensus among all patients to look at the non-neglected side during the first 11 s. The test users do not show this behaviour. Their average head direction is close to 0 degrees throughout the entire session. The standard deviation for the test users remains relatively consistent and is similar to that of the patients after the first 11 s. Figure 2.12 also indicates that, on average, the first key was played after approximately 11 s following the beginning of the traces.

The bias of the head direction during the *Assessment* task is further investigated. As the purpose of the *Assessment* task is to assess the severity of the USN in a patient, it is interesting to compare it to the CBS scores of the patients. Figure 2.13 shows how the CBS score correlates to the average head direction during the first 11 s (left) and the remainder of the task (right). Participants with a CBS score close to zero consistently have an average head direction close to zero. As the CBS score increases, bias in the average head direction can be observed. During the first 11 s, all patients with CBS > 0 have a bias towards the non-neglected side. For the remainder of the task, patients with CBS $<= 8$ show no bias any more, and they position their head in the centre, while patients with CBS > 8 show a bias towards the neglected side.

However, when observing the difference between the averages during the first 11 s of the *Assessment* and the rest of the task, a more significant correlation with the CBS score becomes apparent. In Figure 2.14, this difference is calculated and plotted against the CBS score. Indeed, the correlation appears linear within the range

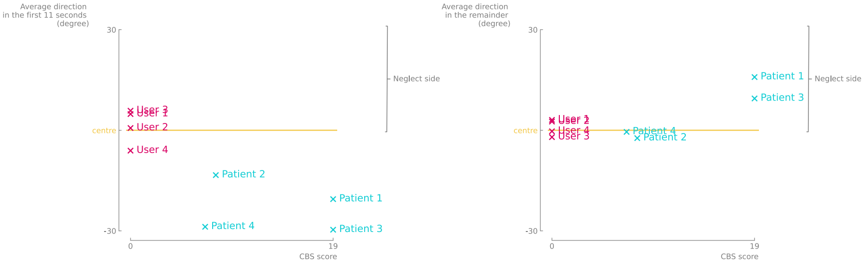

Figure 2.13: (**Left**) Users with a higher CBS score indicate a higher bias towards their non-neglected side compared to the users with a CBS score of 0. Within the patient sample, no significant difference in head direction can be observed based on the CBS score for the first 11 s. (**Right**) The CBS scores of all participants are plotted against the average head direction during the remainder of the Assessment. These show that the bias of the head direction has shifted towards the non-neglected side for users with a higher CBS score.

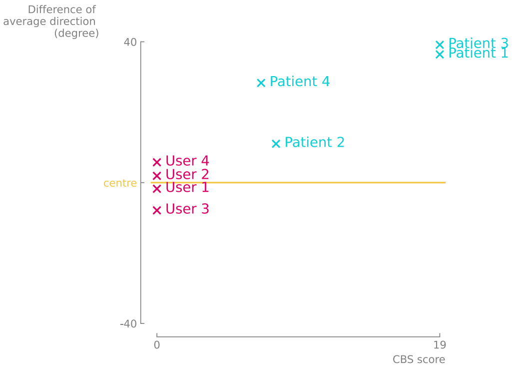

Figure 2.14: The CBS scores of all participants are plotted against the difference between average head direction during the first 11 s and the remainder of the Assessment. These indicate a linear correlation with a bias towards the neglected side. The higher the CBS score, the greater the bias towards the neglected side of space.

of CBS scores of 0 to 19. More specifically, users with a CBS score of 0 show minimal differences during the first 11 s and the remainder of the *Assessment* task. The larger the CBS score, the more significant this difference in bias becomes. The patients appear to apply a correction to their head direction in order to observe more of the environment.

2.7.2 Scales Task

The time to play the following key in the scale is extracted during the *Scales* task. Figure 2.15 shows the aggregated values of all sessions for patients and test users.

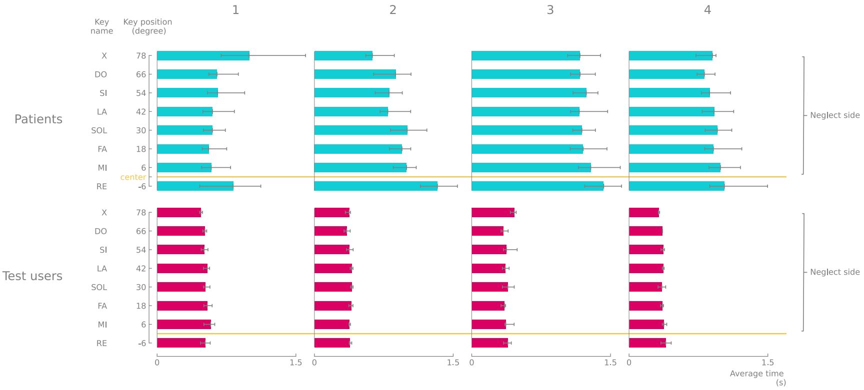

Figure 2.15: The median of the time it took to hit the required note during the Scales task for patients and test users. Quartiles Q1 and Q3 are indicated by the horizontal lines. Patient 1 required more time to hit the final key at the extreme end of their neglected side, whereas, for all patients, the time to hit the next key reduced gradually as they moved along the scale. The test users indicated a significantly faster response time compared to the clinical users.

The data in the graphs are the median time it took to play each key for all sessions, regardless of the difficulty level and the Q1 and Q3 quartiles. The time to play the first note on the scale is omitted in these figures. The value of this first keystroke represents the reaction time to the presentation of the visual stimulus on the first key, while all other values represent the time in between two keys being played. Leaving out the first key allows for a better comparison of the data. Patient 1 had difficulties with the last note in the sequence. It took them significantly longer to play that note than any other note. Moreover, the spread of the time values for this key is significantly wider; this suggests that they were not consistent in the time to play this key. For all patients, except Patient 1, the time to play the following key on the scale gradually reduces as they move further towards the neglected side. The time needed by the test user to play each key is significantly lower than that of the patients. In addition, the spread of the time values is much narrower for the test users compared to the patients.

2.7.3 Memory Task

For the *Memory* task, the correctly played keys and the mistakes are recorded. Firstly, the success rate of correctly repeating a sequence of notes is shown in Table 2.2 for all participants. This measure represents the fraction of correctly played sequences of all sequences played, including every retry of a sequence until they succeeded. In general, the non-clinical test users made fewer mistakes across the board than the clinical patients. Moreover, there are significant differences in success rates between the different patients. Patient 2 played the most erroneous sequences, while Patient 4

Table 2.2: The success rate for replaying sequences correctly during the Memory task for each patient. Patient 2 had the lowest success rate, while the success rate of Patient 4 approached that of the non-clinical users.

User	Success Rate
Patient 1	0.62
Patient 2	0.35
Patient 3	0.60
Patient 4	0.85
Test user 1	0.83
Test user 2	0.92
Test user 3	0.94
Test user 4	1.00

had a success rate approaching that of the non-clinical test users. Test user 4 did not make any mistakes.

Figure 2.16 shows the distributions of the notes in the instruction sequences and the played sequences for patients and test users. The size of the marker indicates the relative frequency of that note in both distributions. For all participants, most keys were played correctly, which can be seen by the large values on the diagonals of the graphs. However, the patients made significantly more mistakes than the test users. In particular, Patient 2 made many mistakes on individual keystrokes. Remarkably, Patient 2 confused almost each key for every other key at least once. A higher concentration can be seen towards the neglected side. This indicates that keys in the instruction sequence on the neglected side were often confused for another key. The data of Patient 3 show a similar pattern, where some keys in the far neglected side are more confused for other keys. The mistakes made by the other users are situated more closely to the instructed keys. In other words, the mistakes by the other users meant that they played a key only a few keys apart from the instructed key. The test users made minimal mistakes, which resulted in a sparse plot.

2.7.4 Free-to-Play Task

During the *Free-to-Play* task, the time for which each ball was resting on the surface was measured. Figure 2.17 presents these data for patients and test users. The data are the median time each key was not played while it should be played, as well as the Q1 and Q3 quartiles to indicate the spread of the timing values. For Patients 1, 2 and 3, an increase in time could be seen for the keys on the far most neglected side. Patients 2 and 4 also showed a significant increase for some keys in the centre of the playing area. Furthermore, in Patients 1 and 3, it was most apparent how keys up until 30 degrees toward the neglected side were played the quickest, while, beyond

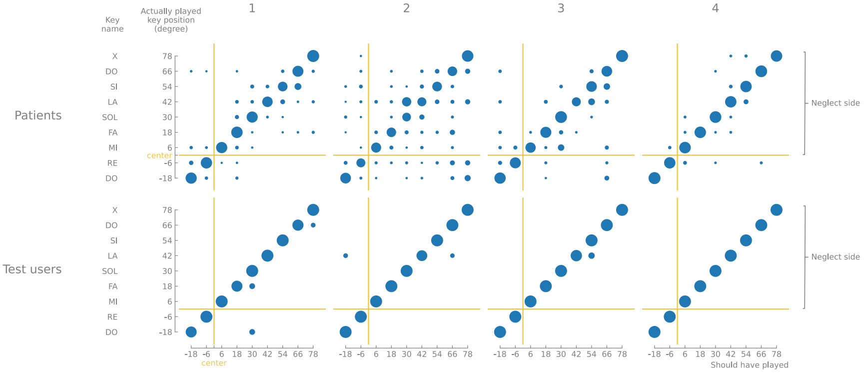

Figure 2.16: The distribution of the notes in the example sequence. The keys that should have been played, the played sequences and the keys that were played indicate that, overall, most keys were played correctly. Nonetheless, patients indicated a higher concentration of mistakes in general, mostly situated in their neglected side.

this angle, they were left unplayed for longer. Moreover, the spread of the timing values increased the further the key was to the neglected side. Finally, the test users left far fewer keys unplayed, and when they did, the duration was always considerably lower compared to the patients.

2.7.5 Evolution

Because the purpose of the rehabilitation tasks was to motivate patients to explore the entire playing area and pay attention to their neglected side, it was reasonable to investigate whether any evolution was noticeable across the two-week period. In particular, the *Memory* and *Free-to-Play* tasks were most interesting to investigate as these two tasks motivated the patient to explore the entire environment to notice stimuli and respond to them. The tasks themselves did not force the participant to look in a particular direction. Figure 2.18 plots the evolution of average head direction for the *Memory* and *Free-to-Play* tasks. The data of all six sessions are used. A slight gradual transition of the average head direction is visible across the two-week period for all patients.

2.7.6 Interviews

The feedback from the questioned patients suggests that they perceived the therapy as neither too complex nor too simple. Nevertheless, according to the participants, a high concentration level was required, which sometimes made it tiring. Two patients mentioned that their performance on the different tasks improved during the two weeks. One patient anecdotally said that now she was more inclined to look towards

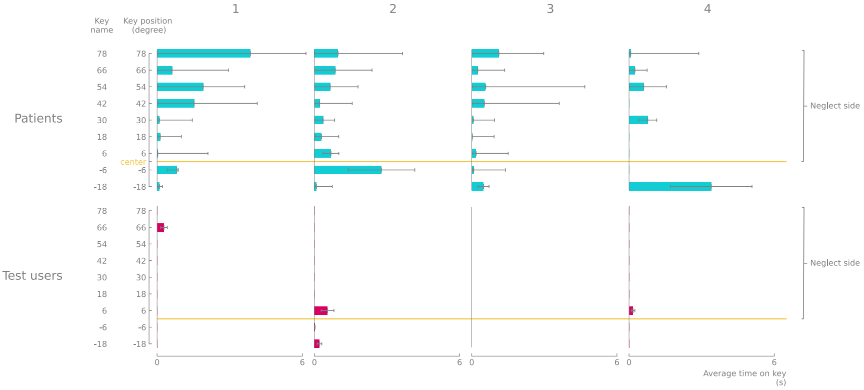

Figure 2.17: The median of the time for which a ball was lying on the surface for each key during the Free-to-Play task is remarkably higher for the patients than for the test users. Moreover, the spread of the values is wider, as seen by the quartiles Q1 and Q3, indicated by the horizontal lines. For most patients, keys on the extremity of the instrument in their neglected side remained unplayed for the longest. Patients 2 and 4 showed a somewhat similar increase for keys in the middle.

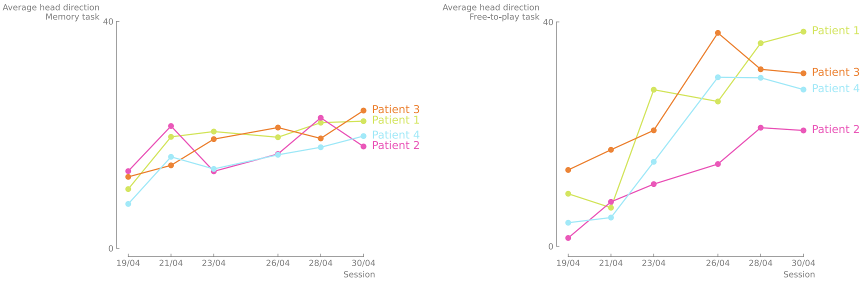

Figure 2.18: (**Left**) The average head direction for the Memory task for each patient during all 6 sessions indicates a gradually increasing correction towards their neglected side. (**Right**) The average head direction for the Free-to-Play task for each patient during all 6 sessions indicates a gradually increasing correction towards their neglected side.

her neglected side while sitting in the car. However, the other two patients mentioned no noticeable differences in real life. Finally, all three questioned patients would be willing to receive this therapy as part of their current treatment.

The medically trained therapists that supervised the VR sessions and who administered regular therapy believed that the proposed therapy tool could treat neglect at an early rehabilitation stage. Training three modalities, visual, auditory and motor, posed a significant advantage for using VR in USN therapy. Moreover, the increased independence and immersion of the therapy were considered beneficial. Motion sickness, epilepsy and the inability to visually explain things were reported as disadvantages of VR in USN therapy. Lastly, it is believed that the proposed tool would be a meaningful addition to the other therapy methods of the clinic.

2.8 Discussion

A thorough discussion of the results and an investigation of the study's limitations are provided in this section. Firstly, the most interesting and notable findings of the different therapy tasks are presented. Next, based on these findings, the research questions are revisited and discussed. Finally, the limitations of the study and the resulting data are investigated and discussed.

2.8.1 Findings

All patients could perform all tasks with sufficient proficiency. However, in all cases, their performance of the tasks was significantly lower than that of the test users. This may indicate the sufficient motor and cognitive challenges that the tasks present. It could also indicate that the tasks do not sufficiently act on the USN, and additional challenges can be added in future iterations. The diagnosed USN did not prohibit any of the patients to perform a task, nor did their diagnosis lead them to completely ignore part of virtual instrument. However, the results of the VR rehabilitation show some patterns that suggest that the USN has an impact on the patients' performance and that they need to adapt their behaviour to perform them successfully. These patterns in behaviour are discussed in detail below, and possible interpretations are presented.

2.8.1.1 Assessment Task

The data of the *Assessment* show a clear and interesting phenomenon. During the first 11 s of the *Assessment*, all patients are biased on the average head direction towards their non-neglected side. The assumption is that this is their natural behaviour, i.e. the patients tend to look and explore their non-neglected side when no stimuli are presented. However, after approximately 11 s, when, on average, the first key is played, the average head direction shifts towards the centre and sometimes even towards the neglected side. It is assumed that this is taught behaviour of the patients, i.e. whenever external stimuli are presented, they shift their attention to the neglected side. Patients 1 and 3 corrected their head direction more severely compared to Patients 2 and 4. This is most likely related to the significantly higher CBS scores of Patients 1 and 3. As they had more severe neglect, a more significant correction to their head direction is warranted, to observe the entire environment successfully. This correlation is evident in Figure 2.14 for the available data. Ultimately, the *Assessment* task should result in a metric that accurately predicts the degree of USN in a patient. Additional data points of more patients would be needed to further investigate this behaviour and the correlation with the CBS score.

2.8.1.2 Scales Task

For the *Scales* task, two patterns are observed. First, for all patients, except Patient 1, the time to play a key gradually decreased the further it was towards the neglected side. Second, Patient 1 needed significantly more time to play the ultimate key. The reduction in the time to play the following key can be explained by the cognitive effort required to play the first key compared to the keys following it. Once the participant has found the pattern, i.e. playing one key after the other, this action can be performed faster and with less cognitive effort. This behaviour can most clearly be seen for Patients 2 and 4. The other patients and the test users also had the same pattern but less pronounced. A possible explanation for the second pattern is that the different nature of the ultimate key impacts the perception of the users on the neglected side. Specifically, the last keys play a sound that is not congruent in pitch compared to the other keys. The patient could be conditioned not to play the last note as it does not belong to the scale. However, this appears to only happen for tasks of the highest difficulty (nine keys). This explanation is in line with the findings of Bernardi et al. [17], which stated that individuals performed better under conditions with congruent sound feedback compared to random sound feedback. In this case, patients needed more time to play the last key, which is the only key to produce a sound not part of the musical scale, i.e. random sound feedback, compared to the rest of the keys, which each produce a pitch part of the musical scale, i.e. congruent sound feedback.

2.8.1.3 Memory Task

In the data of the *Memory* task, there are also two patterns. The first pattern can be seen for all participants. They mistakenly play a key very close to the instructed key, e.g. when the instruction sequence shows an Fa, but the user plays an Mi or a Sol, both adjacent to Fa. This is expected behaviour and can be classified as a consequence of the participants' cognitive capacity, specifically memory. The number of mistakes of this type is relatively low. The second pattern can mainly be seen in Patient 2 and to a lesser extent in Patient 3. These patients make another mistake with a relatively higher occurrence than the former type. When playing a sequence, they make more mistakes when the instruction key is in the most peripheral area of their neglect than closer to the centre, e.g. Patient 2 often plays the first or second key when the eighth or ninth are instructed. Furthermore, Patients 2 and 3 have the lowest success rates for playing a correct sequence. Exploration and reaction to visual and auditory stimuli are crucial in this task. The users can respond to the auditory stimulus to get a general idea of the location of the key, but they usually need to look for the visual cue to observe the exact key to play. The assumption is made that the average head direction during a task is a good indicator of exploration. That is, the greater the deviation of the average head direction from the centre of the playing area, the better the user is exploring that peripheral area. When looking at the evolution of the average head direction during the *Memory* task, a gradual shift can be seen moving away from the centre. This could indicate that the participants perform better exploration as the rehabilitation sessions progress. Thus, it could be taught behaviour from the tasks that persists in between sessions. The test users made very few mistakes in general. Therefore, minimal data on their behaviour are available, and an insightful comparison is infeasible.

2.8.1.4 Free-to-Play Task

In the *Free-to-Play* task, some behaviour is visible in the data of Patients 1, 2 and 3. Specifically, the more towards the neglected side it is, the more likely a key will be left unplayed for longer. This behaviour is unmistakable evidence of USN. This task has no limited exploration phase as with the *Memory* task; the cues appear continuously and thus exploration is required continuously. An action also did not lead to a predictable next stimulus as with the *Scales* task. Indeed, for the *Free-to-Play* task, stimuli could appear at random times and in random order. Furthermore, the stimuli are only visual (the ball turning green and then red while resting on a key). Therefore, the user must continuously scan the playing area for visual cues, and the incentive to do so depends entirely on the user's ability. This can explain why the centre of the playing area is explored the most while the peripheral area is the least. Therefore, it can also explain why the keys in the centre are left unplayed for the shortest time on average. Moreover, also for this task, a noteworthy evolution is visible in the pattern of the average head direction of the different sessions. The patients appear to be exploring more as sessions in VR progress, as is the case for the *Memory* task. This can also indicate that some behaviour is taught to explore the neglected side. This behaviour provides additional evidence that the presented VR system contributes to the rehabilitation of patients with USN. Moreover, for this task, minimal mistakes were made by the test users, meaning that they rarely let a ball touch a key, and therefore, not a lot of data are available. This makes a comparison infeasible. This task aims explicitly to encourage patients to explore their neglected peripheral area. This was the reason for placing most keys on the neglected side instead of distributing them evenly as for the *Assessment* task. Comparable data from the *Assessment* would provide more insights into the behaviour of the patients and the impact of the VR tasks. Unfortunately, these data are not available from this study.

2.8.2 Research Questions

With the available information and insights, answers can be formulated to the research questions first presented in Section 2.3.

- **"Can MNT be effectively translated in a VR environment?"**
  The tests show promising results to support the application of MNT in VR. As indicated by the medical experts in the interviews, the combination of visual and auditory stimuli is beneficial. Combining both triggers and training the patients on both modalities teaches them connections between the two. The results also show some evidence that the addition of auditory stimuli impacts the performance of the exercises. On the one hand, in the *Memory* task, where users also respond to sound cues, half of the patients show some difference in performance based on where the stimuli are shown. That is, they perform worse for stimuli presented in the far most neglected side. On the other hand, in the *Free-to-Play* task, where users only respond to visual stimuli, 3 out of 4 patients show significantly worse performance, which can be linked to the USN. However, precaution is warranted with respect to the adoption of the proposed VR system for individuals susceptible to motion sickness and epilepsy in VR.

- **"Can the newly designed VR system be used for the treatment of adults with USN with an acquired brain injury?"**
  For the *Scales* task, not enough evidence is obtained that the mistakes made by the patient are the result of their USN. However, this does not mean that the task serves no purpose or does not train the patients in any way. The patients' attention is gradually guided towards the peripheral area on the neglected side. The data show that all patients successfully form this motion, and by doing so, they are urged to observe their neglected side as well. The patients performed quite differently in the *Memory* and *Free-to-Play* tasks. The results of these tasks do show the influence of the USN. In general, they performed worse on their neglected side. This provides sufficient evidence for the assumption that the patients were trained to perform better despite their USN, thereby treating the disorder. Furthermore, two of the patients were reported to perceive improvements in their performance of the different tasks. In conclusion, all patients could perform the exercises and no problems arose in the pilot study that would prevent this solution from being researched further. There is evidence to support the notion that the rehabilitation tasks have some effect on the USN disorder in the patients. However, additional studies are needed to investigate the significance and persistence of these effects.

- **"Will the spatial performance of the patient with an acquired brain injury**

evolve positively after treatment with the VR system?"
The two-week limitation of this study prohibits a conclusive answer to this question. However, there is some evidence that suggests intra-session improvements in the exploration of the participants for the *Memory* and *Free-to-Play* tasks. Unfortunately, no insights are gathered on the persistence of this effect towards everyday life situations in the long term. One patient did report that they experienced improvements in daily life during the two-week period. It is also crucial to discuss what else could influence the apparent evolution of the head direction during sessions. Indeed, the gradual increase in the average head direction may result from taught behaviour during previous VR exercises. However, it is also possible that the change in the average head direction is the direct consequence of the different sessions themselves. Specifically, as the sessions progressed, the task's difficulty was often increased. A greater difficulty always meant that more notes were presented, and therefore a larger area of the playing area was needed. Thus, stimuli were presented in a larger area, which inherently would force users to explore more towards the neglected side as well. This would also result in an increase in the average head direction. Finally, it is also possible that the evolution of the behaviour in between sessions is not a result of the VR rehabilitation itself but of the rehabilitation the patients received in between VR sessions. Of course, a combination of any explanations is still possible.

2.8.3 Limitations

To perform a good analysis of the result in Section 2.7, it is important to understand the limitations and shortcomings of the study. Firstly, the sample size of $n = 8$ participants, of which four were clinically diagnosed USN patients, is relatively small. The statistical relevance of the results and the conclusions arising from them should be interpreted with a critical mind. Additional tests with clinical patients and non-clinical test users are required to further support the findings presented in this section. Secondly, the data collected during the tests solely focus on measuring the head direction and the task performance. Thirdly, the VR environment and the xylophone are currently abstract visualisations and can be extended in the future to create a more realistic experience. Furthermore, general prior knowledge of the participants is limited to the severity of USN. Therefore, recognising whether the recorded behaviour is induced by the USN or another underlying condition is impossible, e.g. the diagnosis of apraxia in Patient 4 could also impact the collected data. In this discussion, the assumption is adopted that any behaviour found in a patient is mainly the result of their USN diagnosis.

2.9 Conclusions

Currently used rehabilitation methods for USN often fail to take into account the heterogeneity of the syndrome by solely focusing on the visual modality. MNT shows great potential to bridge this gap, incorporating multiple modalities in the training process. The use of VR in rehabilitation has shown many advantages over traditional methods as it facilitates the modification of the therapy and allows for increased data collection regarding therapy progress.

Therefore, the authors designed, developed and evaluated a novel VR therapy tool for MNT. This paper investigated the feasibility of the tool for the rehabilitation of patients diagnosed with USN. The resulting proof of concept was evaluated during a two-week pilot study with four clinical patients and compared to the results of four non-clinical test users.

The results of the study indicated that the patients with USN were capable of performing the four rehabilitation tasks and indicated increased enjoyment. Next, the results showed that non-clinical test users performed significantly better than clinical users with respect to task performance, which indicates that the system is able to discern between users with USN and users without USN. Furthermore, this result indicates that the tasks were challenging the patients. Nonetheless, for each task, the patients were able to respond to their entire environment and the presented triggers successfully. Over the course of 2 weeks, patients were shown to increasingly adjust their head direction towards their neglected side for the *Memory* and *Free-to-Play* tasks, presumably to improve their task performance. These results indicate that the VR tool managed to successfully translate MNT to a virtual environment and that the tool shows promise for the rehabilitation of USN. Moreover, the participating medical experts of this study responded positively to the developed tool. They believe that it will be a useful tool at an early rehabilitation stage. However, it should be noted that the sample size was limited to four clinical patients and four non-clinical test users. Additionally, the measures used in this study were solely focused on head rotation and task performance.

In conclusion, the tool developed by the authors is a valuable contribution to the current research on rehabilitation for USN as it is the first system to apply MNT in a VR environment. The promising results show increased enjoyment in the patients and sufficient challenges in the tasks. However, the tool and the evaluation have their limitations, specifically the limited sample size and limited metrics. With the enthusiasm to continue the research, future work should, therefore, focus on validating these results over a longer rehabilitation period with a larger sample. Moreover, due to the heterogeneity of the syndrome, future work should explore the incorporation of personalisation and gamification to fulfil the needs of the patients and further increase enjoyment during the rehabilitation process.

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Author Contributions

Conceptualisation, J.H., S.C., E.V., C.V.L. and F.D.B.; methodology, J.H., S.C., E.V. and C.V.L.; software, E.V.; validation, J.H., S.C. and C.V.L.; formal analysis, J.H. and S.C.; investigation, S.C. and E.V.; data curation, J.H. and E.V.; writing—original draft preparation, J.H., S.C. and E.V.; writing—review and editing, J.H., S.C., C.V.L., F.D.B. and F.D.T.; visualisation, J.H. and S.C.; supervision, F.D.T. All authors have read and agreed to the published version of the manuscript.

References

[1] R. Gammeri, C. Iacono, R. Ricci, and A. Salatino. *Unilateral Spatial Neglect After Stroke: Current Insights.* Neuropsychiatric Disease and Treatment, 16:131, jan 2020. Available from: /pmc/articles/PMC6959493//pmc/articles/PMC6959493/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC6959493/, doi:10.2147/NDT.S171461.

[2] A. Puig-Pijoan, E. Giralt-Steinhauer, A. Zabalza de Torres, R. M. Manero Borràs, G. Sánchez-Benavides, G. García Escobar, C. Pérez Enríquez, A. Gómez-González, Á. Ois, A. Rodríguez-Campello, E. Cuadrado-Godía, J. Jiménez-Conde, J. Peña-Casanova, and J. Roquer. *Underdiagnosis of Unilateral Spatial Neglect in stroke unit.* Acta Neurologica Scandinavica, 138(5):441–446, nov 2018. doi:10.1111/ane.12998.

[3] P. Sandercock. *World Stroke Day*, 2018. Available from: https://www.who.int/southeastasia/news/speeches/detail/world-stroke-day-2019, doi:10.1161/STROKEAHA.118.023089.

[4] M. Corbetta and G. L. Shulman. *Spatial Neglect and Attention Networks.* Annual Review of Neuroscience, 34(1):569–599, July 2011. Available from: https://www.annualreviews.org/doi/10.1146/annurev-neuro-061010-113731, doi:10.1146/annurev-neuro-061010-113731.

[5] K. M. Heilman, E. Valenstein, and R. T. Watson. *Neglect and related disorders*, 2000. doi:10.1055/s-2000-13179.

[6] T. Shimizu, T. Abe, Y. Akasaki, and H. Kamiishi. *Unilateral spatial neglect*, 2020. Available from: https://strokengine.ca/en/consequences/unilateral-spatial-neglect/, doi:10.1136/bcr-2020-239770.

[7] I. H. Robertson, R. Tegnér, K. Tham, A. Lo, and I. Nimmo-Smith. *Sustained Attention Training for Unilateral Neglect: Theoretical and Rehabilitation Implications.* Journal of Clinical and Experimental Neuropsychology, 17(3):416–430, jun 1995. doi:10.1080/01688639508405133.

[8] P. Plummer, M. E. Morris, and J. Dunai. *Assessment of unilateral neglect.* Physical Therapy, 83(8):732–740, aug 2003. doi:10.1093/ptj/83.8.732.

[9] A. R. Riestra and A. M. Barrett. *Rehabilitation of spatial neglect.* In Handbook of Clinical Neurology, volume 110, pages 347–355. Elsevier B.V., jan 2013. doi:10.1016/B978-0-444-52901-5.00029-0.

[10] L. Diller and J. Weinberg. *Hemi-inattention in rehabilitation: the evolution of a rational remediation program.* Advances in neurology, 18:63–82, 1977.

[11] M. H. Thaut. *Rhythm, music, and the brain: Scientific foundations and clinical applications.* 2005. Available from: https://books.google.be/books?hl=nl{&}lr={&}id=j25HB8yND80C{&}oi=fnd{&}pg=PP2{&}dq=Rhythm,+Music+and+the+Brain:+Scientific+Foundations+and+Clin-ical+Applications{&}ots=LS2begkrSi{&}sig=vlH-Y76GhkJEeE8XAsvcgwvlWvQ{#}v=onepage{&}q=Rhythm{%}2CMusicandtheBrain{%}3AScientific, doi:10.4324/9780203958827.

[12] K. Li and P. A. Malhotra. *Spatial neglect*, oct 2015. doi:10.1136/practneurol-2015-001115.

[13] M. Li, G. Dong, W. Zhang, X. Ren, H. Jiang, C. Yang, X. Zhao, Q. Zhu, M. Li, H. Chen, K. Yu, Y. Cui, and L. Song. *Combining MGMT promoter pyrosequencing and protein expression to optimize prognosis stratification in glioblastoma.* Cancer Science, 112(9):3699–3710, sep 2021. Available from: /pmc/articles/PMC8409410//pmc/articles/PMC8409410/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC8409410/, doi:10.1111/cas.15024.

[14] N. Montemurro, G. N. Fanelli, C. Scatena, V. Ortenzi, F. Pasqualetti, C. M. Mazzanti, R. Morganti, F. Paiar, A. G. Naccarato, and P. Perrini. *Surgical outcome and molecular pattern characterization of recurrent glioblastoma multiforme: A single-center retrospective series.* Clinical Neurology and Neurosurgery, 207, aug 2021. doi:10.1016/j.clineuro.2021.106735.

[15] A. Bowen, K. McKenna, and R. C. Tallis. *Reasons for variability in the reported rate of occurrence of unilateral spatial neglect after stroke.* Stroke, 30(6):1196–1202, jun 1999. Available from: https://www.ahajournals.org/doi/10.1161/01.STR.30.6.1196, doi:10.1161/01.STR.30.6.1196.

[16] G. Gianotti, L. Giustolisi, and U. Nocentini. *Contralateral and ipsilateral disorders of visual attention in patients with unilateral brain damage.* Journal of Neurology Neurosurgery and Psychiatry, 53(5):422–426, may 1990. doi:10.1136/jnnp.53.5.422.

[17] N. F. Bernardi, M. C. Cioffi, R. Ronchi, A. Maravita, E. Bricolo, L. Zigiotto, L. Perucca, and G. Vallar. *Improving left spatial neglect through music scale playing.* Journal of Neuropsychology, 11(1):135–158, mar 2017. Available from: http://doi.wiley.com/10.1111/jnp.12078, doi:10.1111/jnp.12078.

[18] J. B. Rich and A. K. Troyer. *Clinical neuropsychology.* In C. A. Meyers and J. R. Perry, editors, Cognition and Cancer, pages 6–18. Cambridge University Press, Cambridge, 2008. Available from: https://www.cambridge.org/core/product/identifier/CBO9780511545900A010/type/book_part, doi:10.1017/CBO9780511545900.003.

[19] T. D. Punt and M. J. Riddoch. *Motor neglect: Implications for movement and rehabilitation following stroke*, jul 2006. doi:10.1080/09638280500535025.

[20] D. Grossi, R. Angelini, A. Pecchinenda, and L. Pizzamiglio. *Left imaginal neglect in heminattention: Experimental study with the O'clock Test.* Technical Report 3, 1993. doi:10.3233/BEN-1993-6307.

[21] P. Chen and K. M. Goedert. *Clock drawing in spatial neglect: A comprehensive analysis of clock perimeter, placement, and accuracy.* Journal of Neuropsychology, 6(2):270–289, sep 2012. Available from: /pmc/articles/PMC3371137/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC3371137/, doi:10.1111/j.1748-6653.2012.02028.x.

[22] K. M. Heilman, E. Valenstein, and R. T. Watson. *The What and How of Neglect.* Neuropsychological Rehabilitation, 4(2):133–139, jun 1994. doi:10.1080/09602019408402270.

[23] N. Beschin and I. H. Robertson. *Personal versus extrapersonal neglect: A group study of their dissociation using a reliable clinical test.* Cortex, 33(2):379–384, 1997. doi:10.1016/S0010-9452(08)70013-3.

[24] S. Ferber and H. O. Karnath. *How to assess spatial neglect - Line bisection or cancellation tasks?* Journal of Clinical and Experimental Neuropsychology, 23(5):599–607, 2001. Available from: https://www.tandfonline.com/doi/abs/10.1076/jcen.23.5.599.1243https://pubmed.ncbi.nlm.nih.gov/11778637/, doi:10.1076/jcen.23.5.599.1243.

[25] P. Azouvi. *The ecological assessment of unilateral neglect*, jun 2017. doi:10.1016/j.rehab.2015.12.005.

[26] L. Gamberini, B. Seraglia, and K. Priftis. *Processing of peripersonal and extrapersonal space using tools: Evidence from visual line bisection in real and virtual environments.* Neuropsychologia, 46(5):1298–1304, jan 2008. doi:10.1016/j.neuropsychologia.2007.12.016.

[27] T. Schenkenberg, D. C. Bradford, and E. T. Ajax. *Line bisection and unilateral visual neglect in patients with neurologic impairment.* Neurology, 30(5):509–517, may 1980. Available from: https://n.neurology.org/content/30/5/509https://n.neurology.org/content/30/5/509.abstract, doi:10.1212/wnl.30.5.509.

[28] E. Làdavas. *The Role of Visual Attention in Neglect: A Dissociation between Perceptual and Directional Motor Neglect.* Neuropsychological Rehabilitation, 4(2):155–159, jun 1994. doi:10.1080/09602019408402275.

[29] R. Ronchi, L. Posteraro, P. Fortis, E. Bricolo, and G. Vallar. *Perseveration in left spatial neglect: Drawing and cancellation tasks*. Cortex, 45(3):300–312, mar 2009. doi:10.1016/j.cortex.2008.03.012.

[30] P. Azouvi, C. Samuel, A. Louis-Dreyfus, T. Bernati, P. Bartolomeo, J. M. Beis, S. Chokron, M. Leclercq, F. Marchal, Y. Martin, G. De Montety, S. Olivier, D. Perennou, P. Pradat-Diehl, C. Prairial, G. Rode, E. Siéroff, L. Wiart, and M. Rousseaux. *Sensitivity of clinical and behavioural tests of spatial neglect after right hemisphere stroke*. Journal of Neurology Neurosurgery and Psychiatry, 73(2):160–166, 2002. doi:10.1136/jnnp.73.2.160.

[31] P. Molenberghs and M. V. Sale. *Testing for spatial neglect with line bisection and target cancellation: Are both tasks really unrelated?* PLoS ONE, 6(7):e23017, jul 2011. doi:10.1371/journal.pone.0023017.

[32] W. Sturm, M. Thimm, F. Binkofski, H. Horoufchin, G. Fink, J. Küst, H. Karbe, and K. Willmes. *Combined space and alertness related therapy of visual hemineglect: Effect of therapy frequency*. Frontiers in Human Neuroscience, 7(JUN), jun 2013. Available from: /pmc/articles/PMC3727078//pmc/articles/PMC3727078/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC3727078/, doi:10.3389/fnhum.2013.00373.

[33] B. Wilson, J. Cockburn, and P. Halligan. *Development of a behavioral test of visuospatial neglect*. Archives of Physical Medicine and Rehabilitation, 68(2):98–102, 1987.

[34] P. Zoccolotti and A. Judica. *Functional Evaluation of Hemineglect by Means of a Semistructured Scale: Personal Extrapersonal Differentiation*. Neuropsychological Rehabilitation, 1(1):33–44, jan 1991. doi:10.1080/09602019108401378.

[35] G. Kerkhoff and T. Schenk. *Rehabilitation of neglect: An update*, may 2012. doi:10.1016/j.neuropsychologia.2012.01.024.

[36] J. Luauté, P. Halligan, G. Rode, Y. Rossetti, and D. Boisson. *Visuo-spatial neglect: A systematic review of current interventions and their effectiveness*, 2006. doi:10.1016/j.neubiorev.2006.03.001.

[37] V. Singh-Curry and M. Husain. *Rehabilitation in practice: Hemispatial neglect: Approaches to rehabilitation*. Clinical Rehabilitation, 24(8):675–684, aug 2010. doi:10.1177/0269215509357851.

[38] M. Jeannerod and B. Biguer. *The directional coding of reaching movements. A visuomotor conception of spatial neglect*. Advances in Psychology, 45(C):87–113, 1987. doi:10.1016/S0166-4115(08)61710-0.

[39] F. Frassinetti, V. Angeli, F. Meneghello, S. Avanzi, and E. Làdavas. *Long-lasting amelioration of visuospatial neglect by prism adaptation.* Brain, 125(3):608–623, 2002. doi:10.1093/brain/awf056.

[40] N. Vaes, G. Nys, C. Lafosse, L. Dereymaeker, K. Oostra, D. Hemelsoet, and G. Vingerhoets. *Rehabilitation of visuospatial neglect by prism adaptation: effects of a mild treatment regime. A randomised controlled trial.* Neuropsychological Rehabilitation, 28(6):899–918, aug 2018. doi:10.1080/09602011.2016.1208617.

[41] M. Halicka, A. D. Vittersø, H. McCullough, A. Goebel, L. Heelas, M. J. Proulx, and J. H. Bultitude. *Prism adaptation treatment for upper-limb complex regional pain syndrome: a double-blind randomized controlled trial.* Pain, 162(2):471–489, February 2021. Available from: https://journals.lww.com/10.1097/j.pain.0000000000002053, doi:10.1097/j.pain.0000000000002053.

[42] I. H. Robertson and N. North. *Active and passive activation of left limbs: Influence on visual and sensory neglect.* Neuropsychologia, 31(3):293–300, mar 1993. doi:10.1016/0028-3932(93)90093-F.

[43] Y. G. Yi, M. H. Chun, K. H. Do, E. J. Sung, Y. G. Kwon, and D. Y. Kim. *The effect of transcranial direct current stimulation on neglect syndrome in stroke patients.* Annals of Rehabilitation Medicine, 40(2):223–229, 2016. Available from: /pmc/articles/PMC4855115//pmc/articles/PMC4855115/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC4855115/, doi:10.5535/arm.2016.40.2.223.

[44] H. Samuelsson, E. K. Elisabeth Hjelmquist, C. Jensen, S. Ekholm, and C. Blomstrand. *Nonlateralized attentional deficits: An important component behind persisting visuospatial neglect?* Journal of Clinical and Experimental Neuropsychology, 20(1):73–88, 1998. doi:10.1076/jcen.20.1.73.1481.

[45] A. C. Vink, M. S. Bruinsma, and R. J. Scholten. *Music therapy for people with dementia.* In Cochrane Database of Systematic Reviews, number 4. John Wiley & Sons, Ltd, oct 2003. Available from: https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD003477.pub2/fullhttps://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD003477.pub2/abstract, doi:10.1002/14651858.cd003477.pub2.

[46] C. Gold, T. Wigram, and C. Elefant. *Music therapy for autistic spectrum disorder.* In Cochrane Database of Systematic Reviews, number 2. John Wiley & Sons, Ltd, apr 2006. Available from: https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD004381.pub2/fullhttps://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD004381.pub2/abstract, doi:10.1002/14651858.cd004381.pub2.

[47] V. Underland, I. Sæterdal, and E. S. Nilsen. *Music therapy for acquired brain injury*, mar 2012. Available from: https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD006787.pub2/fullhttps://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD006787.pub2/abstract, doi:10.1002/14651858.cd006787.pub2.

[48] R. J. Zatorre, J. L. Chen, and V. B. Penhune. *When the brain plays music: Auditory-motor interactions in music perception and production*, jul 2007. doi:10.1038/nrn2152.

[49] A. Guilbert, S. Clément, and C. Moroni. *Hearing and music in unilateral spatial neglect neuro-rehabilitation*, dec 2014. doi:10.3389/fpsyg.2014.01503.

[50] E. Altenmüller and G. Schlaug. *Neurologic music therapy: The beneficial effects of music making on neurorehabilitation*. Acoustical Science and Technology, 34(1):5–12, 2013. Available from: http://japanlinkcenter.org/DN/JST.JSTAGE/ast/34.5?lang=en{&}from=CrossRef{&}type=abstract, doi:10.1250/ast.34.5.

[51] J. S. Jenkins. *The Mozart Effect*. Journal of the Royal Society of Medicine, 94(4):170–172, April 2001. Available from: http://journals.sagepub.com/doi/10.1177/014107680109400404, doi:10.1177/014107680109400404.

[52] P. L. Tsai, M. C. Chen, Y. T. Huang, K. C. Lin, K. L. Chen, and Y. W. Hsu. *Listening to classical music ameliorates unilateral neglect after stroke*. American Journal of Occupational Therapy, 67(3):328–335, 2013. Available from: https://ajot.aota.org/article.aspx?articleid=1851684, doi:10.5014/ajot.2013.006312.

[53] M. C. Chen, P. L. Tsai, Y. T. Huang, and K. C. Lin. *Pleasant music improves visual attention in patients with unilateral neglect after stroke*. Brain Injury, 27(1):75–82, 2013. Available from: https://www.tandfonline.com/doi/abs/10.3109/02699052.2012.722255, doi:10.3109/02699052.2012.722255.

[54] P. Lidji, R. Kolinsky, A. Lochy, and J. Morais. *Spatial Associations for Musical Stimuli: A Piano in the Head?* Journal of Experimental Psychology: Human Perception and Performance, 33(5):1189–1207, 2007. Available from: https://www.researchgate.net/publication/5919908, doi:10.1037/0096-1523.33.5.1189.

[55] M. Hartmann. *Non-musicians also have a piano in the head: evidence for spatial–musical associations from line bisection tracking*. Cognitive Processing, 18(1):75–80, feb 2017. Available from: http://audacity.sourceforge.net, doi:10.1007/s10339-016-0779-0.

[56] K. Kang and M. H. Thaut. *Musical neglect training for chronic persistent unilateral visual neglect post-stroke*. Frontiers in Neurology, 10(MAY):474, may 2019. Available from: https://www.frontiersin.org/article/10.3389/fneur.2019.00474/full, doi:10.3389/fneur.2019.00474.

[57] A. Guilbert, S. Clément, and C. Moroni. *A rehabilitation program based on music practice for patients with unilateral spatial neglect: a single-case study*. Neurocase, 23(1):12–21, jan 2017. doi:10.1080/13554794.2016.1265652.

[58] R. Bodak, P. Malhotra, N. F. Bernardi, G. Cocchini, and L. Stewart. *Reducing chronic visuo-spatial neglect following right hemisphere stroke through instrument playing*. Frontiers in Human Neuroscience, 8(JUNE):413, jun 2014. Available from: http://journal.frontiersin.org/article/10.3389/fnhum.2014.00413/abstract, doi:10.3389/fnhum.2014.00413.

[59] R. N. McNish, P. Chembrammel, N. C. Speidel, J. J. Lin, and C. López-Ortiz. *Rehabilitation for children with dystonic cerebral palsy using haptic feedback in virtual reality: Protocol for a randomized controlled trial*. JMIR Research Protocols, 8(1):1–14, 2019. doi:10.2196/11470.

[60] M. Osumi, K. Inomata, Y. Inoue, Y. Otake, S. Morioka, and M. Sumitani. *Characteristics of phantom limb pain alleviated with virtual reality rehabilitation*. Pain Medicine (United States), 20(5):1038–1046, may 2019. Available from: www.edanzediting.com/ac, doi:10.1093/pm/pny269.

[61] J. Heyse, F. Ongenae, B. Depreeuw, T. Van Daele, T. Daeseleire, F. De Backere, and F. De Turck. *An Adaptation Algorithm for Personalised Virtual Reality Exposure Therapy*. Computer Methods and Programs in Biomedicine, 2021 (Manuscript submitted for publication).

[62] J. Heyse, M. Torres Vega, T. De Jonge, F. De Backere, and F. De Turck. *A Personalised Emotion-Based Model for Relaxation in Virtual Reality*. Applied Sciences, 10(17), 2020. Available from: https://www.mdpi.com/2076-3417/10/17/6124, doi:10.3390/app10176124.

[63] K. Thangavelu, J. A. Hayward, N. A. Pachana, G. J. Byrne, L. K. Mitchell, G. M. Wallis, T. R. Au, and N. N. Dissanayaka. *Designing Virtual Reality Assisted Psychotherapy for Anxiety in Older Adults Living with Parkinson's Disease: Integrating Literature for Scoping*, 2020. doi:10.1080/07317115.2019.1709597.

[64] D. Freeman, S. Reeve, A. Robinson, A. Ehlers, D. Clark, B. Spanlang, and M. Slater. *Virtual reality in the assessment, understanding, and treatment of mental health disorders*, oct 2017. Available from: https://doi.org/10.1017/S003329171700040X, doi:10.1017/S003329171700040X.

[65] D. Cano Porras, H. Sharon, R. Inzelberg, Y. Ziv-Ner, G. Zeilig, and M. Plotnik. *Advanced virtual reality-based rehabilitation of balance and gait in clinical practice*. Therapeutic Advances in Chronic Disease, 10:204062231986837, jan 2019. Available from: http://journals.sagepub.com/doi/10.1177/2040622319868379, doi:10.1177/2040622319868379.

[66] S. Rutkowski, A. Rutkowska, P. Kiper, D. Jastrzebski, H. Racheniuk, A. Turolla, J. Szczegielniak, and R. Casaburi. *Virtual reality rehabilitation in patients with chronic obstructive pulmonary disease: A randomized controlled trial.* International Journal of COPD, 15:117–124, 2020. Available from: /pmc/articles/PMC6968810/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC6968810/, doi:10.2147/COPD.S223592.

[67] Y. Cai, N. K. H. Chia, D. Thalmann, N. K. N. Kee, J. Zheng, and N. M. Thalmann. *Design and Development of a Virtual Dolphinarium for Children With Autism.* IEEE Transactions on Neural Systems and Rehabilitation Engineering, 21(2):208–217, March 2013. Available from: https://ieeexplore.ieee.org/document/6419839/, doi:10.1109/TNSRE.2013.2240700.

[68] S. Condino, N. Montemurro, N. Cattari, R. D'Amato, U. Thomale, V. Ferrari, and F. Cutolo. *Evaluation of a Wearable AR Platform for Guiding Complex Craniotomies in Neurosurgery.* Annals of Biomedical Engineering, 49(9):2590–2605, September 2021. Available from: https://link.springer.com/10.1007/s10439-021-02834-8, doi:10.1007/s10439-021-02834-8.

[69] S. Drouin, A. Kochanowska, M. Kersten-Oertel, I. J. Gerard, R. Zelmann, D. De Nigris, S. Bériault, T. Arbel, D. Sirhan, A. F. Sadikot, J. A. Hall, D. S. Sinclair, K. Petrecca, R. F. DelMaestro, and D. L. Collins. *IBIS: an OR ready open-source platform for image-guided neurosurgery.* International Journal of Computer Assisted Radiology and Surgery, 12(3):363–378, March 2017. Available from: http://link.springer.com/10.1007/s11548-016-1478-0, doi:10.1007/s11548-016-1478-0.

[70] E. Wade and C. J. Winstein. *Virtual reality and robotics for stroke rehabilitation: Where do we go from here?* Topics in Stroke Rehabilitation, 18(6):685–700, jan 2011. Available from: https://www.tandfonline.com/doi/abs/10.1310/tsr1806-685, doi:10.1310/tsr1806-685.

[71] M. G. Maggio, G. Maresca, R. De Luca, M. C. Stagnitti, B. Porcari, M. C. Ferrera, F. Galletti, C. Casella, A. Manuli, and R. S. Calabrò. *The Growing Use of Virtual Reality in Cognitive Rehabilitation: Fact, Fake or Vision? A Scoping Review*, aug 2019. Available from: https://pubmed.ncbi.nlm.nih.gov/30739728/, doi:10.1016/j.jnma.2019.01.003.

[72] S. Sharples, G. Burnett, and S. Cobb. *Sickness in virtual reality.* In Advances in Virtual Reality and Anxiety Disorders, pages 35–62. Springer US, jan 2014. Available from: http://link-springer-com-443.webvpn.fjmu.edu.cn/chapter/10.1007/978-1-4899-8023-6{_}3, doi:10.1007/978-1-4899-8023-6_3.

[73] C. Armbrüster, M. Wolter, T. Kuhlen, W. Spijkers, and B. Fimm. *Depth Perception in Virtual Reality: Distance Estimations in Peri- and Extrapersonal*

Space. CyberPsychology & Behavior, 11(1):9–15, 2008. PMID: 18275307. doi:10.1089/cpb.2007.9935.

[74] J. Keil, D. Edler, D. O'Meara, A. Korte, and F. Dickmann. *Effects of Virtual Reality Locomotion Techniques on Distance Estimations.* ISPRS International Journal of Geo-Information, 10(3), 2021. Available from: https://www.mdpi.com/2220-9964/10/3/150, doi:10.3390/ijgi10030150.

[75] S. Pastel, D. Bürger, C. H. Chen, K. Petri, and K. Witte. *Comparison of spatial orientation skill between real and virtual environment.* Virtual Reality, 53:1–14, June 2021. Available from: https://link.springer.com/10.1007/s10055-021-00539-w, doi:10.1007/s10055-021-00539-w.

[76] A. Rizzo and S. Bouchard. *Virtual Reality for Psychological and Neurocognitive Interventions.* 2019. Available from: http://www.springer.com/series/13399{%}0Ahttp://link.springer.com/10.1007/978-1-4939-9482-3.

[77] G. C. Burdea. *Virtual Rehabilitation - Benefits and Challenges*, 2003. doi:10.1055/s-0038-1634378.

[78] T. Ogourtsova, P. S. Archambault, and A. Lamontagne. *Exploring barriers and facilitators to the clinical use of virtual reality for post-stroke unilateral spatial neglect assessment.* Disability and Rehabilitation, 41(3):284–292, 2019. doi:10.1080/09638288.2017.1387292.

[79] K. Baheux, M. Yoshizawa, K. Seki, and Y. Handa. *Virtual reality pencil and paper tests for neglect: A protocol.* Cyberpsychology and Behavior, 9(2):192–195, apr 2006. doi:10.1089/cpb.2006.9.192.

[80] K. Kim, J. Kim, J. Ku, D. Y. Kim, W. H. Chang, D. I. Shin, J. H. Lee, I. Y. Kim, and S. I. Kim. *A virtual reality assessment and training system for unilateral neglect.* Cyberpsychology and Behavior, 7(6):742–749, dec 2004. doi:10.1089/cpb.2004.7.742.

[81] K. Yasuda, D. Muroi, M. Ohira, and H. Iwata. *Validation of an immersive virtual reality system for training near and far space neglect in individuals with stroke: A pilot study.* Topics in Stroke Rehabilitation, 24(7):533–538, 2017. doi:10.1080/10749357.2017.1351069.

[82] H. S. Moon, S. W. Shin, S. T. Chung, and E. Kim. *K-CBS-based unilateral spatial neglect rehabilitation training contents utilizing virtual reality.* ICEIC 2019 - International Conference on Electronics, Information, and Communication, (3):21–23, 2019. doi:10.23919/ELINFOCOM.2019.8706395.

[83] A. Fuji, M. Fujimura, and T. Higashi. *Virtual Environment of Prism Adaptation for Unilateral Spatial Neglect.* In 2018 IEEE 7th Global Conference on Consumer Electronics, GCCE 2018, pages 81–82. Institute of Electrical and Electronics Engineers Inc., dec 2018. doi:10.1109/GCCE.2018.8574783.

[84] H. Morse, L. Biggart, V. Pomeroy, and S. Rossit. *Exploring perspectives from stroke survivors, carers and clinicians on virtual reality as a precursor to using telerehabilitation for spatial neglect post-stroke.* Neuropsychological Rehabilitation, 30:1–25, sep 2020. Available from: https://www.tandfonline.com/doi/full/10.1080/09602011.2020.1819827, doi:10.1080/09602011.2020.1819827.

[85] H. S. Jorgensen, H. Nakayama, H. O. Raaschou, and T. S. Olsen. *Stroke: Neurologic and functional recovery the Copenhagen Stroke Study*, 1999. Available from: https://www.pmr.theclinics.com/article/S1047-9651(18)30169-4/pdf, doi:10.1016/s1047-9651(18)30169-4.

[86] E. Baka, M. Kentros, G. Papagiannakis, and N. Magnenat-Thalmann. *Virtual Reality Rehabilitation Based on Neurologic Music Therapy: A Qualitative Preliminary Clinical Study.* In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), volume 10925 LNCS, pages 113–127. Springer Verlag, jul 2018. doi:10.1007/978-3-319-91152-6_9.

[87] A. Byrns, H. Ben Abdessalem, M. Cuesta, M. A. Bruneau, S. Belleville, and C. Frasson. *Adaptive music therapy for alzheimer's disease using virtual reality.* In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), volume 12149 LNCS, pages 214–219. Springer, jun 2020. doi:10.1007/978-3-030-49663-0_25.

3

A Personalised Emotion-Based Model for Relaxation in Virtual Reality

The system presented in this chapter builds further on the concept of Chapter 2, in that it uses information from an assessment to drive a personalisation algorithm. The virtual reality application is designed and developed for relaxation therapy, mainly for the patient to use at home. Relaxing virtual environments are tailored to the preferences of the user and adapt to changes in their emotional state. In contrast to the more common approach in which information of the user is collected through intrusive measurement instruments or disturbing verbal/textual queries, this work employs a predictive model for emotional state. It avoid the interruption of users which can break their sense of presence. By investigation a new approach for personalisation of Virtual Environment (VE) in a complex system, this chapter contributes specifically to challenge 2 of Section 1.5. As for all the research in this dissertation, the design of the VE and the predictive model are driven by expertise knowledge as prescribed by challenge 4. The proposed system is designed for use at home which requires it to be easy to operate without technological knowledge, as is required for challenge 5.

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Abstract One of the most frequent health problems is stress. It has been linked to negative effects on employee well-being in many occupations, and it is considered responsible for many physical and psychological problems. Traditional in-person relaxation therapy has proven to be effective in reducing stress. However, it has some drawbacks such as high cost, required infrastructure and the need for qualified trainers. Relaxation therapy in Virtual Reality (VR) tries to solve these problems. However, one aspect has received little attention, that is personalised therapy. Indeed, while many studies show the need for patient-tailored relaxation exercises, little existing work focuses on personalised VR content. One reason for this is the complexity of recognising emotions, which is required for emotion-based adaptive VR. In this work, a method for adapting VR content to the emotional state of the user is presented. This model has been applied in a VR relaxation therapy application, which adapts to the user's emotional state utilising a heuristic optimiser. Simulations have proven the performance and usability of the emotion model. Additionally, this paper explores the impact of the order in which adaptations are performed on the effectiveness of the relaxation experience.

3.1 Introduction

According to the World Health Organisation (WHO), stress, especially relating to work activities, is the second most frequent health problem, impacting one-third of employed people in the European Union [1–3]. It has been widely linked with adverse effects on employees, their psychological and physical well-being in many occupations, with teaching and educational professionals at particular risk [4, 5]. Excess of stress contributes to the development of physical ailments such as hypertension, ulcers, skin disorders, headaches, arteriosclerosis, cardiovascular diseases, and other life-threatening diseases [6, 7]. Due to the prevalence of these stress-related health conditions, the cost to a nation's health care system, and the loss of quality of life for individuals, concerns over the effects of stress are increasing among public health professionals [8].

Given the impact of stress, research has focused on means to reduce stress through relaxation therapy [2]. Relaxation therapy resorts to certain stress management techniques which have proven to help in allowing the body to cope with stress. Some of these techniques are biofeedback training to increase heart rate variability, paced breathing, muscle relaxation, or mental imaging and music [1]. While research has shown their effectiveness, most techniques require perseverance and focus of the patient which is difficult to maintain. Exercises can be perceived to be boring, tedious or impractical. Furthermore, escaping to a different environment is not always possible.

Virtual Reality (VR) can provide the required effectiveness for various kinds of therapy [9]. By fully immersing the user in a new environment, they can virtually teleport to a more suited location for relaxation. This immersion eliminates the many distracting factors of the real environment. Furthermore, it reduces costs, as the user only requires a Head Mounted Display (HMD) and an Internet connection, instead of the dedicated trainers and infrastructures of traditional relaxation therapy. Finally, where real-life relaxation therapy adopts a personally tailored approach, the VR counterpart should follow in this path. Indeed, given its individualistic essence, VR has the potential to provide personalised solutions to the users. However, due to the absence of a trainer or therapist, the personalisation needs to be automated by a computer system.

In previous research, the potential of personalised VR for relaxation have been explored. For example, Pizzoli et al. [10] proposed a user-centered VR experience for general relaxation. However, current solutions are either too tailored for a very particular user-type or very generic thus decreasing their effectiveness. Furthermore, they tend to rely fully on sensor data and subjective user evaluations. While employing user data aids to tailor and adapt the applications, the variability makes it difficult to create models that could be utilised for a broad range of users. For such cases, there is a need for objectively driven models able to fit a broad range of users.

This work proposes a personalised and adaptive VR model for relaxation therapy in VR. Employing a broad set of possible adaptations in a Virtual Environment (VE), our approach models relaxation as a function of three other emotions, namely stress, arousal and fear. We have evaluated our approach both for relaxation indoor and outdoor environments and for a wide range of users. Our results illustrate the potential of employing objective models for personalisation approaches in VR.

The remainder of this paper is structured as follows. Section 3.2 describes the state of the art on VR for relaxation therapy. Section 3.3 introduces our method providing all the equations and theoretical reasoning behind the definition of the model. Sections 3.4 and 3.5 present the evaluation setup details and evaluation results. Finally, Section 3.6 concludes this paper.

3.2 Related Work

VR has been used in clinical settings to treat a range of cognitive, emotional and motor problems in various psychological and psychiatric disorders [9, 11–16]. Many studies have shown that the VR-based therapy is as effective as their in-vivo (traditional) counterpart [13, 17, 18].

Shah et al. [19], Soyka et al. [20], Gerber et al. [21] and Anderson et al. [22] performed studies providing empirical evidence for the effect of using VR for reducing stress in various domains of application. Indeed, the study by Shah et al. reported positive results on stress reduction and/or anxiety through exposure to natural imagery in VR. Additionally, the authors employed abdominal breathing and muscle relaxation as well as psycho-education in their study. Their tests were focused on people with mood disorders who had been submitted to a hospital. Gerber et al. restricted themselves to patients in an intensive care unit (ICU) while Anderson et al. explored the effect on people living and working in isolated and confined environments (e.g. submarines, space). Whereas, Soyka et al. did not envision a particular target group but focused on underwater scene imagery. Additionally, Anderson et al. discussed the need for a personalised experience in relaxation VR. They suggest that the effect of natural imagery on stress reduction depends on personal preference. Many of the existing work focuses on (personalised) relaxation in the context of a specific condition (e.g. cancer treatment, ICU) and not for general relaxation or de-stressing. This work focuses on the latter.

It has been suggested in previous research that providing a personalised treatment would indeed improve the therapy, either in effectiveness or in user satisfaction [23]. In 1987, Graffam and Johnson [24] already did a comparative study between two relaxation strategies. Their finding was that both strategies were equally effective while one was more preferred than the other by patients. Hyland et al. [25] came to similar conclusions as well when performing a study comparing six different relaxation techniques. This shows there is a definite and clear need for personalised relaxation therapy. However, most studies on VR based relaxation lack this personalised and adaptive approach [26]. Only a few papers in literature make contributions to this specific domain. In their paper [10], Pizzoli et al. propose a VR experience with personalised content as an alternative to generic story-telling or guided activities for regulating emotions in VR.

Personalised systems need input to adapt to the user. For real-time adaptations, continuous data streams are preferred to estimate a certain state of the user, e.g. predicting the emotional state for biofeedback. Substantial research has been done on detecting this emotional state from various sensor data [27, 28]. Healey et al. [29] developed a system for predicting stress while driving based on heart rate and skin conductance data. Miranda et al. [30] also used heart rate but in combination with spontaneous blink rate to detect anxiety. They did, however, find that heart rate was the most prominent predictor.

Other work researches the use of machine learning techniques such as Convolutional Neural Network (CNN) [31] and Support Vector Machine (SVM) [32] in detecting emotions. These algorithms are often very complex and need large amounts of computing power and expensive wearables. In some cases, they are designed for one particular setting without proof for application to other settings [29]. For many use cases, aimed at relaxation, these are unacceptable requirements. These use cases require simple usage, non-intrusive and non-obstructing sensors, and preferably cheap hardware. Therefore, there is a need for simpler models predicting the emotional state of a person. Developing such a model needs a deep understanding of emotions on a biological and physiological level [33].

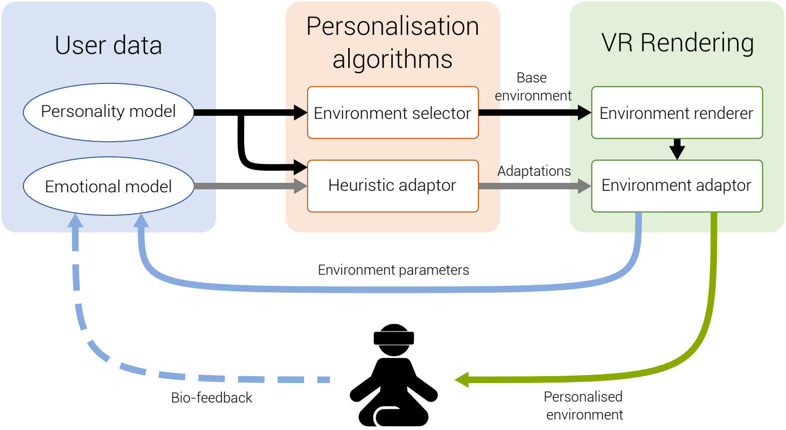

Figure 3.1: High level view of the architecture.

3.3 Methodology

This section presents the methodology employed on the design of the adaptive and personalised VR approach to relaxation therapy. The high-level overview of the system is illustrated in Figure 3.1. At the start of the session, the user provides data regarding their personality and their initial emotional state. Based on both types of information, a virtual environment is created. To provide smooth transitions to the user and not to disturb the immersiveness, radical changes in the environment are avoided. Therefore, first, a blueprint of the environment is chosen based solely on the personality of the user and independent of the emotional state of the user. Choosing this blueprint is done by the environment selector, resulting in a raw environment to render. Next, the blueprint is enhanced to create the final environment that is shown to the user, this enhancement is done by the adaptor component. Subsequently, the VE can be shown to the user. This is done by the VR render component. Visualising the environment will trigger an emotional reaction in the user, which is simulated by the emotional model, resulting in new emotional data. This data is then returned to the adaptor, completing the cycle. In a hybrid approach, the estimation of the emotional state could be improved by incorporating biofeedback from the user. However, this is outside the scope of this paper. Next, further details are given on the personality and emotional models as well as on the heuristic adaptor.

3.3.1 Personality Model

The environment selector is responsible for generating a raw environment based on the personality of the user. To achieve this, it uses decision trees. The decisions taken at every decision node depend solely on the user's personality data and each outcome represents a different raw environment. The set of possible raw environments is fixed and thus the same for every user. Therefore, users with similar personalities could generate the same raw environment. However, their final environments may still show significant differences as the environment details get decided upon later, as they are based on the user's emotional status. The decision tree will be modified depending on the available virtual environments and options.

3.3.2 Emotional Model

The main purpose of the emotional model is to estimate the level of relaxation, or rather the state of relaxation $s_{relaxation}$, of the user based on the current settings of the environment. Relaxation has been shown to be influenced by stress, fear and arousal [33]. Therefore, the model estimates relaxation from the three latent variables (s_{stress}, s_{fear}, and $s_{arousal}$). At the most abstract level, relaxation can be expressed as a function of the three other emotional states and the preference of the user on the adaptations in the environment. This is formalised in Equations (3.1)–(3.4), where $\mathbf{a} = (a_{x_1}, ..., a_{x_n})$ is the vector representing the values of all adaptations $x_i, i \in \{1, \ldots, n\}$ in the environment.

$$s_{relaxation} = relaxation\left(s_{fear}, s_{stress}, s_{arousal}, pref(\mathbf{a})\right) \tag{3.1}$$

$$s_{fear} = fear\left(\mathbf{a}\right) \tag{3.2}$$

$$s_{stress} = stress\left(\mathbf{a}\right) \tag{3.3}$$

$$s_{arousal} = arousal\left(\mathbf{a}\right) \tag{3.4}$$

Adaptations can influence the model either by the preference for the adaptation or directly by its value. Given the large variety of options and the variability of users, when the user first starts the system, they will answer questions regarding their preferences on some of the adaptations. In that way, for example, if the user is afraid of darkness, the created environment will be made in a manner that it maintains light throughout the session. Therefore, a preference function $pref_x(a_x)$ for each adaptation x_i is defined according to Equation (3.5) which determines the impact of the individual adaptations on the user's emotional state. Human perception has been deemed to be highly nonlinear, following more the shape of a sigmoid or a Gaussian curve [34]. Therefore, a Gaussian function is used. The Gaussian has a maximum value of 1, centred around the adaptation's optimal intensity (x_{opt}). This optimal intensity is a fixed value derived from the questionnaire data. The range of the $pref_x(a_x)$ function is between 0 and 1, where 0 indicates that the user does not like the adaptation and 1 that the user likes it very much. As can be seen in Figure 3.2, the more the optimal intensity leans towards 0.5, the more the user feels indifferent about the adaptation, thus the flatter the Gaussian becomes. In other words, large changes in the adaptation intensity have little effect on the preference function's outcome. The

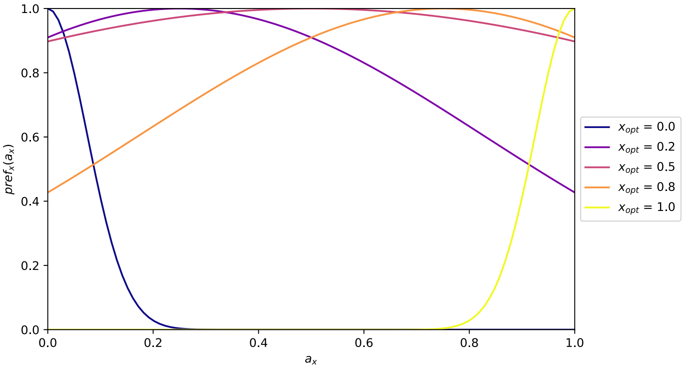

Figure 3.2: Plots showing different preference functions for different optimal values.

more the optimal intensity reaches 0 or 1, the stronger the user feels about the adaptation, thus the more narrow the bell shape becomes. Meaning that small changes in the adaptation intensity already have a big impact on the preference function's outcome.

$$pref_x(a_x) = \exp\left(\frac{-\left(x_{opt} - a_x\right)^2}{2 \cdot \left(1.075 - 2 \cdot \left(\left|0.5 - x_{opt}\right|\right)\right)^2}\right) \tag{3.5}$$

With the definitions for the adaptations and preferences, the three emotion models will be explained. Since some of the adaptations in the system could potentially induce fear on the user, these are called (fear) inductors. For example, a user can be afraid of darkness, fire or animals. Therefore, in this model fear is calculated as a weighted sum of the possible fear inductors independently (Equation (3.6)). The weights (F_{a_x}) can be chosen based on the user's personality. Each inductor is modeled by a function based on the user profile's optimal value (x_{opt}) as in Equation (3.7). The fear inductor function, $f(a_x)$, is a linear function based on the adaptation's current intensity and the fixed optimal intensity. This is plotted in Figure 3.3 for different values of optimal intensity. This plot shows that if the adaptation has an optimal intensity value below 0.5, it frightens the user, thus contributing to a positive impact on the overall fear. An optimal intensity above 0.5 indicates comfort, thus contributing to a negative impact on the overall fear. The magnitude of fear or comfort depends on how much the value leans towards 0 or 1 respectively. As $fear(a)$ is a linear combination of instances of $f(a_x)$, it also is a linear function similar to Figure 3.3. The resulting function for fear always provides an output value between -1 and 1. Negative fear indicates that the user is not afraid and feels comfortable, whilst positive fear indicates the user is afraid.

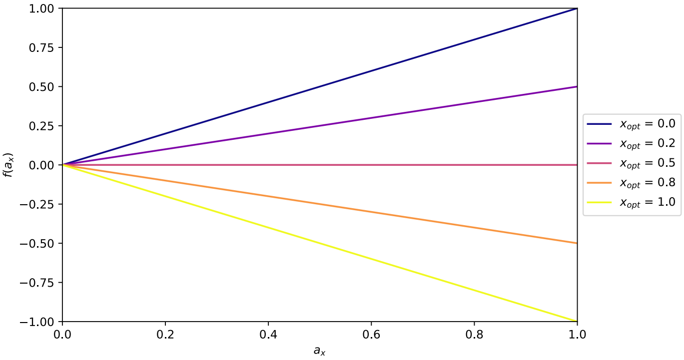

Figure 3.3: Plots showing different fear inductor functions for different optimal values.

$$s_{fear} = fear\left(\mathbf{a}\right) = \frac{\sum_{a_x \in \mathbf{a}} F_{a_x} \cdot f(a_x)}{\sum_{a_x \in \mathbf{a}} F_{a_x}} \tag{3.6}$$

$$f(a_x) = (1 - 2 \cdot x_{opt}) \cdot a_x \tag{3.7}$$

The second emotion is stress. In Equation (3.8), it is formulated as a max-function of three arguments.The first element is the value of s_{fear}, as the level of fear will directly translate into stress. The second is a new candidate value for s_{stress} which depends on the preference functions of adaptations that can induce stress. As the adaptations current values approach the optimal preference, the stress decreases (Equation (3.9)). Lastly, the value of s_{stress} at the previous time step is considered.

$$\begin{aligned} s_{stress} &= stress\left(\mathbf{a}\right) \\ &= \max(s_{fear}, stress_{new}(\mathbf{a}), stress_{prev}) \end{aligned} \tag{3.8}$$

$$stress_{new}(\mathbf{a}) = 1 - \frac{\sum_{a_x \in \mathbf{a}} Sp_{a_x} \cdot pref_{a_x}(a_x) + \sum_{a_x \in \mathbf{a}} S_{a_x} \cdot a_x}{\sum_{a_x \in \mathbf{a}} S_{a_x} + \sum_{a_x \in \mathbf{a}} Sp_{a_x}} \tag{3.9}$$

The final emotion is arousal (Equation (3.10)). Much like stress arousal is non-linear and formulated as a max function with three arguments. The first is the emotional state of fear (s_{fear}), with high fear comes high arousal. The second is the emotional state of stress (s_{stress}), analogous to fear, with high stress comes high arousal. The last argument is the minimum of a new candidate value for arousal and the value of $s_{arousal}$ at the previous time step. The candidate value of arousal is based on the preference of some adaptations and the direct effect of others. For example, users have a preference for music. Therefore, based on their preference for this adaptation, the user will feel more or less aroused. On the other hand, other adaptations, such as the presence of light, has been shown to increase arousal in all users [35]. Thus, their effect needs to be directly added to the arousal calculation. The value of arousal always lies between 0 and 1.

$$\begin{aligned} s_{\mathit{arousal}} &= \mathit{arousal}\left(\mathbf{a}\right) \\ &= \max(s_{\mathit{fear}}, s_{\mathit{stress}}, \min(\mathit{arousal}_{\mathit{new}}(\mathbf{a}), \mathit{arousal}_{\mathit{prev}})) \end{aligned} \tag{3.10}$$

$$\mathit{arousal}_{\mathit{new}}(\mathbf{a}) = 1 - \frac{\sum_{a_x \in \mathbf{a}} Ap_x \cdot \mathit{pref}_x(a_x) + \sum_{a_x \in \mathbf{a}} A_x \cdot a_x}{\sum_{a_x \in \mathbf{a}} Ap_x + \sum_{a_x \in \mathbf{a}} A_x} \tag{3.11}$$

Based on the preferences of the users and the latent emotional states, $s_{\mathit{relaxation}}$ can be expressed. Equation (3.12) shows relaxation as a combination of the adaptation preferences which directly affect relaxation, the adaptations that affect the relaxation independent from the user preference, the stress, arousal and fear values. It is important to note that adaptations will either affect as a preference or directly as an adaptation. Therefore for an adaptation a_x, either Rp_{ax} or R_{a_x} will be set to a value higher than zero. To keep the value of relaxation between 0 and 1, relaxation is divided by the sum of the weights of the elements.

$$\mathit{relaxation} = \frac{\begin{aligned} \textstyle\sum_{a_x \in \mathbf{a}} Rp_{a_x} \cdot \mathit{pref}(a_x) + \sum_{a_x \in \mathbf{a}} R_{a_x} \cdot a_x - R_{\mathit{fear}} \cdot s_{\mathit{fear}} \\ - R_{\mathit{stress}} \cdot s_{\mathit{stress}} - R_{\mathit{arousal}} \cdot s_{\mathit{arousal}} \end{aligned}}{\sum_{a_x \in \mathbf{a}} Rp_{a_x} + \sum_{a_x \in \mathbf{a}} R_{a_x} + R_{\mathit{stress}} + R_{\mathit{arousal}} + R_{\mathit{fear}}} \tag{3.12}$$

3.3.3 Heuristic Adaptor

The adaptor is the component in charge of updating the adaptation intensities in real-time. It observes the current state of the VE and the user's emotional data. Based on this, it decides which adaptation intensity should be changed next. The adaptor updates one adaptation each time step. It calculates which action is best, performs this action, and waits for the user's emotional state to update. This process is repeated until the user reaches his optimal emotional state, at which point no more adaptations are necessary. Finding this optimal state and the maximal relaxation linked to it can be formulated as an optimisation problem. The emotional model is non-linear and can be solved using Mixed Integer Non-Linear Programming (MINLP). As MINLP problems are not easy to solve, the problem (and thus, the model) need to be linearised. This results in a linear problem that can be solved using Mixed Integer Linear Programming (MILP) [36]. However, this optimisation problem cannot be solved in real-time. Therefore, a heuristic approach is used.

The heuristic approach first determines the absolute maximum achievable relaxation for the environment and user profile. It achieves this by sampling the adaptation intensities and comparing all possible combinations, i.e. a brute force approach. The

(a) (b)

Figure 3.4: The two types of indoor environment. (a) Lake house, (b) Forest cabin.

combination that leads to the maximal relaxation value is the combination the heuristic optimiser should work towards. As it can only change one adaptation intensity per step, it should choose an order in which to change the intensities.

3.4 Use Case Implementation

This section discusses the use case implemented to test our model and algorithm. Two different VE settings have been designed, one is for indoor environments and the other for outdoor environments. For each, two different types are provided. The indoor settings resemble a living room of a house either near a lake (Figure 3.4a) or in a forest (Figure 3.4b), while the outdoor setting replicates a cosy camp spot around a campfire either near a lake (Figure 3.5a) or in the mountains (Figure 3.5b). These two VEs have been chosen as they are very different from each other as well as offer different possibilities for adaptations which could influence relaxation. All adaptations which are implemented for this use case are listed in Table 3.1 with a short description. The second and third columns indicate whether they are implemented for indoor or outdoor environments. The VEs are implemented in Unity3D, it provides an easy to use framework for VR content. These environments have been designed for use with the HTC Vive HMD. The emotional model and heuristic optimiser runs as a separate Java application which can communicate with the VR application.

3.4.1 Personalisation Model and Environment Selector

A questionnaire is used to gather both the personality data and the initial emotional data. Questions one through nine in Table 3.2 are designed specifically for the developed VE to gather the personality data of the user. This data consists of optimal intensities (used by the emotional model) and binary variables (used by the environment selector). Based on the chosen optimal intensity for each adaptation, the system

Table 3.1: Summary of all possible adaptations implemented in the VEs.

Full Name	Notation	Indoor	Outdoor	Description
Artificial light	al	x		Artificial light coming from light bulbs in the ceiling of the room.
Natural light	nl	x	x	Natural light coming from the sun and moon.
Light colour	lc	x		The colour of the artificial light. The available colors are white and blue and any mixture of these two.
Fire	py		x	A simulation of a campfire. This also generates some artificial light.
Dog	dg	x	x	A dog playing around. The dog can be either playing around further away or be near the user.
Music	ms	x	x	Some relaxation music or sounds are playing in the background. These are birds sounds for the indoor environments and soothing music for the indoor environments.
Controlled breathing	cb	x		An visual aid for a controlled breathing exercise is shown.

(a) (b)

Figure 3.5: The two types of outdoor environment. (a) Lake camp, (b) Mountain camp.

may decide to remove that adaptation from the environment. e.g. for a very low optimal intensity for dog it is better not to show the dog at all. The threshold value is chosen at 0.25, anything below this value will remove the adaptation. It was observed that any value bellow 0.25 had little effect on the users. The questions asked to gather the initial emotional data are given by questions ten to twelve. Based on this data, a rough estimate of the initial adaptation intensities is derived. Afterwards, the initial state of $s_{relaxation}$ is computed using the emotional model.

The environment selector uses the personality data and transforms it into a raw environment using a decision tree. This tree is given in Figure 3.6. Based on three decision nodes in the tree, four different outcomes are possible. The first node determines whether to select an indoor or outdoor environment, which are fundamentally different from each other. As mentioned before, each indoor and outdoor environment has 2 variations. For the indoor, the second decision checks whether a view over the water is preferred. For the outdoor, the second decision checks whether a view from a height is preferred. For every possible outcome, a raw VE is prepared. The decision tree decides which VE to load.

3.4.2 Emotional Model

The emotional model is implemented for the presented VEs. Based on the adaptations found in Table 3.1 the formulas in Section 3.3.2 are completed. Table 3.3 shows the range of values for each adaptation as well as the weights they are given for each of the formulas. The adaptations are discussed in more detail. First, artificial light (al) corresponds to light artificially produced, e.g. a light bulb. The light intensity scales linearly between 0 and 1, where 0 is no light and 1 is maximum light. This artificial light will only be present for indoor environments. Second, natural light (nl) denotes naturally produced light, such as the sun. The light intensity scales linearly between 0 and 1, where 0 is late at night (low light) and 1 is around noon (maximum light).

Table 3.2: The amount of possible answers that can be given to every question from the questionnaire.

No.	Question	Possible Answers
1	Would you prefer an indoor or outdoor environment to relax?	[indoor, outdoor]
2	Could the presence of water help you to relax?	[yes, no]
3	Are you afraid of heights?	[yes, no]
4	What is you favourite season?	[summer, winter]
5	How does having a calm campfire nearby make you feel?	{relaxed, anxious}
6	How do you feel when a dog is in your presence?	{relaxed, anxious}
7	How does darkness make you feel?	{relaxed, anxious}
8	How do you find classical relaxation music?	{very relaxing, not relaxing at all}
9	Blue light gives you a relaxed feeling, do you agree?	{agree, disagree}
10	How afraid do you feel right now?	{not at all, very much}
11	How stressed do you feel right now?	{not at all, very much}
12	How aroused do you feel right now?	{not at all, very much}

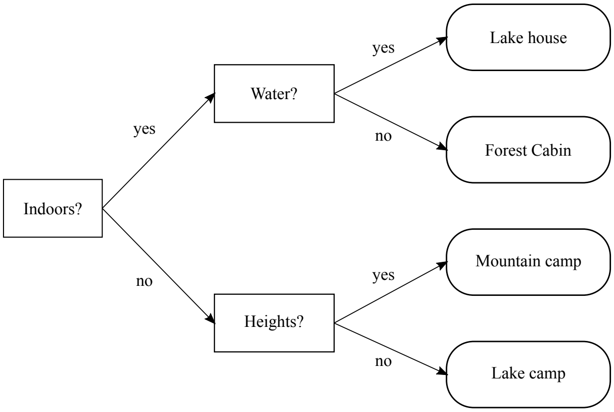

Figure 3.6: Decision tree used by the environment selector.

Light has a significant impact on arousal [35]. Therefore, the system has to control the parameters for light. Third, it has been shown that the colour of artificially created light has a strong influence on the relaxation of the user [37]. Therefore, we defined the adaptation light colour (lc). If artificial light is activated, the colour of the light can be set. The colour of the lights scales linearly between white and blue light, where 0 is with white light and 1 is blue light. The fourth adaptation is the fire (py). It has been shown that a source of fire, such as a fireplace or an outdoor campfire, can be relaxing for some users [38], while at the same time fire can distress people with pyrophobia. The intensity of the fire scales linearly between 0 and 1, where 0 is no fire and 1 is a large fire. The fire adaptation is only defined for the outdoor environment. Fifth, for both the indoor and outdoor environments, it is possible to add a dog. The dog adaptation (dg) activates a dog playing around unless the user prefers otherwise. Dogs have proven to provide comfort and reduce stress in patients [39]. The distance of the dog to the user can be controlled choosing from three values, where for 0 the dog is far away, for $^1/_2$ the dog is closer and for 1 the dog is very close. Music has shown very good results to induce relaxation. Therefore, music is also set as a part of the adaptation set. When music (ms) is selected, relaxation music (indoor) or sounds (outdoor) are playing in the background, e.g. birds. The music can be turned on (1) or off (0). Finally, control breathing (cb) provides a visual aid for a controlled breathing exercise. This visualisation is either turned on (1) or off (0).

Based on the adaptations, for this use case, we defined three sources of fear which are modelled with the $f(a_x)$ function defined in Equation (3.7). These are pyrophobia, cynophobia [40] and nyctophobia [41]. Pyrophobia is the fear of fire. It is therefore induced by the fire adaptation ($f(a_{py})$). Cynophobia, or fear of dogs, is induced by the dog adaptation ($f(a_{dg})$). Finally, to model the fear of darkness or nyctophobia ($f(a_{dark})$), we modelled it by the combination of the fire, natural light, and artificial

Table 3.3: Summary of all possible adaptations used by the emotional model. For each of the adaptations, the value of the constants defines the presence of the emotions in the equation.

a_x	Range a_x	F_{a_x}	Sp_{a_x}	S_{ax}	Ap_{a_x}	A_{a_x}	Rp_{a_x}	R_{a_x}
al	$[0,1]$	1	0	0	0	1	1	0
nl	$[0,1]$	1	0	0	0	1	1	0
lc	$[0,1]$	0	0	0	0	0	1	0
py	$[0,1]$	1	1	0	0	0	0	0
dg	$\{0, 1/2, 1\}$	1	1	0	0	0	0	0
ms	$\{0,1\}$	0	0	0	1	0	1	0
cb	$\{0,1\}$	0	0	1	0	0	0	1

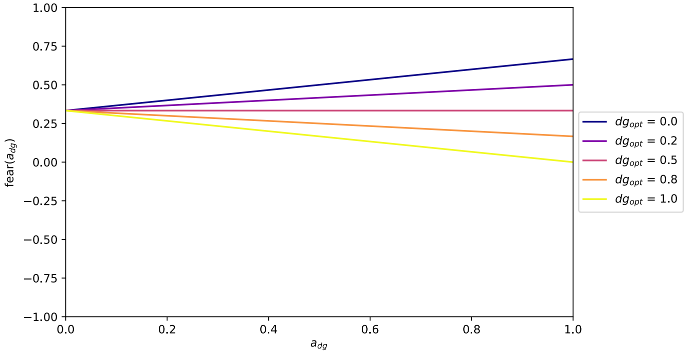

Figure 3.7: The progression of the fear function $f(x)$ for a changing intensity of dg and different values for dg_{opt}, where $a_{py} = a_{dark} = 0.5$ and $py_{opt} = dark_{opt} = 0$ are fixed.

light adaptations. The adaptation intensity of dark is give by Equation (3.13) and defines how dark the environment is. In this equation, D_{al}, D_{nl} and D_{py} are weights for each adaptation, indicating their significance to the overall darkness intensity.

$$a_{dark} = 1 - \frac{D_{al} \cdot a_{al} + D_{nl} \cdot a_{nl} + D_{py} \cdot a_{py}}{D_{al} + D_{nl} + D_{py}} \tag{3.13}$$

Figure 3.7 illustrates the behaviour of the fear functions for changing intensities of an adaptation. In this case s_{fear} is plotted out in function of a_{dg} where the intensities of fire (a_{py}) and darkness (a_{dark}) equal 0.5 and their optimal values py_{opt} and $dark_{opt}$ respectively, equal 0. Different plots show a different optimal intensity for dog (dg_{opt}).

Regarding stress, as explained in Section 3.3, it is modelled as a non-linear max function of the current fear, the possible new stress and the stress of the previous interval if the controlled breathing was enabled. Taking into account the possible adaptations, and the defined formulas in the methodology, the possible new stress has been set to be influenced by the fire (*py*) and the dog (*dg*) as formulated in Equa-

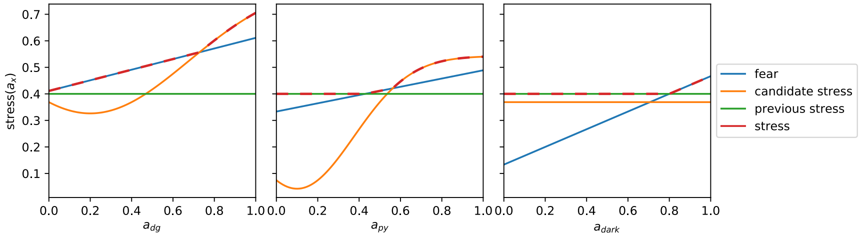

Figure 3.8: Plots showing the calculation of stress as it depends on other functions. Each plot shows stress in function of a different adaptation.

tion (3.9). Figure 3.8 illustrates an example of the calculation of stress. The figure shows stress as a function of three different adaptations: dog, fire and darkness. Each plot shows the three arguments of the maximisation function from Equation (3.8) and the resulting value of stress. As can be seen from the figure, in each case stress takes the greatest value of all other functions. Moreover, note how the candidate value for stress is constant in the third plot as it does not depend on the intensity of darkness. However, fear does depend on darkness in the emotional model and can overtake the candidate value resulting in an increased level of stress.

The arousal is again a max function of the current values of stress, fear and the new candidate values of arousal. The candidate new arousal is based on the preference towards music, the intensity of natural light and the intensity of artificial light as defined in Equation (3.11). In short, arousal will only increase when fear or stress increases, and it will only decrease when the music is optimal and/or the environment is bright. Figure 3.9 shows the evaluation of arousal as an example. The three plots show arousal in function of music, artificial light and dog respectively. Each plot shows the 4 arguments of the maximisation and minimisation functions from Equation (3.10) as well as arousal itself. The plots clearly show how arousal takes the maximum of fear and stress but the minimum of the candidate arousal and previous arousal values. Indeed, as explained before, arousal decreases as music approaches the optimal value (0.8 in this case) or as the environment gets brighter. Additionally, arousal increases as fear or stress increase.

Finally, the preferences of music, light colour, natural light and artificial light, the adaptation values of controlled breathing and the latent emotional states s_{fear}, s_{stress} and $s_{arousal}$ conform the relaxation model.

As the heuristic optimiser, which takes care of applying the appropriate adaptations based on the output of the emotional model, can only change one adaptation intensity per step, it should choose an order in which to apply the adaptations. The order the heuristic optimiser applies is fixed as follows:

1. dog

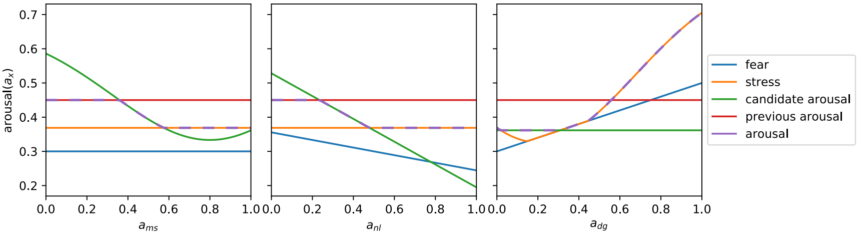

Figure 3.9: Plots showing the calculation of arousal as it depends on other functions. Each plot shows arousal in function of a different adaptation.

2. fire
3. natural lighting
4. artificial lighting
5. controlled breathing on
6. controlled breathing off
7. music
8. light colour

This order is chosen as the default order for the heuristic optimiser based on logical reasoning, e.g. “controlled breathing on” should come before “controlled breathing off”. However, there is no proof yet this order is the optimal approach. This will be analysed in detail in Section 3.5.

3.5 Experimental Evaluation

This section presents the experimental evaluation of the personalised adaptive emotion system for relaxation therapy in VR. Given the broad range of users and personalisation options, an approach with simulated users was opted for. Through this approach, the performance of the system can be assessed in a controlled environment and for iterations. Section 3.5.1 presents the simulation approach and the user profiles employed in the analysis. These users have been put through the system to evaluate its performance, the results of these experiments are presented in Section 3.5. Finally, further analysis and lessons learned are provided in Section 3.5.3.

3.5.1 Simulating Users

To fully analyse the performance of the system, it needs to be evaluated on a wide range of user profiles. To this end, user profiles have been created and the outcome is analysed in an offline simulation for evaluation of the system. The output of the simulation shows the evolution of the adaptions and the effect on the emotional state.

In a real setup, the user profiles would be defined by the information that is provided through the questionnaire in Table 3.2. One possibility would be to generate every combination of answers to the questions and perform a simulation for every possible profile. However, doing this is computationally infeasible as some questions from the questionnaire accept continuous values which would result in an infinite amount of user profiles. While at the same time many combinations of answers would lead to the same decisions and therefore the same results or very similar results. Therefore, a less naive approach is adopted by creating 12 user profiles with very different characteristics. These 12 profiles are sufficient to cover all edge cases and some average users for both indoor and outdoor environments.

The 12 profiles are constructed by specifying the seven parameters which are normally derived from the questionnaire, these are preferred environment and the optimal intensity of the six adaptations (dog, fire, natural light, artificial light, light colour and music). The 12 selected profiles with their values for these parameters are listed in Table 3.4.

The first six profiles are extreme cases used for observing general trends and comparing adaptations objectively. This is because the optimal intensity of all adaptations is the same, and thus they will have the same impact on the model. The six last profiles are average users. Users 7 and 8 prefer a dark environment with a fire or blue lights. They also prefer music when relaxing and dislike dogs. Users 9 and 10 are the opposite, they like dogs and bright environments but dislike fire, blue light, and music. Lastly, users 11 and 12 are somewhat in between. They are quite neutral towards a dog and darkness, dislike music, and like fire and blue light. The environment parameter has only two possibilities, either an indoor or an outdoor environment. Therefore, six profiles are created for each. Finally, we note that the initial emotional state should also be set and has an infinite amount of possible combinations. However, a simulation with a mild initial emotional state (already high relaxation) does not provide many insights. It would merely result in fewer adaptations to reach optimal relaxation. Therefore, the initial state for each simulation is set to be the most severe, that is high fear, high stress and high arousal which leads to low relaxation.

3.5.2 Results

In this section, the results of the evaluation of the two tests are discussed. First, the performance of the heuristic optimiser, as described before, is evaluated on the 12 generated users. Second, the impact of order in which the adaptations are applied is

Table 3.4: User profiles used for simulations.

Id	Environment	Optimal Intensity						Description
		dg	py	nl	al	lc	ms	
User 1_{in}	indoor	0.9	n/a	0.9	0.9	0.9	0.9	Dog lover; Afraid of darkness; Likes music and blue light.
User 1_{out}	outdoor	0.9	0.9	0.9	n/a	n/a	0.9	Dog lover; Afraid of darkness; Likes music and fire.
User 2_{in}	indoor	0.5	n/a	0.5	0.5	0.5	0.5	Neutral towards every adaptation.
User 2_{out}	outdoor	0.5	0.5	0.5	n/a	n/a	0.5	Neutral towards every adaptation.
User 3_{in}	indoor	0.1	n/a	0.1	0.1	0.1	0.1	Afraid of dogs; Loves darkness; Dislikes music and blue light.
User 3_{out}	outdoor	0.1	0.1	0.1	n/a	n/a	0.1	Afraid of dogs and fire; Loves darkness; Dislikes music.
User 4_{in}	indoor	0.0	n/a	0.1	0.1	0.7	0.9	Afraid of dogs; Loves darkness, music and blue light.
User 4_{out}	outdoor	0.0	0.7	0.1	n/a	n/a	0.9	Afraid of dogs; Loves darkness, music and fire.
User 5_{in}	indoor	1.0	n/a	0.8	0.8	0.1	0.3	Dog lover; Afraid of darkness; Dislikes music and blue light.
User 5_{out}	outdoor	1.0	0	0.8	n/a	n/a	0.3	Dog lover; Afraid of darkness and fire; Dislikes music.
User 6_{in}	indoor	0.6	n/a	0.4	0.4	0.8	0.1	Likes blue light; Dislikes music.
User 6_{out}	outdoor	0.6	0.8	0.4	n/a	n/a	0.1	Loves fire; Dislikes music.

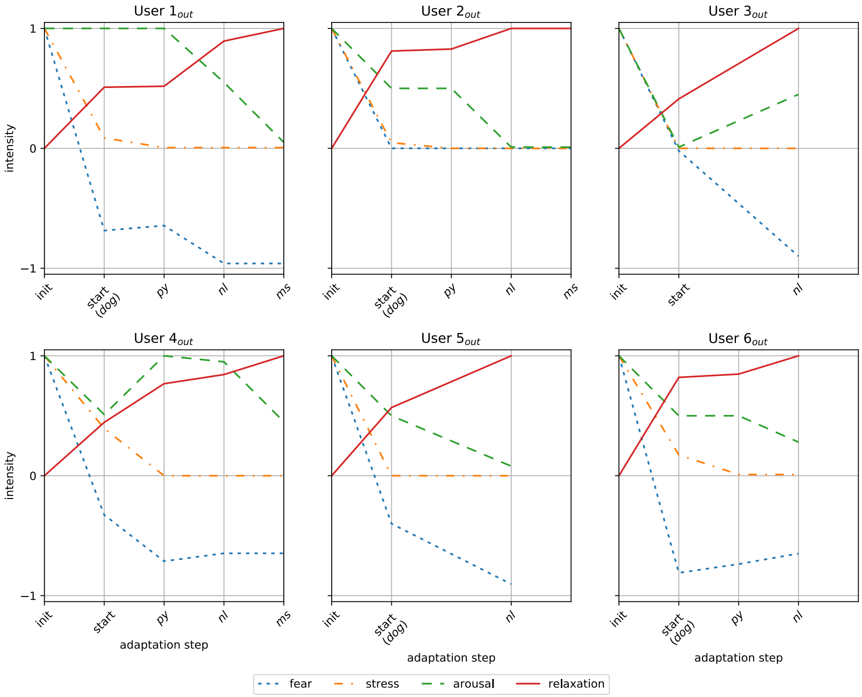

Figure 3.10: Plots showing the evolution of the emotional states at each time step for the outdoor environment. The heuristic optimiser applies the adaptations in the same order for each user.

observed.

3.5.2.1 Performance Analysis

The purpose of this first analysis is to assess the performance of the personalised relaxation model. For this, the default heuristic order configuration (dog, fire, natural lighting, artificial lighting, controlled breathing on, controlled breathing off, music, light colour) is taken and we evaluate the 12 user profiles.

The evolution of the emotional state in the simulations for the outdoor and indoor environments are shown in Figures 3.10 and 3.11 respectively. The plots show the evolution of the different emotional parameters with every adaptation in the environment. The adaptations are shown on the x-axis while the four emotions are presented on the y-axis. While the most important emotion is relaxation (which needs to be maximised), the other parameters, fear, stress and arousal are also interesting to the observer as these need to decrease. For some of the users, not all possible adaptations appear. This is due to the profile of these users which prevents these adaptations form being used.

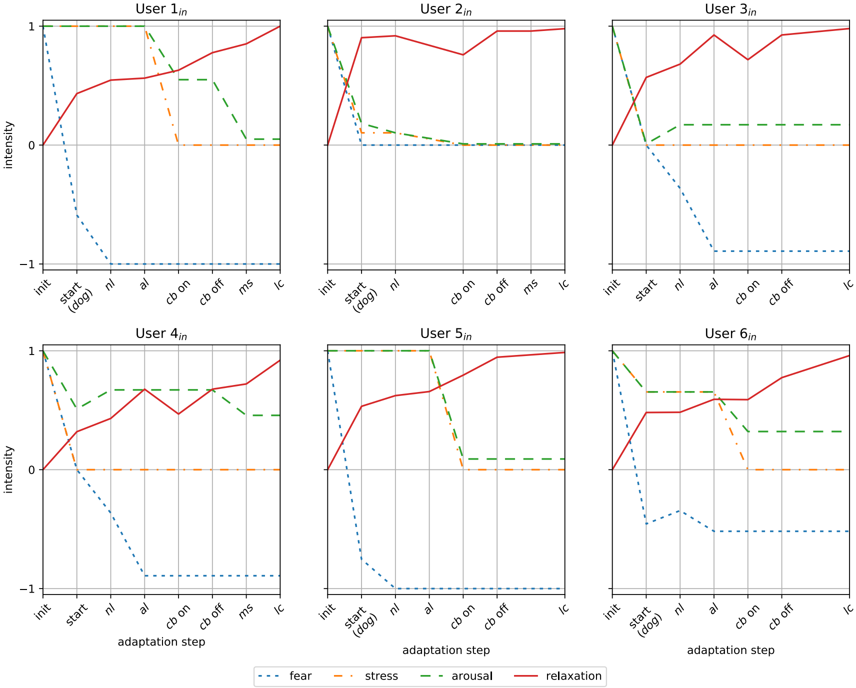

Figure 3.11: Plots showing the evolution of the emotional states at each time step for the indoor environment. The heuristic optimiser applies the adaptations in the same order for each user.

The initial emotion state is observed at init and is the same for every user. The emotional state at time step start depends on the user itself. At this time step environment is generated and initial values for the adaptations are calculated, these have an impact on the emotional state already as shown in each plot. In the case where the user has the dog adaptation, this will be activated at time step start, this is indicated in the plots as well.

For every simulated user in the outdoor environment the maximum relaxation of 1 is reached. While the stress parameter disappears (value of 0) in every simulation as well, the others, fear and arousal, do not always reach their minimum. Fear never reaches -1. Similarly, arousal is also never completely gone. However, these sub-optimal final emotional parameters do not have an impact on the final relaxation parameter as they are counteracted by the high evaluation of the preference functions.

In the case of the indoor environments, for every user, the relaxation increases significantly over the duration of the simulation. However, in many cases, the optimal value of 1 is not reached. In those cases, the arousal value does not approach 0 which could be the reason for the sub-optimal result. In some cases (Users 2_{in}, 3_{in}, 4_{in} and 6_{in}) fear does not reach its minimal value of -1, however, this does not seem to impact the final relaxation too much either. Finally, the relaxation curve shows slight reductions for users 3, 5 and 7 suggesting relaxation cannot be reached through a greedy approach, in other words, local optima in the curve are not to be considered as a global optimum.

These simulations indeed show how, even with a fixed order for activating the adaptations, near-optimal relaxation can be researched. Additionally, the heuristic optimiser can find a solution which leads to an acceptable final relaxation. However, it is also clear that maximising relaxation is not sufficient in every case. The other emotions should be minimised as much as possible to reach perfect relaxation. This could potentially be achieved by changing the order of the adaptations.

3.5.2.2 Adaptation Order

As seen in the previous evaluation, the order in which adaptations occur could have an impact on the effectiveness of the adaptations and, thus, the final emotional state. To evaluate this, tests are performed which change this order. Every time interval, exactly one adaptation takes place, which leads to a change of emotional values. Eight adaptations occur (dg, fr, nl, al, cb on, cb off, ms, and lc). Therefore, 40.320 possible permutations of these adaptations exist, however, as "cb off" will only happen after "cb on", only 20.160 permutations are valid. Fortunately, some more redundancies can be removed to reduce the number of permutations further down. While in indoor environments the fire (fr) adaptation is not present, outdoor environments do not contain artificial light (al), controlled breathing (cb), and light colour (lc). Therefore, the number of permutations for indoor environments is reduced to 5040 possible permutations and for outdoor to 24. To further reduce the number of permutation of

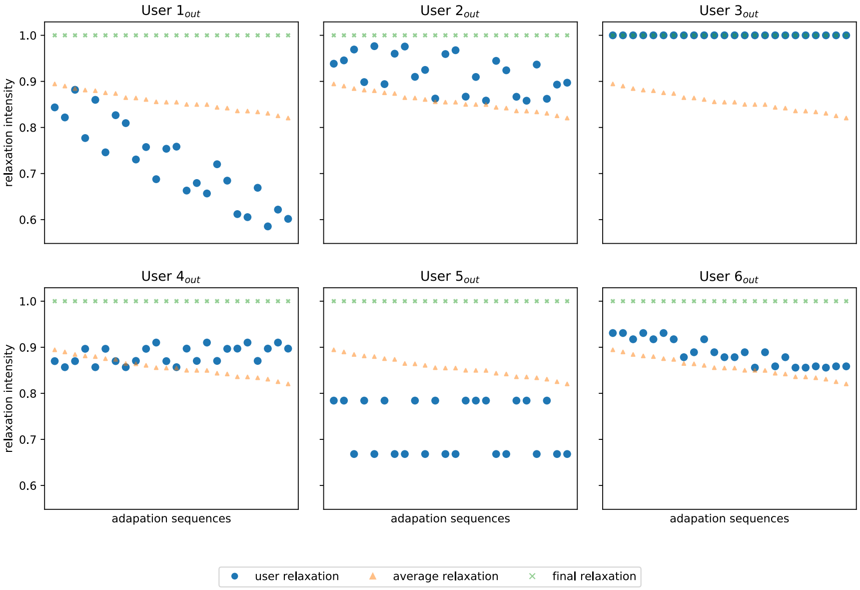

Figure 3.12: The average relaxation over all simulations plotted for every permutation of adaptations for the outdoor environment. The adaptation sequences are sorted according to decreasing final and average relaxation.

indoor environments, the actions "*cb* on" and "*cb* off" are combined into one, lowering the number of valid permutations to 720. This leads to a simulation run time of a maximum of 12 minutes for indoor environments and around 25 seconds for outdoor environments. In total, simulating the twelve users takes approximately 45 minutes.

The results of the simulations on the effect of changing the order in which adaptations occur are shown in Figures 3.12 and 3.13 for the outdoor and indoor environments respectively. These plots show the relaxation, averaged over all sessions of every simulated user, and the relaxation at the end of each session averaged over all users. The different sequences (x-axis) are first sorted by decreasing final relaxation than by decreasing average relaxation. In these plots, a relaxation value of 1 corresponds to the maximum relaxation achievable for that particular environment and user profile. This normalisation is performed to enable a proper comparison of the different user profiles. Tables 3.5 and 3.6 show the same sequences with the actual values for the averaged and final relaxation. The following sections discuss the results in more detail.

The first thing to notice for the outdoor environment in Figures 3.12 is that for the outdoor environment every sequence of adaptations the maximum relaxation is achieved. This implies that the order of the adaptations has no impact on the final relaxation for this set of adaptations. However, the order does have an impact on the average relaxation over each session. A higher average relaxation means that early on in the session a higher relaxation is obtained. This translates into first applying adaptions with a big impact and finishing with the lower impact adaptations. Reaching high relaxation as soon as possible is the desired outcome. Interestingly, three groups of users are observed in terms of average relaxation. Users 1_{out} and 5_{out} have a relaxation below the average (orange) for every permutation of the adaptations, users 2_{out} and 3_{out} are always above the average relaxation, while users 4_{out} and 6_{out} perform around the average for each sequence. This could be partially explained by the profile of the simulated users in Section 3.5.1. The first three user profiles are extreme cases, resulting in above or below average results. The last three are rather average users resulting in average relaxation except for user 5_{out}. This user shows a rather low average relaxation with little variation for different sequences. This could be explained by the fact that this user has many restrictions which resulted in only two effective adaptation. These same applies for user 3_{out} which has only one effective adaptation.

In Table 3.5 the 24 permutations of the adaptions are listed with the average relaxation over every user. This list is also sorted according to this relaxation metric. Sequences 1, 2, 3 and 5 have in common that the first two adaptation are dog (dg) and natural light (nl) while the last two adaptation in the sequence are music (ms) and fire (py) which is not the case for any of the other sequences. The highlighted row in Table 3.5 indicates the sequence which is used by the heuristic optimiser. Indeed this sequence is not the optimal order.

Now we can consider the indoor environments in Figure 3.13 for which Table 3.6 shows some of the most interesting sequences. These are also indicated on the plots. The order of the adaptations does have an impact on the final relaxation. Certain permutations are sub-optimal in the sense that they do not guarantee maximal relaxation. Furthermore, the order also has an impact on the average relaxation per user and the average relaxation overall. Interestingly, the same three groups of users can be identified for the indoor environments as for the outdoor. Namely, users 1_{in} and 5_{in} achieve below average relaxation for every permutation, users 2_{in} and 3_{in} achieve above-average relaxation, while users 4_{in} and 6_{in} perform on average.

Figure 3.13 and Table 3.6 indicate that from sequence 360 to 361 a big decrease in final and average relaxation occurs. Every sequence before 361 has the dog (dg) adaptation before the controlled breathing (cb).

Next, out of all 720 sequences, exactly 72 achieve maximal final relaxation for all users. These 72 sequences turn out not to be random. As indicated earlier, in all 72 sequences dg occurs before cb. For 60 of the 72 best sequences, the sequence ends with artificial light (al). The other 12 sequences end with the al adaptation immediately followed by the light colour (lc) adaptation. When inspecting the plots, it can be observed that for all users, except 3_{in} and 4_{in}, the optimal sequence is within the first 72 sequences. Users 3_{in} and 4_{in} have the combination of a low optimal al and dg

Table 3.5: Effect of different adaptation sequences on the average relaxation for outdoor environments. The list is ordered according to decreasing final and average relaxation. The highlighted sequence is the order used in the heuristic implementation.

No.	Sequence				Average Relaxation	Final Relaxation
1	*dg*	*nl*	*ms*	*py*	0.894	1.000
2	*dg*	*nl*	*py*	*ms*	0.890	1.000
3	*nl*	*dg*	*ms*	*py*	0.884	1.000
4	*dg*	*ms*	*nl*	*py*	0.881	1.000
5	*nl*	*dg*	*py*	*ms*	0.880	1.000
6	*ms*	*dg*	*nl*	*py*	0.875	1.000
7	*nl*	*ms*	*dg*	*py*	0.874	1.000
8	*nl*	*py*	*dg*	*ms*	0.865	1.000
9	*dg*	*py*	*nl*	*ms*	0.864	1.000
10	*ms*	*nl*	*dg*	*py*	0.861	1.000
11	*dg*	*ms*	*py*	*nl*	0.856	1.000
12	*nl*	*ms*	*py*	*dg*	0.855	1.000
13	*nl*	*py*	*ms*	*dg*	0.855	1.000
14	*dg*	*py*	*ms*	*nl*	0.850	1.000
15	*py*	*dg*	*nl*	*ms*	0.850	1.000
16	*ms*	*dg*	*py*	*nl*	0.850	1.000
17	*py*	*nl*	*dg*	*ms*	0.844	1.000
18	*ms*	*nl*	*py*	*dg*	0.842	1.000
19	*py*	*dg*	*ms*	*nl*	0.836	1.000
20	*ms*	*py*	*dg*	*nl*	0.836	1.000
21	*py*	*nl*	*ms*	*dg*	0.834	1.000
22	*py*	*ms*	*dg*	*nl*	0.831	1.000
23	*ms*	*py*	*nl*	*dg*	0.825	1.000
24	*py*	*ms*	*nl*	*dg*	0.820	1.000

Table 3.6: Effect of different adaptation sequences on the final and average relaxation for indoor environments. The list is ordered according to decreasing final and average relaxation. The highlighted sequence is the order used in the heuristic implementation.

No.	Sequence						Average Relaxation	Final Relaxation
1	*lc*	*dg*	*ms*	*cb*	*nl*	*al*	0.782	1.000
⋮								
72	*ms*	*nl*	*dg*	*cb*	*lc*	*al*	0.736	1.000
73	*lc*	*dg*	*ms*	*cb*	*al*	*nl*	0.793	0.996
⋮								
221	*dg*	*nl*	*al*	*cb*	*ms*	*lc*	0.759	0.982
⋮								
276	*ms*	*al*	*nl*	*dg*	*cb*	*lc*	0.751	0.982
277	*dg*	*al*	*lc*	*ms*	*cb*	*nl*	0.793	0.972
⋮								
360	*al*	*ms*	*nl*	*dg*	*cb*	*lc*	0.745	0.972
361	*lc*	*nl*	*ms*	*al*	*cb*	*dg*	0.719	0.858
⋮								
528	*cb*	*ms*	*al*	*nl*	*dg*	*lc*	0.622	0.858
529	*lc*	*nl*	*al*	*cb*	*dg*	*ms*	0.720	0.848
⋮								
660	*cb*	*al*	*ms*	*nl*	*dg*	*lc*	0.621	0.848
661	*al*	*lc*	*nl*	*ms*	*cb*	*dg*	0.719	0.838
⋮								
720	*al*	*cb*	*ms*	*nl*	*dg*	*lc*	0.644	0.838

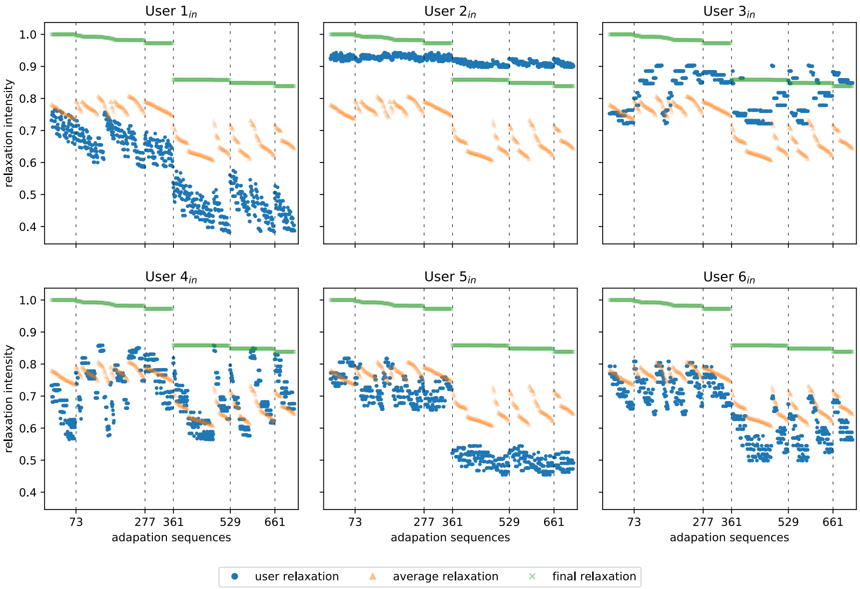

Figure 3.13: The average relaxation over all simulations plotted for every permutation of adaptations for the indoor environment. The adaptation sequences are sorted according to decreasing final and average relaxation.

intensity. A low optimal dg intensity deactivates the dg adaptation, and thus the occurrence of dg before cb does not make a difference. Furthermore, the absence of the dg adaptation means that fear and stress need to be decreased by another adaptation before activating cb, i.e. by nl and al. The highlighted row in Table 3.6 indicates the sequence which is used by the heuristic optimiser. As for the outdoor environment this sequence is also not the optimal order in this case.

3.5.3 Discussion

The results on the order of the adaptations have indicated that each user has an optimal order for the adaptations to occur in, this order depends entirely on the profile of the user. In fact, an algorithm in the form of a decision tree can be constructed which selects the optimal order. Before constructing this decision tree, the findings which lead to the algorithm are summarised. For the outdoor environment it was observed that natural light and dog should occur early in the sequence and music and fire can occur near the end. However, when natural light has a low optimal value, and therefore had little impact, the optimal sequences would end with natural light instead. More specifically, the set of optimal sequences are dg, nl, py, ms; dg, nl, ms, py; nl, dg, py, ms; and nl, dg, ms, py. Expect if natural light has a low optimal value, than the

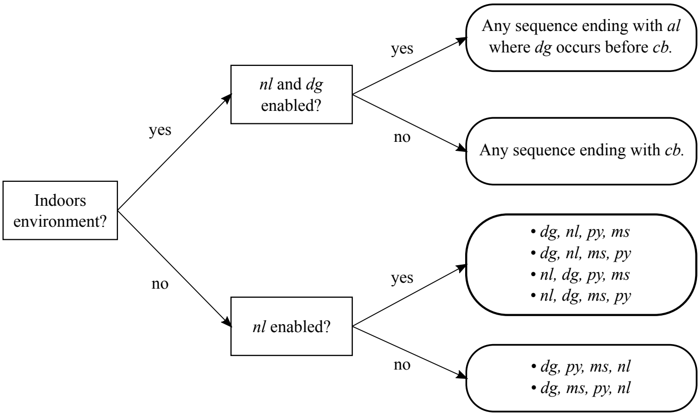

Figure 3.14: Visualisation of the decision process that leads to an optimal sequence.

optimal sequences are dg, py, ms, nl; and dg, ms, py, nl.

Since the indoor environments contain other adaptations as well, different rules apply. It was observed that every sequence should end with artificial light and that dog should also come before controlled breathing. However, when artificial light and dog are not enabled because their optimal value is too low, the sequence should simply end with controlled breathing.

Structuring this logic into a decision tree results in Figure 3.14. This tree can be used to reduce the set of all possible permutation of adaptions to a small set of sequences which are guaranteed to perform better than any other sequence. Depending on the available computing power, a simulation can be run to select the very best sequence from this reduced set, or a random sequence can be selected.

This result, which shows that different sequences result in a different outcome, indeed proves that personalisation is needed. Additionally, it is shown that through the described algorithms this personalisation can be achieved. More complex algorithms and more data could potentially further improve the benefits of a personalised approach. For example, the addition of biofeedback could ensure a quicker and more accurate response to changes in emotion and behaviour of the patient.

At this stage, the focus of the research is on simulated users as they provide full control over the users. In a next stage, these tests will be extended to real human users. A demo application was already developed for these VE and the proposed model and algorithm. This demo application was presented in [42]. The response to this demo during its presentation at the conference was very positive. However, no formal subjective study was conducted. In future work, structured tests will be performed with this demo application to evaluate the relevance of the model on real users.

3.6 Conclusion and Future Work

In this work, a mathematical model for simulating emotional response for VR-based relaxation therapy is presented. The model makes use of both a personality profile as well as the user's emotional state to create a fully adaptive and personalised relaxation environment for the user. This is a simple yet effective model that does not need more complication as only a limited set of base environments are possible. To illustrate its potential, it has been implemented and used in a system that provides a personalised VR experience for relaxation therapy. The system selects an environment based on a decision tree. The information for evaluating the decision tree is collected through a short list of questions. From these base environments, small adaptations are made through adaptation parameters, to personalise the environment and thus maximise the relaxation.

In this paper, the potential of the emotional model has been shown through preliminary results from simulations. Furthermore, this work shows the capability of personalised, adaptive applications in VR, not only for relaxation therapy but also for other exposure therapy applications.

As future work, we aim to further tune the emotional model by incorporating biofeedback. This biofeedback could insure that the estimated emotional state is in sync with the user's actual state. Moreover, it could make it possible to react on small, sudden changes in the user's state, which are not caused by the environment or are not captured explicitly in the mathematical model. Additionally, tests with actual users will be performed to collect further evidence for the effectiveness of this approach.

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References

[1] L. Varvogli and C. Darviri. *Stress Management Techniques: evidence-based procedures that reduce stress and promote health.* Health Science Journal, 5(2):74–89, 2011.

[2] A. S. Bell, D. Rajendran, and S. Theiler. *Job stress, wellbeing, work-life balance and work-life conflict among Australian academics.* E-Journal of Applied Psychology, 8(1):25–37, December 2012. Available from: http://pandora.nla.gov.au/tep/147390, doi:10.7790/ejap.v8i1.320.

[3] J. Skakon, K. Nielsen, V. Borg, and J. Guzman. *Are leaders' well-being, behaviours and style associated with the affective well-being of their employees? A systematic review of three decades of research.* Work & Stress, 24(2):107–139, April 2010. Available from: http://www.tandfonline.com/doi/abs/10.1080/02678373.2010.495262, doi:10.1080/02678373.2010.495262.

[4] G. Kinman and S. Wray. *Taking its toll: rising stress levels in further education UCU Stress Survey 2014.* London: University and College Union, 2015. Available from: http://rgdoi.net/10.13140/RG.2.2.31578.64967, doi:10.13140/RG.2.2.31578.64967.

[5] M. Carder, S. Turner, R. McNamee, and R. Agius. *Work-related mental ill-health and 'stress' in the UK (2002-05).* Occupational Medicine, 59(8):539–544, December 2009. Available from: https://academic.oup.com/occmed/article-lookup/doi/10.1093/occmed/kqp117, doi:10.1093/occmed/kqp117.

[6] S. B. Hanser. *Music Therapy and Stress Reduction Research.* Journal of Music Therapy, 22(4):193–206, December 1985. Available from: https://academic.oup.com/jmt/article-lookup/doi/10.1093/jmt/22.4.193, doi:10.1093/jmt/22.4.193.

[7] A. Steptoe and M. Kivimäki. *Stress and cardiovascular disease.* Nature Reviews Cardiology, 9(6):360—370, 2012.

[8] M. B. Schure, J. Christopher, and S. Christopher. *Mind-Body Medicine and the Art of Self-Care: Teaching Mindfulness to Counseling Students Through Yoga, Meditation, and Qigong.* Journal of Counseling & Development, 86(1):47–56, January 2008. Available from: http://doi.wiley.com/10.1002/j.1556-6678.2008.tb00625.x, doi:10.1002/j.1556-6678.2008.tb00625.x.

[9] A. Trappey, C. V. Trappey, C.-M. Chang, R. R. Kuo, A. P. Lin, and C. Nieh. *Virtual Reality Exposure Therapy for Driving Phobia Disorder: System Design and Development.* Applied Sciences, 10(14):4860, July 2020. Available from: https://www.mdpi.com/2076-3417/10/14/4860, doi:10.3390/app10144860.

[10] S. F. M. Pizzoli, K. Mazzocco, S. Triberti, D. Monzani, M. L. Alcañiz Raya, and G. Pravettoni. *User-Centered Virtual Reality for Promoting Relaxation: An Innovative Approach.* Frontiers in Psychology, 10, March 2019. Available from: https://www.frontiersin.org/article/10.3389/fpsyg.2019.00479/full, doi:10.3389/fpsyg.2019.00479.

[11] A. Gutiérrez, D. Sepúlveda-Muñoz, A. Gil-Agudo, and A. de los Reyes Guzmán. *Serious Game Platform with Haptic Feedback and EMG Monitoring for Upper Limb Rehabilitation and Smoothness Quantification on Spinal Cord Injury Patients.* Applied Sciences, 10(3):963, February 2020. Available from: https://www.mdpi.com/2076-3417/10/3/963, doi:10.3390/app10030963.

[12] L. N. Lee, M. J. Kim, and W. J. Hwang. *Potential of Augmented Reality and Virtual Reality Technologies to Promote Wellbeing in Older Adults.* Applied Sciences, 9(17):3556, August 2019. Available from: https://www.mdpi.com/2076-3417/9/17/3556, doi:10.3390/app9173556.

[13] L. R. Valmaggia, L. Latif, M. J. Kempton, and M. Rus-Calafell. *Virtual reality in the psychological treatment for mental health problems: An systematic review of recent evidence.* Psychiatry Research, 236:189–195, February 2016. Available from: http://www.sciencedirect.com/science/article/pii/S0165178116300257, doi:10.1016/j.psychres.2016.01.015.

[14] P. M. G. Emmelkamp. *Effectiveness of cybertherapy in mental health: a critical appraisal.* Studies in Health Technology and Informatics, 167:3–8, 2011.

[15] K. Meyerbröker and P. M. Emmelkamp. *Virtual reality exposure therapy in anxiety disorders: a systematic review of process-and-outcome studies.* Depression and Anxiety, 27(10):933–944, August 2010. Available from: http://doi.wiley.com/10.1002/da.20734, doi:10.1002/da.20734.

[16] Y. A. Sekhavat and P. Nomani. *A Comparison of Active and Passive Virtual Reality Exposure Scenarios to Elicit Social Anxiety.* International Journal of Serious Games, 4(2):3–15, June 2017. Available from: https://journal.seriousgamessociety.org/index.php/IJSG/article/view/154, doi:10.17083/ijsg.v4i2.154.

[17] M. B. Powers and P. M. Emmelkamp. *Virtual reality exposure therapy for anxiety disorders: A meta-analysis.* Journal of Anxiety Disorders, 22(3):561–569, April 2008. Available from: https://linkinghub.elsevier.com/retrieve/pii/S088761850700103X, doi:10.1016/j.janxdis.2007.04.006.

[18] D. Opriş, S. Pintea, A. García-Palacios, C. Botella, Ş. Szamosközi, and D. David. *Virtual reality exposure therapy in anxiety disorders: a quantitative meta-analysis: Virtual Reality Exposure Therapy.* Depression and Anxiety, 29(2):85–93,

February 2012. Available from: http://doi.wiley.com/10.1002/da.20910, doi:10.1002/da.20910.

[19] L. B. I. Shah, S. Torres, P. Kannusamy, C. M. L. Chng, H.-G. He, and P. Klainin-Yobas. *Efficacy of the Virtual Reality-Based Stress Management Program on Stress-Related Variables in People With Mood Disorders: The Feasibility Study.* Archives of Psychiatric Nursing, 29(1):6–13, February 2015. Available from: http://www.sciencedirect.com/science/article/pii/S0883941714001381, doi:10.1016/j.apnu.2014.09.003.

[20] F. Soyka, M. Leyrer, J. Smallwood, C. Ferguson, B. E. Riecke, and B. J. Mohler. *Enhancing stress management techniques using virtual reality.* In Proceedings of the ACM Symposium on Applied Perception - SAP '16, pages 85–88, Anaheim, California, 2016. ACM Press. doi:10.1145/2931002.2931017.

[21] S. M. Gerber, M.-M. Jeitziner, P. Wyss, A. Chesham, P. Urwyler, R. M. Müri, S. M. Jakob, and T. Nef. *Visuo-acoustic stimulation that helps you to relax: A virtual reality setup for patients in the intensive care unit.* Scientific Reports, 7(1), December 2017. doi:10.1038/s41598-017-13153-1.

[22] A. P. Anderson, M. D. Mayer, A. M. Fellows, D. R. Cowan, M. T. Hegel, and J. C. Buckey. *Relaxation with Immersive Natural Scenes Presented Using Virtual Reality.* Aerospace Medicine and Human Performance, 88(6):520–526, June 2017. doi:10.3357/AMHP.4747.2017.

[23] M. E. Hyland, D. M. Halpin, S. Blake, C. Seamark, M. Pinnuck, D. Ward, B. Whalley, C. J. Greaves, A. L. Hawkins, and D. Seamark. *Preference for different relaxation techniques by COPD patients: comparison between six techniques.* International Journal of Chronic Obstructive Pulmonary Disease, 11:2315–2319, 2016. doi:10.2147/COPD.S113108.

[24] S. Graffam and A. Johnson. *A comparison of two relaxation strategies for the relief of pain and its distress.* Journal of Pain and Symptom Management, 2(4):229–231, 1987. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0885392487800611, doi:10.1016/S0885-3924(87)80061-1.

[25] C. L. Macnamara, E. Cvejic, G. B. Parker, A. R. Lloyd, G. Lee, J. E. Beilharz, and U. Vollmer-Conna. *Personalised relaxation practice to improve sleep and functioning in patients with chronic fatigue syndrome and depression: study protocol for a randomised controlled trial.* Trials, 19(1):371, December 2018. Available from: https://trialsjournal.biomedcentral.com/articles/10.1186/s13063-018-2763-8, doi:10.1186/s13063-018-2763-8.

[26] J. L. Maples-Keller, B. E. Bunnell, S.-J. Kim, and B. O. Rothbaum. *The Use of Virtual Reality Technology in the Treatment of Anxiety and Other Psychi-*

atric Disorders. Harvard Review of Psychiatry, 25(3):103–113, June 2017. doi:10.1097/HRP.0000000000000138.

[27] E. Garcia-Ceja, M. Riegler, T. Nordgreen, P. Jakobsen, K. J. Oedegaard, and J. Tørresen. *Mental health monitoring with multimodal sensing and machine learning: A survey.* Pervasive and Mobile Computing, 51:1–26, December 2018. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1574119217305692, doi:10.1016/j.pmcj.2018.09.003.

[28] M. Egger, M. Ley, and S. Hanke. *Emotion Recognition from Physiological Signal Analysis: A Review.* Electronic Notes in Theoretical Computer Science, 343:35–55, May 2019. Available from: https://linkinghub.elsevier.com/retrieve/pii/S157106611930009X, doi:10.1016/j.entcs.2019.04.009.

[29] J. Healey and R. Picard. *Detecting Stress During Real-World Driving Tasks Using Physiological Sensors.* IEEE Transactions on Intelligent Transportation Systems, 6(2):156–166, June 2005. Available from: http://ieeexplore.ieee.org/document/1438384/, doi:10.1109/TITS.2005.848368.

[30] D. Miranda, M. Calderón, and J. Favela. *Anxiety detection using wearable monitoring.* In Proceedings of the 5th Mexican Conference on Human-Computer Interaction - MexIHC '14, pages 34–41, Oaxaca, Mexico, Mexico, 2014. ACM Press. Available from: http://dl.acm.org/citation.cfm?doid=2676690.2676694, doi:10.1145/2676690.2676694.

[31] M. S. Lee, Y. K. Lee, D. S. Pae, M. T. Lim, D. W. Kim, and T. K. Kang. *Fast Emotion Recognition Based on Single Pulse PPG Signal with Convolutional Neural Network.* Applied Sciences, 9(16):3355, August 2019. Available from: https://www.mdpi.com/2076-3417/9/16/3355, doi:10.3390/app9163355.

[32] J. Domínguez-Jiménez, K. Campo-Landines, J. Martínez-Santos, E. Delahoz, and S. Contreras-Ortiz. *A machine learning model for emotion recognition from physiological signals.* Biomedical Signal Processing and Control, 55:101646, January 2020. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1746809419302277, doi:10.1016/j.bspc.2019.101646.

[33] T. Steimer. *The biology of fear- and anxiety-related behaviors.* Dialogues in Clinical Neuroscience, 4(3):231–249, September 2002.

[34] C. R. Sims. *Rate–distortion theory and human perception.* Cognition, 152:181–198, July 2016. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0010027716300750, doi:10.1016/j.cognition.2016.03.020.

[35] K. C. Smolders and Y. A. de Kort. *Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal.* Journal of Environmental Psychology,

39:77–91, September 2014. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0272494413001060, doi:10.1016/j.jenvp.2013.12.010.

[36] D. G. Luenberger and Y. Ye. *Linear and Nonlinear Programming*, volume 228 of *International Series in Operations Research & Management Science*. Springer International Publishing, Cham, 2016. Available from: http://link.springer.com/10.1007/978-3-319-18842-3, doi:10.1007/978-3-319-18842-3.

[37] B. Manav. *Color-emotion associations and color preferences: A case study for residences.* Color Research & Application, 32(2):144–150, April 2007. Available from: http://doi.wiley.com/10.1002/col.20294, doi:10.1002/col.20294.

[38] C. Dana Lynn. *Hearth and Campfire Influences on Arterial Blood Pressure: Defraying the Costs of the Social Brain through Fireside Relaxation.* Evolutionary Psychology, 12(5):147470491401200, April 2014. Available from: http://journals.sagepub.com/doi/10.1177/147470491401200509, doi:10.1177/147470491401200509.

[39] E. Friedmann and H. Son. *The Human–Companion Animal Bond: How Humans Benefit.* Veterinary Clinics of North America: Small Animal Practice, 39(2):293–326, March 2009. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0195561608001940, doi:10.1016/j.cvsm.2008.10.015.

[40] C. Suied, G. Drettakis, O. Warusfel, and I. Viaud-Delmon. *Auditory-Visual Virtual Reality as a Diagnostic and Therapeutic Tool for Cynophobia.* Cyberpsychology, Behavior, and Social Networking, 16(2):145–152, February 2013. Available from: http://www.liebertpub.com/doi/10.1089/cyber.2012.1568, doi:10.1089/cyber.2012.1568.

[41] E. Paulus, F. Yusuf, M. Suryani, and I. Suryana. *Development and Evaluation on Night Forest Virtual Reality as Innovative Nyctophobia Treatment.* Journal of Physics: Conference Series, 1235:012003, June 2019. Available from: https://iopscience.iop.org/article/10.1088/1742-6596/1235/1/012003, doi:10.1088/1742-6596/1235/1/012003.

[42] J. Heyse, T. D. Jonge, M. Torres Vega, F. D. Backere, and F. De Turck. *A personalized Virtual Reality Experience for Relaxation Therapy.* In 2019 Eleventh International Conference on Quality of Multimedia Experience (QoMEX), pages 1–3. IEEE, June 2019. Available from: https://ieeexplore.ieee.org/document/8743335/, doi:10.1109/QoMEX.2019.8743335.

4

PATRONUS: Towards an Architecture for Personalised Virtual Reality Exposure Therapy

In this chapter, the PATRONUS platform is presented. It takes the research presented in Chapters 2 and 3 even further by incorporating the Virtual Reality (VR) system in a patient-centred blended care platform. Thereby, contributing to the third challenge in Section 1.5. PATRONUS provides a platform composed of various tools to help psychotherapists in providing better care and treatment for patients with anxiety disorders. The main functionality of the system are, (i) Virtual Environment (VE) for specific scenarios in which patients are exposed to their anxiety, (ii) support in personalising these VE through automatic suggestion generation based on history context of the patient, (iii) a mobile coaching app for the patient to perform VR and in vivo exposure exercises at home and to register relevant events in their daily lives, (iv) support for psychotherapists in the assessment of patients through the automated analysis of physiological data, and (v) a centralised information system with a dashboard interface through which the psychotherapist can consult all information of a patient and manage therapy sessions. The personalisation algorithm is discussed in more detail in Chapter 5. This chapter further contributes to challenge 4 and 5 in Section 1.5 by adopting an inclusive design process.

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Abstract Exposure therapy in virtual reality has increasingly been investigated as treatment for anxiety disorders. However, most of studies do not yet research the integration of virtual reality exposure therapy as part of a blended care solution. Therefore, no studies are available that present such a platform. In this paper, the PATRONUS platform is presented as a patient-centred blended care solution for virtual reality exposure therapy. The methodology for the design of the platform focusses on the incorporation of needs and wishes of patients and psychotherapists which have been collected through focus groups and workshops. The result is a system that enables exposure therapy in virtual reality for specific and generalised anxiety disorders. The virtual environments can be tailored to the needs of the patient, either manually or through an intelligent adaptation algorithm. Furthermore, the patient is empowered to perform virtual reality exposure exercises at home through a mobile application. A preliminary effectiveness study shows potential for this platform. However, extensive user studies with large populations are needed to further prove its effectiveness.

4.1 Introduction

Anxiety disorders are extremely common in the world population. According to World Health Organisation (WHO), it is the 6th largest contributor to global disability [1]. The most effective treatment for anxiety disorders is Exposure Therapy (ET) [2]. By confronting an individual with the source of their anxiety, they learn to control their fear instead of letting it control them. In recent years, there has been an increasing interest in Virtual Reality Exposure Therapy (VRET), an approach in which ET is provided in Virtual Reality (VR). VR allows for much more control over the environment in which exposure happens which allows for better patient-centred therapy. Meanwhile, plenty of studies show evidence that VRET is at least as effective as regular in vivo ET [3–5].

However, most research focuses solely on the ET in VR itself and not on its integration in a patient-centred or blended care solution. Blended care is the combination of regular face-to-face care with technology assisted tools for individual self-management. Blended care is relatively new and requires more research but early studies show promising results [6]. Its benefit is that treatment can be much more effective in the long term if patients are stimulated to follow up on their treatment by themselves. To the authors' knowledge, there are currently no publications that discuss an architecture for a patient-centred, blended care platform for VRET. This paper aims to fill this gap by discussing the design, and implementation of such a platform.

PATRONUS is an interdisciplinary effort between psychotherapist, scientists and IT experts to design, develop and evaluate an advanced system for VRET. The key features that characterise PATRONUS and make it unique are: (1) configurable Virtual Environment (VE) for various scenarios, (2) a support algorithm for personalised VE tailored to the needs of the patient, (3) automatic analysis of physiological data from a wearable device for presentation of an objective metric for anxiety, (4) VRET homework exercises through a mobile app, (5) longitudinal follow-up by self-reporting in a mobile app, (6) a centralised system for patient and therapy session management. Because PATRONUS aims to provide better care for the patient and the proper tools for the psychotherapist to deliver this, both their needs and wishes need to be carefully considered in the creation of this platform. Co-design is the process of creating a solution in close collaboration with the end users during the entire design process. This approach ensures that the product meets the expectations of the end users. Therefore, it has been rigorously applied in the design process of PATRONUS.

The remainder of this paper is structured as follows. First related work regarding co-design techniques is covered in Section 4.2. In Section 4.3, the methodologies for extracting the requirements for the presented platform through focus groups and workshops are discussed. This is followed by a hypothetical script of an VRET procedure to illustrate what patients and psychotherapists expect of the system in Section 4.4. Next, these expectations are formally summarised in Section 4.5, this is the result of the focus groups and workshops with end users. Based on these requirements, Section 4.6 introduces the design of the architecture. The specifications of the implementation are formulated in Section 4.7. Finally, a pilot study with patients and a conclusion are presented in Sections 4.8 and 4.9 respectively.

4.2 Related Work

Co-design approaches have many benefits for the development of eHealth solutions [7, 8]. In fact, one could argue that it is a necessity for creating useful solutions of high quality as it ensures that the needs, wishes and insights of the end users are incorporated in the design process. However, co-design refers to the process of including end users in the entire design process [9]. Some examples of these methods are observation sessions, questionnaires and surveys [10], interviews [11], focus groups [12] and interactive workshops [13]. The methods differ in the amount of engagement with the end users, the level of detail that can be discussed and the interaction between the different participators (end users, researchers, designers or other stakeholders) [14]. Each approach has its benefits and challenges. For example, observation sessions are interesting for researchers and designers to understand context and test the implementation of new concepts. However, the inclusion of the end user in the creation itself is limited. Questionnaires can provide large amounts of data from a wide range of different end users to steer the creation process, but the set of questions is the same for every end user, therefore in-depth discussions are not possible. Interviews do allow for an in-depth discussion as the researcher or designer can ask follow-up questions to the end users, but this makes them quite time consuming. Focus groups, then again, are more efficient as they bring together multiple stakeholders, which, in turn, encourages interactions and discussions. Interactive workshops are perhaps the least formal and because of this can result in the most out of the box and tangible concepts. This method encourages creation through brainstorming, storytelling, wall storms and other techniques. Many different interactive workshops formats exist such as hackathons [15], design jams [10] or design charrettes [10]. As the available technologies keep evolving, the co-design techniques that put them into practice will keep evolving as well [16].

Many studies and use cases have been documented that incorporate any of the previously mentioned techniques or adaptation thereof. For example, co-design has lead to the development of a self-monitoring app for young people during treatment of depression [17]. They used co-design workshops to develop the app to the young people's needs. By developing prototypes and mock-ups of the app, peers could evaluated each others ideas. Also for less tangible but more technical problems have co-design approaches been used. For example, Ongenae et al. developed a co-design framework for constructing detailed semantic ontologies containing highly specific domain knowledge in the context of health [18]. The approach consists of workshop sessions in which discussion are engaged with health domain experts to extract the knowledge they employ during their professional activities. This knowledge is structured on large canvases during the workshops which are then used to construct the ontology containing the extracted knowledge. These workshops are mostly focussed on uncovering tacit knowledge of the domain experts.

4.3 Methodology

The design of a platform such as PATRONUS is complex because of the different stakeholders involved. A combination of methods such as focus groups, workshops and brainstorm sessions were used to gather the required information to build the system and iteratively work towards a final proof of concept. In this section, these methods and their application for this work are discussed.

4.3.1 Focus groups

Designing a new application requires to understand the needs and wishes of the end users of the product. Especially in research, this is important because those needs and wishes might not be very clear from the beginning. For example, when exploring a new technology, there is no precedent for it, therefore, it is important to investigate how end users want to use it. Furthermore, if the goals is to innovate by incorporating new technology, caution is warranted in making sure that the technology contributes to the problem to be solved. An inclusive design process in which various stakeholders, including the end users, are involved from the beginning of the process is also referred to as co-creation design [19]. This approach is also followed for the design and development of the PATRONUS platform.

In an early stage of the project, focus groups were organised with potential patients and psychotherapists. Two sessions with each four participants were held with patients diagnosed with an anxiety disorder, while one session was held with six psychotherapists who had experience with ET. During these sessions the patients were asked about their own experiences with regular ET and possible experiences with technology in support of their anxiety disorder. The patients also focussed on ideas they might have that would be beneficial to them. In general they were asked what the system should be able to do. The psychotherapists were asked the same question, but from the perspective of their profession. Furthermore, features were prioritised in functionality the system should definitely have and functionality that would be nice to have. These psychotherapists were also asked about their concerns and limitations of the technology.

The findings and ideas of these focus groups were gathered and prioritised based on the input of the participants. Next, a list of requirements was created which could be discussed with the other stakeholders of the project such as the developers and researchers.

4.3.2 VR Prototyping

Developing a VR environment is complex and time consuming. This can pose a problem when the requirements of the VE are not yet known at the beginning of a project. This was the case for this research where novel VEs needed to be created. Uncovering the requirements for these VEs was an iterative process in which intermediate results were tested and evaluated. Traditional software development approaches, in which the VE are designed from an agreed upon set of requirements, are not suitable for developing VR environments. Therefore, a rapid game prototyping technique was used that had been tested before on VR environments. This technique employs a workflow that allows multiple iterations and easy experimentation with various prototypes. The findings of the experiments are taken into account for the next iteration and thus, gradually the desired result is obtained. The prototyping process results in the delivery of clear requirements and recommendations for the final product. Below, the methodology of the process is discussed in more detail.

Based on the ideas from the focus groups described in Section 4.3.1, several prototypes were developed. Each prototype starts with an in-depth analysis to make sure all information to create the prototype is available. This analysis results in a Prototype Design Document (PDD) containing the structure and features of the prototype. The features are divided into “must have” features for the first prototype iteration and “nice to have” features for possible later iterations. This distinction can be made based on the prioritisation of ideas of the focus groups. The PDD requires final approval of the domain experts before implementation can start. If needed, changes can still be made to the PDD before approval.

Multiple first-iteration prototypes are created to compare concepts and ideas. By using the iterative approach, prototypes can be adjusted and improved to fine-tune the concepts into a satisfactory result. With each iteration, new features and adjustments are defined which are documented in the PDD. The prototypes were built with a parameter tuning system in place. This means that certain properties of the VE, e.g. the size of a room or the appearance of objects, could be changed through simple configuration and this without requiring additional modeling or programming. This allows to quickly change the behaviour of the prototype and enables easy experimentation with variations of a prototype without requiring programming knowledge.

For every prototype, design recommendations are added to the documentation. These recommendations include various insights and ideas that came forward during the development and testing of the prototype that could be relevant for the implementation of the final product.

4.3.3 Expert Knowledge Workshops

The intelligent algorithm for the adaptation of exposure environments was also developed in close collaboration with domain experts. Workshops were organised to uncover the knowledge that needs to be incorporated in those algorithms. Specifically, these workshops were designed to understand the decision making process of the psychotherapists in detail such that part of these processes could be digitised to use them in intelligent algorithms such as the adaptation algorithm. The result of these workshops is a knowledge model containing the most important concepts used by the psychotherapists and information on how they were used to make decisions. This knowledge model was formalised into a semantic ontology, which is a formalised description of concepts, relation between them and logical rules which are interpretable by a computer system. The advantage of such an ontology is that reasoning can be used to process data using the knowledge in this ontology.

Two workshop sessions were organised with psychotherapists who had experience with regular in vivo ET. One sessions had four participants, the other three. The results of the workshops were processed and combined afterwards. This approach ensures that the results are not limited to the view of one group of people and it enables covering a broader section of the domain. The psychotherapists participating in the workshops had no prior knowledge of the PATRONUS project itself. This is to prevent biased decisions on the design of the system. The workshops were led by a moderator which asks follow-up question when clarification is needed or when the discussion runs silent. An ontology engineer writes down, on large sheets of paper, the concepts and relations mentioned by the psychotherapists and the decision steps which will be processed and formalised after the workshop. Finally, an observer transcribes the sessions. Ongenae et al. [18] discusses the general approach of the

Figure 4.1: Pictures of the workshops showing one person writing down on large sheets of paper while the psychotherapists are discussing the therapy workflow.

workshop in more detail.

The workshop starts with a warm-up exercise through which the psychotherapists experience a therapy scenario in VR to get them familiar with the technology and allow them to better understand its potential and limitations. Next, each participant is asked to describe a particular therapy session from their own experience. These are used during the workshop as use cases to validate the decision processes the psychotherapists are explaining. After that, the discussion is initiated by having the psychotherapists explain how they think a VRET system could automatically adapt to the needs of the patient and which information it needs to have for this. Every major decision step is challenged during the discussion to filter out the most relevant ones and reduce them to their essence. Figure 4.1 gives an impression of one of the workshops.

4.4 Exposure Therapy Script

Based on the findings of the focus groups with users and psychotherapists the following fictitious scenario can be created which illustrates the goal and vision of the PATRONUS platform.

A patient, called Alice, experiences severe anxiety any time she needs to drive in a car as a passenger. It has reached a point where she cannot get in a car with someone else if she is not driving herself. To find a solution for her problem, Alice decides to go to a psychotherapist for help, his name is Bob.

During her first appointment, Bob does an intake interview with Alice. He asks her question about her anxiety and avoidance behaviour to get a clear view of the problem. Bob also checks for some criteria to make sure Alice is eligible for ET in VR. Once Bob verifies that VRET can be part of Alice's treatment, he asks her to fill in some questionnaires. This includes a questionnaire that will be used by the PATRONUS platform to understand how the patient can be treated.

In between the first and the second appointment, Bob uses a dashboard application to creates a patient account for Alice to which he uploads the questionnaires that Alice filled in. On her second appointment, Alice receives psycho-education about anxiety and avoidance behaviour and Bob explains to her how the therapy works. During this appointment, Bob logs in on the PATRONUS platform through the dashboard application and starts a new session for Alice. Before any exercises can be performed, a baseline measurement needs to be taken of Alice's physiological parameters. She is asked to strap a wearable device on her wrist which contains sensors that can measure various physiological parameters. During a 10 minute period, data is collected and stored on the PATRONUS platform.

When the baseline measurement is finished and Alice is ready, a first exposure exercise in VR can be performed. When Alice puts on the VR headset, she first sees a quiet and neutral environment. It represents some kind of lounge area in which she is seated on a couch. In the meantime, Bob is creating a new VR exercise for the current session on the dashboard of the PATRONUS platform. He chooses a VR exercises set in a car scenario. The scenario still needs to be configured to the specific requirements of Alice at that time. The dashboard shows a list of parameters that Bob can change based on his expertise. Each parameter changes something about the VR environment. Bob configures the exercise such that Alice is sitting in the passenger seat of a car, driving at low speed, on a road with little traffic. Before Alice can start the exercise, she first needs to answer a few questions about her expectations, Bob writes down the answers to these questions in the dashboard.

It is time for Alice to start her first VRET exercise which Bob initiates through the dashboard. Immediately, Alice is transitioned to virtual car according to the configuration chosen by Bob. At regular time intervals Bob asks Alice to say how much discomfort she is experiencing on a scale of 0 to 100 which he enters in the dashboard. When Alice is suddenly overtaken by a lorry, Bob notice on the screen that an algorithm predicts a very high anxiety level in Alice. The algorithm is able to make this prediction based on the wearable device collecting physiological data that Alice is still wearing. Bob decides to ask Alice about this and writes down his observations. He can also register other specific observations such as when Alice is showing avoidance behaviour during an exercise.

After a predetermined time, the exercises is terminated by Bob. Alice can keep the Head Mounted Display (HMD) on while she is transitioned back to the relaxing lounge. After each exercise, Bob will ask her again a few questions about the exercise to which he will enter the answers in the dashboard. In agreement with Alice a new exercise will be started. This time Bob decides to let the system make suggestions on what a good configuration would be for the next exercise. It does this based on information that was provided for previous exercises. Based on his expertise and knowledge of Alice's case, Bob chooses one of the suggestions but tweaks it a little but further before saving it. He then starts the new exercise in the same way as the previous one.

At the end of the session, Alice can take of the HMD again. Because Bob felt that the exercises went very well, he proposes that Alice does some of the exposure exercises at home on her own. Bob creates a new homework exercises for Alice based on the configuration of the first VR exercise they did together. Now Alice can also see this exercise in the coaching application she had to install on her smartphone.

The next day, when Alice is at home, she decides to do her homework exercise. She navigates to the exercise in the application and is instructed to put her smartphone in a mobile VR headset. This way she can perform the VR exercise on her mobile phone. Sometime later that day, Alice is presented with a real life situation in which she has the opportunity to get in a car with someone else. Afterwards, she logs her experience in the coaching app because Bob has asked her to keep a journal of noteworthy moments throughout the day. This information then becomes available to Bob.

4.5 Requirements Analysis

Based on conversations during the focus groups, the needs and wishes of all stakeholders were uncovered. This led to the formulation of the requirements for the PATRONUS platform. Domain experts and potential users of the system explained what they expect to be able to do with the system. This includes general functionality to support regular therapy and specific functionality for VRET. These are the functional requirements of PATRONUS. Additionally, a certain level of quality is expected of a software system. This is captured in the non-functional requirements. These were also discussed during focus groups with the stakeholders. Lastly, there are constraints on the system that need to be taken into account during the design of the system. These constraints are the result of limitations imposed by the stakeholders. In this section, all major requirements and constraints of the proposed PATRONUS system are discussed in detail.

4.5.1 Functional Requirements

There are two groups of users of the proposed system, psychotherapists that administer the therapy, and patients that undergo the therapy. Both user groups have a set of functionalities that need to be implemented by the system to support therapy sessions in VR and in vivo. The remainder of this subsection provides a summary of these functionalities in the form of use cases. Each use cases is described in detail.

The system should have three different user interfaces. There is a dashboard application which is the main interface for most administration and configuration tasks, this is only used by the psychotherapist. A mobile application which is used by the patient at home and the VR headset through which the patient interacts with the VR environments.

4.5.1.1 Manage users

Psychotherapists should be able to manage users within the system. A patient's account first needs to be linked to a psychotherapist's account. The psychotherapist also needs to provide information to the system about the patient. This information includes answers to questions collected through external questionnaire systems such as Qualtrics[1]. The results of these questionnaires can be uploaded into the system by the users through the dashboard application.

4.5.1.2 Manage Scenarios and Exercises

A scenario describes the general setting of a VE for exposure exercises. It defines the appearance of the VE and possible events and actions that may occur during the exercise. Most scenarios will have some variable parameters to further specify the exercises, these can be controlled by the psychotherapists. The ranges of possible values of these variables parameters are also defined by the scenario description. Scenarios can be divided into two groups, in vivo scenarios and VR scenarios. In vivo scenarios are very versatile and can be anything the psychotherapists wishes to describe. VR scenarios are much more constraint but offer more fine grained control. These scenarios need to be implemented as VR environments by developers. A VR scenario is defined by the look and feel of the virtual environment, the actions the user can perform, events that can happen in the scenario and the set of parameters that can be configured. In vivo scenarios can be created and managed by the psychotherapists. VR scenarios cannot be created by the psychotherapist themselves as they require 3D-modeling and programming. A team of VR developers could create new scenarios for the system.

An exercise is an instantiation of a scenario. Within the constraints described by a scenario, an exercise can be created which adheres to these constraints and configures the values for the variable parameters of the scenario. In vivo exercises follow in vivo scenarios while VR exercises originate from VR scenarios. Psychotherapists can create and manage exercises as they see fit.

Specifically for VR exercises, each parameter of the VR scenario will need to be set to a specific value. The psychotherapist can do this manually for each parameter of each exercise. They can also copy the configuration of a previous exercise and change only a few parameters if needed. Furthermore, the proposed system is able to support the psychotherapist during the configuration of new VR exercises. The system will analyse previous exercises of a patient together with available prior information of the

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[1] https://www.qualtrics.com, accessed on 16/03/2022

patient. Based on this, four suggestions are generated from which the psychotherapists can choose the most appropriate one. The psychotherapist can further modify a generated configuration if they wish.

4.5.1.3 Manage Sessions

A session is a period of time during which a patient performs a number of exposure exercises. The psychotherapist should start and stop a session manually when a patient is with them. First, sessions needs to be created and managed. It is usually created beforehand such that the psychotherapist can do some administrative tasks, e.g. linking it to the patients account, providing notes and descriptions. The psychotherapist can create one or more exercises beforehand and add them to the session. Exercises can also be created during the session. Information of the exercises during a session are linked to this session. A psychotherapists can consult a session afterwards and get an overview of all the information of that session.

4.5.1.4 Conducting Sessions at the Therapy Office

A psychotherapist should be able to given the actual therapy. Therefore, they begin by select a session that has created before, and start it. Next, a baseline measurement of the patient's physiological parameters is taken with a wearable device. The device needs to be worn by the patient and data should be gathered over a period of time while the patient is not engaged in any particular therapy. The baseline measures are used by the fear registration algorithm to predict the perceived level of fear by the patient.

During this time, the psychotherapist can create an exercise or select one that has already been made beforehand. At the start of each exercise, a pre-exposure log is filled in by the patient. This form contains a few questions that gauge the expectations of the patient. The answers to these questions can be filled in through the dashboard application.

Once this information is provided to the system, the exercise can be started. For VR exercises, the patient would put on the HMD at this point. During an exercise there is a lot of information that a psychotherapist might want to write down to review later. This can all be done through the dashboard. The most prominent and important metric used during an exposure exercise is the Subjective Units of Distress Scale (SUDS) score which registers the perceived level of fear in the patient [20]. At regular intervals the psychotherapist will ask the patient to state their current SUDS score and input it into the system. A psychotherapist might also recognise specific behaviours that need to be recorded. The system provides a predefined list of common behaviours from which the psychotherapist can easily pick one and tag it with a timestamp. These are mostly avoidance behaviour. Of course, the psychotherapist can at all times make free text notes in the dashboard as well.

In case the current exercise is a VR exercise, the system will provide some additional features. While a VR exercise is completely configured beforehand, certain parameters can still be tweaked during the exercise. This ensures that the psychotherapist is in full control of the therapy. Should the patient respond too violently or too mildly to the environment, the parameters can be changed appropriately. Of course, the psychotherapist can also follow along with what the patient is seeing in the VR environment.

When the exercise is finished, the psychotherapist indicates so in the dashboard and a post-exposure log is presented. Similar to the pre-exposure log, the post-exposure log gauge about the perceived experience of the patient during the exercise. This information will be used by the adaptation algorithm to generate possible configuration for future exercises.

A session can contain any number of exercises. After the last exercise, the psychotherapist should indicate the session has ended.

4.5.1.5 Fear Algorithm

To help the psychotherapist, and avoid disturbing the patient by probing them for a SUDS score, and experimental algorithm will show the estimated current fear level of the patient based on the current psychological data collected through the wearable device in realtime. This estimation is presented as a label with three possible values: low, medium and high level of fear.

The system should support two wearable device. The first is the Chillband+ developed by imec[2], a member of the project consortium. The second is the Empatica E4 wristband[3], a commercially available wearable device that allows real time streaming of raw data at acceptable sample rates.

4.5.1.6 Adaptation Algorithm

Psychotherapists need to receive suggestions for VR exercise configurations based on what happened in past sessions. An intelligent adaptation algorithm will need knowledge of the patient and its therapy history. Based on this information it can suggest four configurations for a new VR exercise. The psychotherapist can select one or modify it if needed. The psychotherapist always makes the final decision of what is presented to the patient. The algorithm will never steer the therapy directly and unsupervised.

4.5.1.7 Mobile Coaching App

The patient can install an app on their smartphone as a support tool for their therapy. The app has three functions, (1) providing homework exercises, (2) acting as a journal

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[2] https://www.imec-int.com/en/chill, accessed on 16/03/2022

[3] https://www.empatica.com/en-gb/research/e4, accessed on 16/03/2022

in which daily life events can be logged, (3) allowing data collection from the wearable device.

A homework exercise is like a therapy session but that can be performed by the patient on its own. The exercises can be in vivo or in VR. The exercises are created beforehand by the psychotherapist and cannot be changed by the patient themselves.

The journal functionality of the app is aimed at collecting information of the patient during daily life activities. This information can help the psychotherapist to better understand the disorder and allows them to tailor the therapy better to the needs of the patient. Patients can log situations of panic throughout the day. A log record contains a SUDS score, a description and a timestamp. Also avoidance behaviour can be logged by the patient in a similar way. Lastly, physical complaints can be logged, e.g. heart palpitations or difficulty breathing. The patients selects a symptom and assigns a score to it between 0 and 100.

During exposure exercises with the psychotherapist, the patient can wear a wearable device which collects physiological data. Based on this data, an algorithms will predict the level of fear in the patient and present it to the psychotherapist. The data for this algorithm is streamed from the wearable device, to the coaching app on the smartphone which relays it to the backend system where the algorithm can process it.

4.5.2 Non-Functional Requirements

The proposed PATRONUS system not only sets goals for the functionality it provides but it also makes assumptions on the operation of the system. These assumptions need to be met by the design of the system to ensure effective adoption of the system in extensive testing settings with actual clinical end users. The assumptions translate in non-functional requirements and are presented in this section.

4.5.2.1 Usability

As a patient-centred rehabilitation system that supports the psychotherapists in performing therapy, the usability of the system is paramount. For the patients and the psychotherapists, the system has to be easy to use and intuitive. Psychotherapists need to be able to operate the system with minimal technical knowledge or training.

4.5.2.2 Security and Privacy

Due to the delicate nature of the proposed system, strict security requirements are imposed with a specific focus on privacy of user data. The guidelines set by the General Data Protection Regulation (GDPR) need to be followed as well.

4.5.2.3 Modifiability

Certain subsystems of the VRET system need to be interchangeable for different implementation if the need arises. Especially since the system is primarily designed as a proof of concept and the subject of a research project, multiple implementation of various subsystems will need to be tested. Other subsystems can also require multiple iterations in which they are adapted and updated based on user feedback. Examples are the potential use and support of different wearable devices and iterations of the adaptation algorithm.

4.5.3 Constraints and Limitations

Some requirements of the system are the result of constraints or limitation imposed by the environment in which it will be deployed. Specifically, the design phase needs to take into account the existing situation and ensure it can operate in that environment. Firstly, the psychotherapists requested that the system could be used on a single monitor. This was to avoid requiring additional investments for secondary monitors in each psychotherapist's office. Secondly, after a technical analysis it was revealed that the supported wearable devices are most reliable when streaming to an Android smartphone. Therefore, the constraints was set that the streaming of the wearable data to the backend system should happen through the mobile coaching app running on the Android smartphone. Lastly, as certain parts of the system rely on continuous data streams, it is expected that the Android application and Dashboard application have a stable and permanent internet connectivity available.

4.6 The PATRONUS Software Design

In this section, the design of the PATRONUS system that fulfils the requirements is described in detail. The system has been decomposed into several components based on their functionality and software patterns that are used in the design. Figure 4.2 shows an overview of the architecture of the system. The first things to notice are that the system offers two points of entry for user interaction with the system, the system contains two algorithms that rely on realtime data streams and security is baked into the architecture. Each component, its responsibilities, and the interfaces between the components are discussed in the remainder of this section.

The PATRONUS system contains a *web app* (Figure 4.3) which hosts the dashboard for the psychotherapist and a *mobile app* (Figure 4.4) which provides access to homework exercises and the journal log for patients but also enables real time streaming of data from the wearable device. The patients experience the VE through an *HMD* connected to the *VR system*. This system will communicate with the *web app* directly to allow control and configuration of the VR environments. Events from the *VR system* are also relayed thought the *web app* to the rest of the system. The *API app*

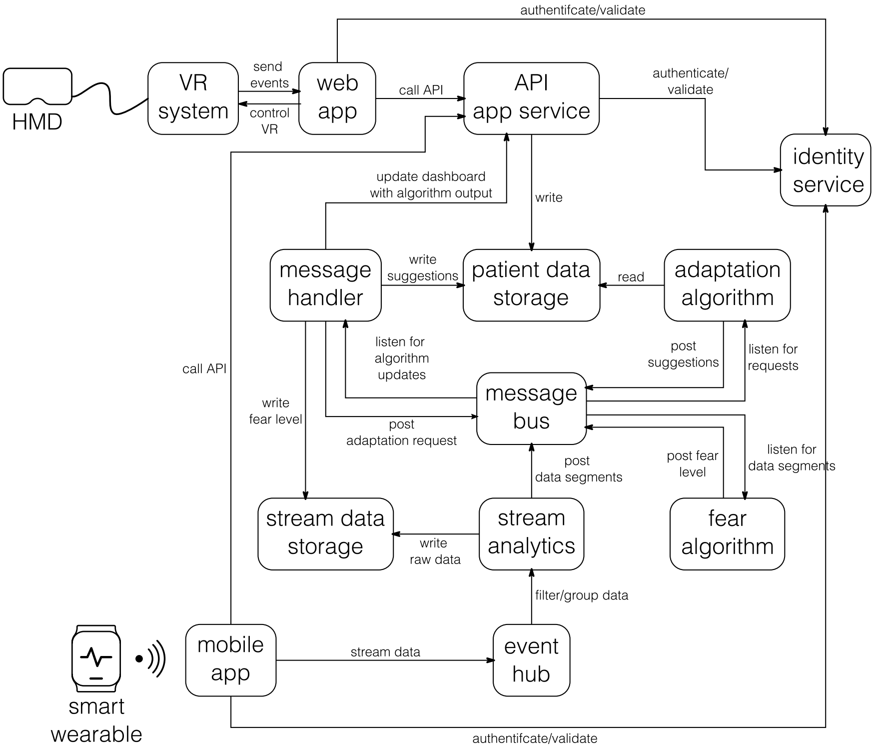
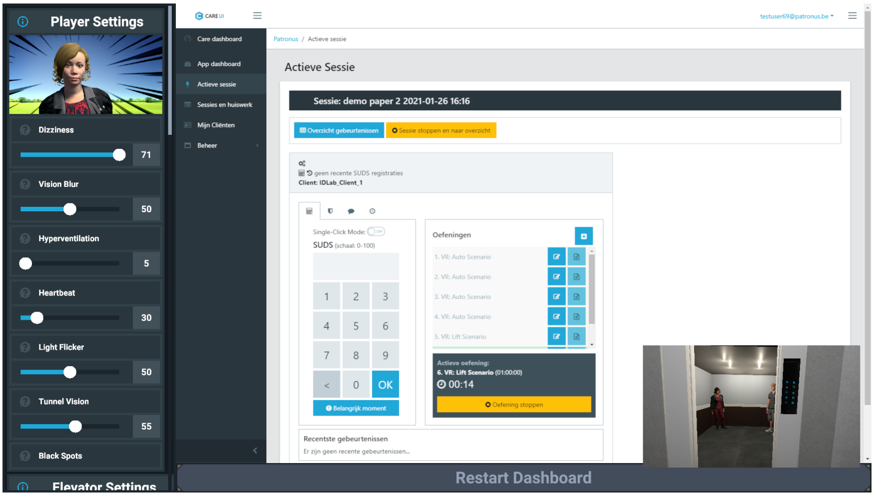


Figure 4.2: Overview of the software architecture of the PATRONUS system



Dizziness 71

Vision Blur 50

Hyperventilation 5

Heartbeat 30

Light Flicker 50

Tunnel Vision 55

Sessie: demo paper 2 2021-01-26 16:16

geen recente SUDS registraties

Client: IDLab_Client_1

Single-Click Mode: OFF

SUDS (schaal: 0-100)

1. VR: Auto Scenario

2. VR: Auto Scenario

3. VR: Auto Scenario

4. VR: Auto Scenario

5. VR: Lift Scenario

Actieve oefening:
6. VR: Lift Scenario (01:00:00)
00:14

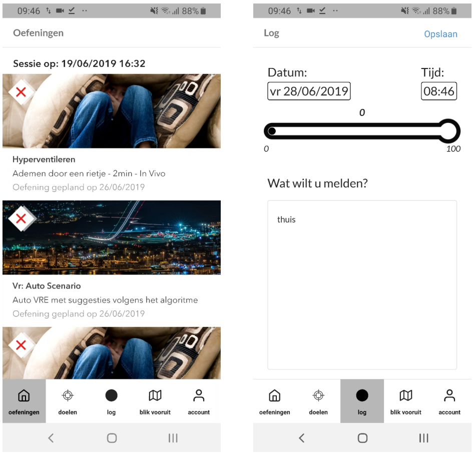
Er zijn geen recente gebeurtenissen...

Figure 4.3: The web application is a dashboard through which the psychotherapists can control the therapy.

service is the request handler of the system. It deploys an API to which frontend applications can send request for user, scenario, exercise and session management and control of the adaptation algorithm. The *API app service* itself is responsible for the management task by reading and writing the data to the appropriate data store in the *patient data storage*. The *web app*, *mobile app*, and the *API app service* require the *identity service* for authentication and authorisation of their request. Only psychotherapists are able to perform management tasks and patients are limited to reading their own data. The *API app service* is the only component through which data can leave the the backend system, this single point of entry creates an additional security barrier. The decoupling of the frontend application allows for cheap adaptations to the UI elements of the dashboard and the mobile app. This enables experimentation with different UI configurations which is fitting for this research project.

The algorithms rely on a lot of data, sometimes coming from different sources, and they are controlled from the web application. Therefore, a *message bus* is used as part of the publish subscribe pattern. Messages indicating data changes and messages relaying requests from the frontend are pushed on this bus. The relevant algorithms subscribe to the data and control messages they rely on.

The *message handler* of the *API service* injects messages on the *message bus* whenever a request for an algorithm is sent from a frontend application. These messages are picked up by either the *adaptation algorithm* or the *fear algorithm*. The *adaptation algorithm* will listen for messages that request new configuration suggestions. This message will contain some information regarding the location of the patient, session and exercise data for which suggestions need to be generated. The algorithm will produce suggestions in response to this message by collected the data from the specified location in



Sessie op: 19/06/2019 16:32

Hyperventileren
Ademen door een rietje - 2min - In Vivo
Oefening gepland op 26/06/2019

Vr: Auto Scenario
Auto VRE met suggesties volgens het algoritme
Oefening gepland op 26/06/2019

Datum: vr 28/06/2019
Tijd: 08:46

Wat wilt u melden?
thuis

(a) (b)

Figure 4.4: The app is used by the patient, (a) to perform their exposure exercises at home, and (b) to record self-reports of their mental state.

the *patient data storage*. Next the algorithm will publish a new message on the *message bus* containing the suggestions which are picked up by the *message handler* and forwarded to the dashboard application. The *message handler* will also make sure the suggestions are permanently stored in the *patient data storage*. This process is illustrated by means of a sequence diagram in Figure 4.5. When the *fear algorithm* receives a message to start predicting the fear levels, it acts in a similar way. The main difference is that this algorithm relies on a semi-real-time stream of datapoints of physiology data. This data originates from a *wearable device* which is connected to the *mobile app*. This application is able to stream data to an *event hub* in the backend. Next, this data is passed to a *stream analytics* component. This component does two things, it stores the streamed data in a *stream data storage*, and it prepares the data for the fear algorithm. This data preparation consists of filtering, grouping and buffering the data stream and sending it in 5 s segments to the *message bus*. The *fear algorithm* can then fetch the data messages from the bus and use them in its prediction algorithm. Each time the algorithm produces a new fear level, this is published on the *message bus*. The *message handler* picks this up, and forward these values to the dashboard application. It will also store the predicted value in the *stream data storage*. Figure 4.6 further details this process with a sequence diagram.

This loose coupling of the algorithms with the rest of the system enables easy modifiability of the algorithms, easy deployment and scalability, as multiple copies of the same algorithms or different variations of the algorithms can simultaneously be deployed. Furthermore, by eliminating write operations by the algorithms to a complex and delicate database, the implementation of these algorithms requires very little

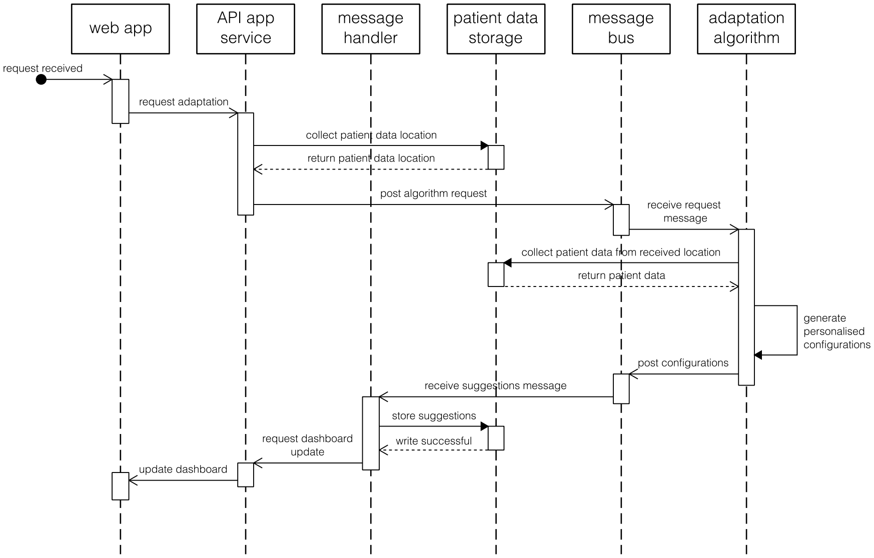


Figure 4.5: The process to generate new suggestions with the adaptation algorithm involves the transmission of messages on a bus communication system.

knowledge of the rest of the system. They simply need to listen to certain topics on the *message bus*. This was a requirement to enable rapid prototyping of the algorithms.

As can be seen in this design, it heavily relies on internet communication between the frontend and backend systems for reliable operation. There are no mechanisms installed to cope with loss of connection, e.g. buffering of the data stream in the mobile app. This design decision is acceptable as this was included in the business constraints of the requirements.

4.7 Implementation Details

The platform presented in the previous sections is further discussed in this section. The focus is on the most prominent technologies that were use to implement the system. Additionally, details about the VE and intelligent algorithms are discussed. Finally, the approach for the deployment of the system is described.

4.7.1 Azure

The backend system is developed and deployed on the Microsoft Azure Cloud Platform[4]. This platform was chosen for its inherent flexibility, scalability and security. Microsoft Azure provides confidentiality, integrity, and availability of customer data,

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[4] https://azure.microsoft.com, accessed on 16/03/2022

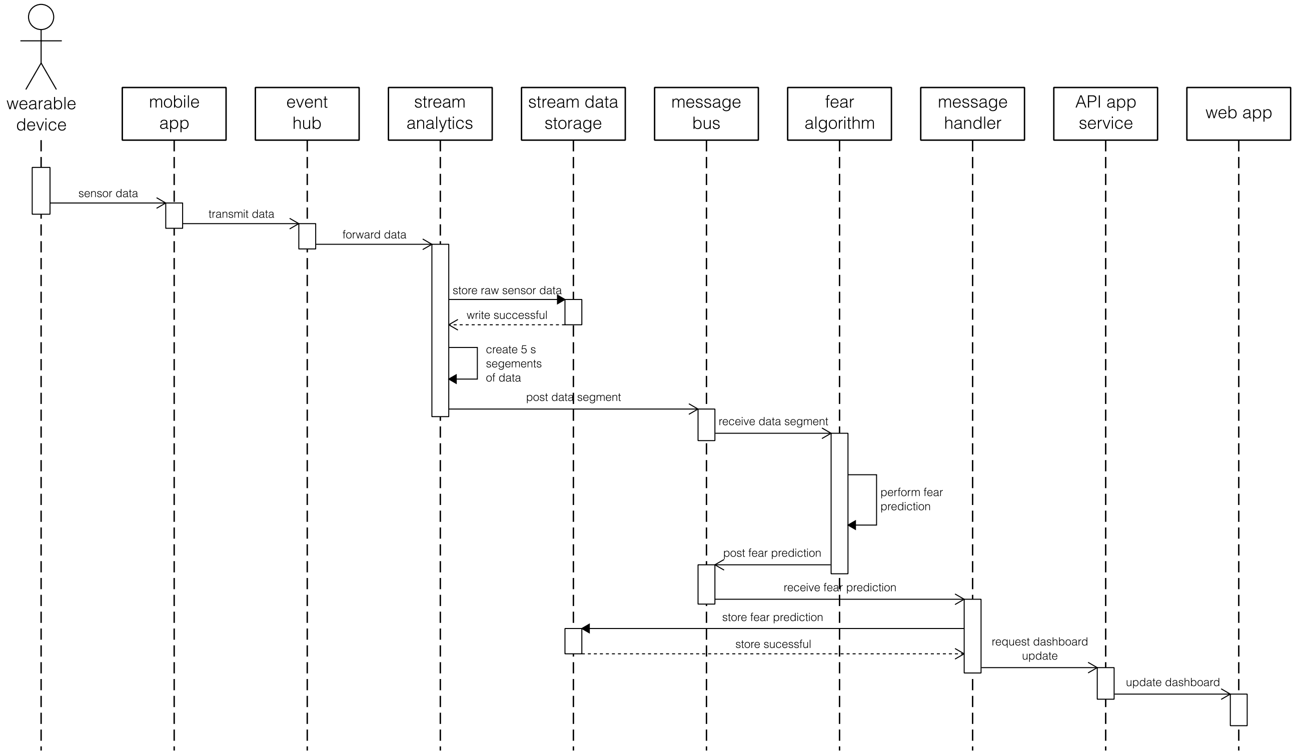

Figure 4.6: The fear algorithm makes prediction of fear level on a data stream of physiological data that is partitioned and send on the message bus.

while also enabling transparent accountability. It offers a lot of tools and features to manage resources and enforce certain policies to access resources. Through the Azure portal it was made sure that only a select number of people have access to the necessary resources. Certain resources are not available from the outside or are limited to be accessed via certain IP ranges for any outside access. The resources inside the portal itself can have access to each other without having to be exposed to outside parties. Connection strings and service URL's are stored in Azure in environment variables and are injected during the continuous integration and continuous delivery pipelines, such that these are not accessible by unauthorised resources and this sensitive data is not available in source control for non-development environments. Source control access is also limited to only those who need access for development.

One of the useful features offered by Azure is the ability to easily scale to the demands of the application usage. Both scaling out and scaling up is relatively simple. Scaling out means adding extra instances of a specific service to offload parts of the traffic to the other instance. Scaling up means adding extra hardware resources to a service, e.g. more CPU power or additional RAM. One of the main benefits over traditional hosting is that in most cases the system does not need to go offline.

4.7.2 Docker

The algorithms in the presented system have specific software, operating system and dependency requirements, furthermore, these are developed by the researchers contributing to the project which belong to a separate team developing the rest of the backend. Containerisation through Docker enables to easily deploy the custom environments needed for the algorithms without introducing much dependencies. The Azure platform contains docker registries with images that can be instantiated as containers in the Azure container instance service. These containers can be run when needed and scaled both horizontally and vertically without the need to change the container image itself.

4.7.3 Identity Server 4

For authentication, Identity Server 4 is used as the Azure Active Directory was not entirely mature at the start of the project. Implementations of identity provider are easily switchable, and the setup of the project allows for interchanging identity providers with a relatively small effort.

Identity Server 4 is an OpenID Connect and OAuth 2.0 framework for ASP.NET Core. For PATRONUS it enables authentication as a service with a centralised authentication workflow for both the therapy dashboard and the mobile coaching application.

4.7.4 Virtual Environments for Exposure Exercises

The VE are developed using the Unity 3D[5] game engine. It provides an easy to use workflow to create VR applications and deploy them on various platforms. This was a requirement for this project as the VE need to run on a high-end computer system for use in the psychotherapist's office, and on mobile devices for homework exercises.

It was decided to implement two distinct VR scenarios for ET. Each had a specific focus but both could be used for generalised anxiety disorders such as a panic disorder. One VR scenario presents an elevator environment. In this VE the patient can freely walk around in a lobby area by physically walking around. The lobby gives access to an elevator, the patient needs to physically enter the elevator in order to use it. Inside the elevator are buttons to choose the floor to go to. Just like in a real elevator the patient selects a floor by pressing the buttons. Visual effects give the sensation that the elevator is moving. Elements such as the size and look of the elevator can be configured by the psychotherapist. Other events like flickering elevator lights, the elevator getting stuck and noises can also be controlled. This environment can be used for specific phobias including fear of elevators and claustrophobia.

The other VR scenario is a car driving on a straight road. The patient has no control over the movement of the car but the psychotherapist can control many elements of the car and its surrounding, including traffic. The patient is seated in one of the positions of a car, e.g. behind the wheel or in the back, and can look around. The speed of the patient's car and of the other cars on the road can be changed in realtime, this allows for creating queues of traffic as well. Additionally, sound can be generated, e.g. the radio in the car, sirens, or engine sounds. This environment is designed for fear of driving and claustrophobia.

Both VR scenarios allow the introduction of environment independent stimuli. These are simulations of interoceptive sensations. For example, common triggers for panic attacks are hearing ones own heartbeat. This sound can be simulated with the PATRONUS platform. Also tunnel vision, blurred vision, and light flickers are some of the other interoceptive stimuli.

One last VR environment has been implemented with the purpose of being a neutral environment in which no stimuli are present that could trigger the patient's anxiety. The lounge environment is the first environment patient enter when putting on the HMD. In between exercises, it is also the environment they return to.

More details of these environments and the controllable parameters can be found in [21].

4.7.5 Intelligent Algorithms

The intelligent algorithms are the personalised adaptation algorithm for VEs and the fear algorithm which provides an objective measure of anxiety.

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[5] https://www.unity.com, accessed on 16/03/2022

The purpose of the adaptation algorithm is to support the psychotherapist in configuring new exercises because it is a tedious and sometimes complex process. Therefore, the algorithm suggests four configurations based on the information is has on the patient and previous exercises performed by the patient. Because this algorithm needs to process the available information in a similar way as a psychotherapist would, it requires quite some knowledge. This knowledge, collected during the domain knowledge workshops, is captured in a semantic ontology. It allows the algorithm to understand which information new data hold. The implementation of the algorithm utilises the Rescorla-Wanger model [22] to predict which stimuli the patient requires. The model, presented by Rescorla and Wagner, provides a mathematical foundation that describes learning for ET. The objective of the adaptation algorithm then becomes to maximise the learning of the patient by selecting the appropriate stimuli. The algorithm is described in much more detail in [21].

For the development of the fear algorithm, it quickly became clear that SUDS scores are not the most appropriate metric to evaluate objective levels of anxiety. Therefore, they could not be used as target value to train an artificial intelligence system. Further experimentation made clear that deriving anxiety level from physiological data is extremely complex and very much depends on personal and contextual characteristics, e.g. caffeine intake, amount of sleep or resting heart rate. Eventually, the chosen approach is to use a Gaussian mixture model [23] to predict the likelihood that the physiological data of a patient is indicating a low, medium or high level of anxiety. This approach allowed to take the personal and contextual characteristics into account by comparing the data during the exposure exercises against a baseline measurement of the same patient.

4.7.6 Deployment

Several environments were set up to either be able to separate concerns and have the ability to offer certain environments to certain stakeholders without having to worry about downtime or impacting stakeholders when changes needed to be deployed. For example, while end users had to do effectivity tests with real clients, they might also have to test new features for an upcoming release, while third party integrators needed to test certain integrations, while a local development team had to be able to develop and test daily work. To make sure these processes could happen smoothly the following environments were setup:

- DEV (development environment): used for daily development, this environment can contain bugs and unfinished work and has no availability guarantee. This is to be used only by the parties developing the PATRONUS software.
- TEST (test environment): used to test features in development teams without having to affect development environments. This environment serves no availability guarantees.

- ACC (acceptance environment): used to test features by stakeholders, this environment is used to deploy finished work, and have it tested by the actual users of the product. Before anything ships to production, stakeholders must give their approval by validating the requested functionality on the ACC environment. This environment will be available according to agreements. In practice this environment will always be available except for times when a new deployment is done, these always happen during a short time-window.
- PROD (production environment): used in production, this environment is the actual environment that serves the finished and approved product and can be used by the stakeholder for the effectivity study. Real patients data should only use this environment. Deployments are schedules according to agreement with minimal downtime.

4.8 User study

Though there is strong evidence for the effectiveness of VRET, the focus lies on specific phobias (i;e., fear of small animals, flying, etc.). Studies on the effectiveness of more general phobias are scarce and mainly focus on social phobia and Post Traumatic Stress Disorder (PTSD). Moreover, most studies are focused on VR therapy at the psychotherapist's office, while previous research has shown that exercises at home are an important aspect of the treatment. Therefore, a user study was set up that aims to investigate the effectiveness of VRET for claustrophobia and panic disorder with the PATRONUS blended care platform that also includes a coaching app with homework exercises.

Randomised controlled trials ask for a significant amount of participants and administering a therapy to a large amount of people is not possible to integrate in the daily operations of a psychotherapist organisation. Moreover, administration of a therapy to a large amount of people that has not yet been proven to be effective, might be unethical. Single case intervention research is becoming increasingly prominent across multiple fields in the behavioural sciences and is considered a valuable research method for evidence based practices in clinical psychology [24]. In single case intervention research, the focus lies on repeated measurements before and after the introduction of one or several manipulations. To provide more research support for potential findings, a multiple baseline single case study was applied. In multiple baseline design, several patients that have started treatment at a different time are investigated.

In close collaboration with the psychotherapists, six people with different types of anxiety issues were selected, of which three were given VRET and three followed the regular in-vivo ET. The anxiety disorders in the selected participants ranged from claustrophobia and panic disorder to driving anxiety. The study was divided in to three phases, a baseline phase in which not treatment was given, a psycho-education phase consisting of one therapy session, and the ET phase in which between three to five ET sessions with the psychotherapist and homework exercises were given. Of the six participants, three received blended care using the PATRONUS platform, while three received regular treatment involving in vivo exposure therapy. Data was collected through questionnaires in a pre test, a post test and daily measurements. Standardised and validated questionnaires were used such as the Panic Opinion List (POL) [25], the Overall Anxiety Severity and Impairment Scale (OASIS) [26] and the Insomnia Severity Index (ISI) [27].

Based on the collected data during the user test, a reliable conclusion on the effectiveness of PATRONUS blended care cannot be made. A clearly distinguishable, uniformly decreasing trend in the daily anxiety measurements could not be observed for participants receiving the PATRONUS VRET. However, such a trend was also not observed for participants receiving the traditional in vivo treatment. It is clear that three exposure sessions are not sufficient to reliably detect a decrease in anxiety levels. Nevertheless, some important insights were found with this user study:

- The initial reported anxiety was much lower than expected. It is likely that a more significant decrease in anxiety would be observed with people with more severe anxiety issues, this is referred to as the floor effect. This might indicate that the PATRONUS blended care solution should be further optimised in order to also be effective in helping people with mild anxiety disorders.

- An interesting trend was observed in the daily measurements regarding the homework exercises for both in vivo and VR. More specifically, initial homework exercises elicit a peak in self-reported anxiety scores, followed by a decrease. It is thus important to take this homework assignment aspect of ET into account in design and research of VRET. This merits further investigation.

- Depending on the nature of the anxiety disorder, e.g. general panic vs. specific fear of driving a car, the variability of the reported daily anxiety measurements could vary significantly. Therefore, with this limited number of patients, it is hard to detect meaningful patterns in the data.

- The therapist's dashboard has proven to be a reliable research tool to get a deep understanding of what occurred during sessions both at the psychotherapist and at home.

- The psychotherapists had the feeling that the best flow of therapy was obtained with a combination of in vivo and VRET. This is reflected in the homework exercises that combined the two. Unfortunately, VR in combination with in vivo was not a formal condition in this user study, therefore and a systematic comparison between VR, in vivo or a combination of both was not possible. Further research should focus on this combined approach.

4.9 Conclusion

Anxiety disorders are extremely common but the can be treated with ET. In recent years, the interest to move ET to VR has increased significantly. However, most research focuses on specific case studies with VRET without considering the integration of VRET in a blended care treatment procedure. Furthermore, the advantages of VR for ET are barely exploited, e.g. semi-automated personalisation of ET environments. In this paper, an architecture for the PATRONUS platform is presented, an effort to create a platform for patient-centred blended care for VRET with the incorporation of advanced support systems. The methodology used in this work focusses on the inclusion of patients and psychotherapists during the design process. Their needs and knowledge is the driver for the decision made in the development of the PATRONUS platform. This led the design of two configurable exposure environments, an elevator and a car scenario. The configuration of these environments is supported by an intelligent algorithm which makes suggestions for new configurations based on prior knowledge about the patient. Furthermore, based on physiological data collected through a wearable device, an objective measure of anxiety is shown to the psychotherapist. To support the patients at home, a mobile applications provides them the opportunity to also experience the VR exposure exercises in their own home. Additionally, a journal in the mobile app allows them to register noteworthy events in their daily live which become available to their psychotherapist. Finally, the effectiveness of the PATRONUS blended care solution was tested during a pilot effectiveness study. The results show that homework exercises appear to have a positive effect. However, the limited data made clear that additional tests over longer periods of time with a larger population are needed to form clear conclusions on the effectiveness of the system. Therefore, future studies will further investigate the effectiveness and usability of PATRONUS.

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References

[1] WHO. *Depression and Other Common Mental Disorders: Global Health Estimates.* Technical report, World Health Organization, 2017. Available from: https://apps.who.int/iris/bitstream/handle/10665/254610/WHO-MSD-MER-2017.2-eng.pdf.

[2] D. H. Barlow, S. D. Raffa, and E. M. Cohen. *Psychosocial treatments for panic disorders, phobias, and generalized anxiety disorder.* In A guide to treatments that work, 2nd ed., pages 301–335. Oxford University Press, New York, NY, US, 2002.

[3] G. M. Reger, K. M. Holloway, C. Candy, B. O. Rothbaum, J. Difede, A. A. Rizzo, and G. A. Gahm. *Effectiveness of virtual reality exposure therapy for active duty soldiers in a military mental health clinic: Effectiveness of Exposure for Active Duty Soldiers.* Journal of Traumatic Stress, 24(1):93–96, February 2011. Available from: https://onlinelibrary.wiley.com/doi/10.1002/jts.20574, doi:10.1002/jts.20574.

[4] L. R. Valmaggia, L. Latif, M. J. Kempton, and M. Rus-Calafell. *Virtual reality in the psychological treatment for mental health problems: An systematic review of recent evidence.* Psychiatry Research, 236:189–195, February 2016. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0165178116300257, doi:10.1016/j.psychres.2016.01.015.

[5] J. L. Maples-Keller, B. E. Bunnell, S.-J. Kim, and B. O. Rothbaum. *The Use of Virtual Reality Technology in the Treatment of Anxiety and Other Psychiatric Disorders.* Harvard Review of Psychiatry, 25(3):103–113, May 2017. Available from: https://journals.lww.com/00023727-201705000-00003, doi:10.1097/HRP.0000000000000138.

[6] D. Richards and T. Richardson. *Computer-based psychological treatments for depression: A systematic review and meta-analysis.* Clinical Psychology Review, 32(4):329–342, June 2012. Available from: https://linkinghub.elsevier.com/retrieve/pii/S027273581200027X, doi:10.1016/j.cpr.2012.02.004.

[7] M. Steen, M. Manschot, and N. De Koning. *Benefits of co-design in service design projects.* International Journal of Design, 5(2), 2011.

[8] J. Langley, D. Wolstenholme, and J. Cooke. *'Collective making' as knowledge mobilisation: the contribution of participatory design in the co-creation of knowledge in healthcare.* BMC Health Services Research, 18(1):585, December 2018. Available from: https://bmchealthservres.biomedcentral.com/articles/10.1186/s12913-018-3397-y, doi:10.1186/s12913-018-3397-y.

[9] E. B.-N. Sanders and P. J. Stappers. *Co-creation and the new landscapes of design.* CoDesign, 4(1):5–18, March 2008. Available from:

http://www.tandfonline.com/doi/abs/10.1080/15710880701875068, doi:10.1080/15710880701875068.

[10] E. Hodson, N. Dadashi, R. Delgado, C. Chisholm, R. Sgrignoli, and R. Swaine. *Co-design in mental health; Mellow: a self-help holistic crisis planning mobile application by youth, for youth.* The Design Journal, 22(sup1):1529–1542, April 2019. Available from: https://www.tandfonline.com/doi/full/10.1080/14606925.2019.1594975, doi:10.1080/14606925.2019.1594975.

[11] G. I. Christie, M. Shepherd, S. N. Merry, S. Hopkins, S. Knightly, and K. Stasiak. *Gamifying CBT to deliver emotional health treatment to young people on smartphones.* Internet Interventions, 18:100286, December 2019. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2214782919300302, doi:10.1016/j.invent.2019.100286.

[12] A. Radovic, A. L. DeMand, T. Gmelin, B. D. Stein, and E. Miller. *SOVA: Design of a Stakeholder Informed Social Media Website for Depressed Adolescents and Their Parents.* Journal of Technology in Human Services, 35(3):169–182, July 2017. Available from: https://www.tandfonline.com/doi/full/10.1080/15228835.2017.1347552, doi:10.1080/15228835.2017.1347552.

[13] S. Rice, J. Gleeson, C. Davey, S. Hetrick, A. Parker, R. Lederman, G. Wadley, G. Murray, H. Herrman, R. Chambers, P. Russon, C. Miles, S. D'Alfonso, M. Thurley, G. Chinnery, T. Gilbertson, D. Eleftheriadis, E. Barlow, D. Cagliarini, J.-W. Toh, S. McAlpine, P. Koval, S. Bendall, J. E. Jansen, M. Hamilton, P. McGorry, and M. Alvarez-Jimenez. *Moderated online social therapy for depression relapse prevention in young people: pilot study of a 'next generation' online intervention: Online depression relapse prevention.* Early Intervention in Psychiatry, 12(4):613–625, August 2018. Available from: https://onlinelibrary.wiley.com/doi/10.1111/eip.12354, doi:10.1111/eip.12354.

[14] R. Bevan Jones, P. Stallard, S. S. Agha, S. Rice, A. Werner□Seidler, K. Stasiak, J. Kahn, S. A. Simpson, M. Alvarez□Jimenez, F. Rice, R. Evans, and S. Merry. *Practitioner review: Co□design of digital mental health technologies with children and young people.* Journal of Child Psychology and Psychiatry, 61(8):928–940, August 2020. Available from: https://onlinelibrary.wiley.com/doi/10.1111/jcpp.13258, doi:10.1111/jcpp.13258.

[15] D. Wiljer, A. Johnson, E. McDiarmid, A. Abi-Jaoude, G. Ferguson, E. Hollenberg, N. van Heerwaarden, T. Tripp, and M. Law. *Thought Spot: Co-Creating Mental Health Solutions with Post-Secondary Students.* Studies in Health Technology and Informatics, 234:370–375, 2017.

[16] H. Thabrew, T. Fleming, S. Hetrick, and S. Merry. *Co-design of eHealth Interventions With Children and Young People.* Frontiers in Psychiatry, 9:481, October

2018. Available from: https://www.frontiersin.org/article/10.3389/fpsyt.2018.00481/full, doi:10.3389/fpsyt.2018.00481.

[17] S. E. Hetrick, J. Robinson, E. Burge, R. Blandon, B. Mobilio, S. M. Rice, M. B. Simmons, M. Alvarez-Jimenez, S. Goodrich, and C. G. Davey. *Youth Codesign of a Mobile Phone App to Facilitate Self-Monitoring and Management of Mood Symptoms in Young People With Major Depression, Suicidal Ideation, and Self-Harm.* JMIR Mental Health, 5(1):e9, January 2018. Available from: http://mental.jmir.org/2018/1/e9/, doi:10.2196/mental.9041.

[18] F. Ongenae, P. Duysburgh, N. Sulmon, M. Verstraete, L. Bleumers, S. De Zutter, S. Verstichel, A. Ackaert, A. Jacobs, and F. De Turck. *An ontology co-design method for the co-creation of a continuous care ontology.* Applied Ontology, 9(1):27–64, 2014.

[19] M. van Limburg, J. Wentzel, R. Sanderman, and L. van Gemert-Pijnen. *Business Modeling to Implement an eHealth Portal for Infection Control: A Reflection on Co-Creation With Stakeholders.* JMIR Research Protocols, 4(3):e104, August 2015. Available from: http://www.researchprotocols.org/2015/3/e104/, doi:10.2196/resprot.4519.

[20] R. E. McCabe. *Subjective Units of Distress Scale.* In Phobias: The Psychology of Irrational Fear, pages 361–362. ABC-CLIO, LLC, Santa Barbara, California, 2015.

[21] J. Heyse, F. Ongenae, B. Depreeuw, T. Van Daele, T. Daeseleire, F. De Backere, and F. De Turck. *An Adaptation Algorithm for Personalised Virtual Reality Exposure Therapy.* Computer Methods and Programs in Biomedicine, 2021 (Manuscript submitted for publication).

[22] R. Rescorla and A. R. Wagner. *A Theory of Pavlovian Conditioning : Variations in the Effectiveness of Reinforcement and Nonreinforcement.* Classical conditioning: current research and theory, 1972.

[23] D. A. Reynolds. *Gaussian mixture models.* Encyclopedia of biometrics, 741(659-663), 2009. Publisher: Berlin, Springer.

[24] American Psychological Association. *Evidence-based practice in psychology.* American Psychologist, 61(4):271–285, 2006. Available from: http://doi.apa.org/getdoi.cfm?doi=10.1037/0003-066X.61.4.271, doi:10.1037/0003-066X.61.4.271.

[25] M. J. Telch, M. Brouillard, C. F. Telch, W. Agras, and C. Taylor. *Role of cognitive appraisal in panic-related avoidance.* Behaviour Research and Therapy, 27(4):373–383, 1989. Available from: https://linkinghub.elsevier.com/retrieve/pii/0005796789900077, doi:10.1016/0005-7967(89)90007-7.

[26] S. B. Norman, S. Hami Cissell, A. J. Means-Christensen, and M. B. Stein. *Development and validation of an Overall Anxiety Severity And Impairment Scale (OASIS).* Depression and Anxiety, 23(4):245–249, 2006. Available from: https://onlinelibrary.wiley.com/doi/10.1002/da.20182, doi:10.1002/da.20182.

[27] C. Bastien. *Validation of the Insomnia Severity Index as an outcome measure for insomnia research.* Sleep Medicine, 2(4):297–307, July 2001. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1389945700000654, doi:10.1016/S1389-9457(00)00065-4.

5

An Adaptation Algorithm for Personalised Virtual Reality Exposure Therapy

The PATRONUS platform presented in Chapter 4 relies on personalised suggestions for new virtual reality exposure therapy exercises. These suggestions are generated by an intelligent algorithm that uses profile and history data of a patient to find possible configurations for new exposure exercises. This chapter will discuss the design, implementation and evaluation of this algorithm in detail. It is an interesting case study for the use of personalisation in extremely complex systems. This work is a further exploration of personalisation techniques as set out by challenge 3 in Section 1.5. Additionally, the system is designed in close collaboration with psychotherapists, leveraging their domain expertise on this subject and thereby contributing to challenge 4 and 5.

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Abstract

Background: Anxiety disorders are highly prevalent in mental health problems. The lives of people suffering from an anxiety disorder can be severely impaired. Virtual Reality Exposure Therapy (VRET) is an effective treatment, which immerses patients in a controlled Virtual Environment (VE). This creates the opportunity to confront feared stimuli and learn how to deal with them, which may result in the reduction of anxiety. The configuration of these VEs requires extensive effort to maximise the potential of Virtual Reality (VR) and the effectiveness of the therapy. Manual configuration becomes infeasible when the number of possible virtual stimuli combinations is infinite. Due to the growing complexity, acquiring the skills to truly master a VR system is difficult and it increases the threshold for psychotherapists to use such useful systems. We therefore developed a prototype of a supportive algorithm to facilitate the use of VRET in a clinical setting. This automatised system assists psychotherapists to use the wide range of functionalities without burdening them with technical challenges. Thus, psychotherapists can focus their attention on the patient.

Methods: In this paper both the prototype of the algorithm and a first proof of concept are described. The algorithm suggests environment configurations for VRET, tailored to the individual therapeutic needs of each patient. The system aims to maximise learning during exposure therapy for different combinations of stimuli by using the Rescorla-Wagner model as a predictor for learning. In a first proof of concept, the VE configurations suggested by the algorithm for three anonymised clinical vignettes were compared with prior manual configurations by two psychotherapists.

Results: The prototype of the algorithm and a first proof of concept are described. The first proof of concept demonstrated the relevance and potential of the proposed system, as it managed to propose similar configurations for the clinical vignettes compared to those made by therapists. Nonetheless, because of the exploratory nature of the study, no claims can yet be made about its efficacy.

Conclusions: With the increasing ubiquity of immersive technologies, this technology for assisted configuration of VEs could make VRET a valuable tool for psychotherapists.

5.1 Introduction

Anxiety disorders are highly prevalent, often chronic, mental health disorders. On average, one in four individuals in the United States and Europe suffer from such a condition across their lifetime [1, 2]. Specific phobias, panic disorders, and Post Traumatic Stress Disorders (PTSDs) are examples of anxiety and trauma-related disorders that can severely impact disability and impairment. Fortunately, effective treatments exist, like Exposure Therapy (ET), which is grounded in Cognitive Behavioural Therapy (CBT) [3, 4]. During ET, the patient is repeatedly and systematically exposed to a feared stimulus in a safe context. For example, patients with arachnophobia are exposed to spiders and gradually learn to deal with the elicited fear. ET tends to make a patient less anxious or makes the anxiety less debilitating for specific stimuli, although this is not a necessity [5]. Understanding what makes the patient anxious is essential to create a proper exposure exercise. If a patient is afraid of an external cue, e.g. driving a car on a freeway or in a tunnel or taking an elevator, they should be exposed to similar contexts. Complementary, interoceptive cues, e.g. feeling one's heartbeat or experiencing blurred vision, are often both the object of a patient's fears and essential symptoms of their condition. Therefore, elicitation of these cues is fundamental to conduct the proper exposure exercise. With these requirements, different forms of ET are possible, e.g. in vivo (in real life), imaginary, or in Virtual Reality (VR) [6, 7]. To augment both the reach and effectiveness of existing treatments and services, this latter form of Virtual Reality Exposure Therapy (VRET), in which VR technology enhances exposure treatment, is increasingly being explored [8]. With VR technology, it is possible to simulate almost any scenario. This creates the opportunity for fine-tuned personalised VR environments for ET. However, configuring these environments is not trivial and introduces an additional workload for the psychotherapist.

This manuscript is the product of interdisciplinary research between psychotherapists and computer scientists. The main objective of this paper is the presentation of a prototype of a novel adaptation algorithm for VRET which generates personalised VR environments to treat patients with anxiety. The scalability of the algorithm is investigated in terms of execution time relative to the amount of input data. Furthermore, a proof of concept VRET application called PATRONUS has been designed and implemented in which the algorithm is integrated. The proof of concept focusses on fear of driving a car, claustrophobia, and panic disorders. In this proof of concept, data of three prior anonymised clinical vignettes are used to generate suggestions with the adaptation algorithm. These suggestions are compared with the manual configurations of two psychotherapists. The adaptation algorithm was not used in a clinical setting to steer the patients' therapy.

This paper presents the algorithm by describing the underlying theory and techniques from both the psychological and computer science point of view, making it relevant for experts from both domains. The remainder of the paper is structured as follows. Section 5.2 gives a theoretical foundation of the psychological learning mechanisms that are relevant for ET. Section 5.3 continues with the methodology for the design of the presented adaptation algorithm and proof of concept application. This section covers the outline of the system in which the adaptation algorithm is integrated as well as the knowledge and data management techniques used. In Section 5.3.4, the PATRONUS proof of concept, a VRET system that integrates the adaptation algorithm, is described in detail. The prototype of the adaptation algorithm is presented in 5.4.1, the technical details of the implementation are explained in Section 5.4.2. A scalability test on the execution time of the algorithm is presented in Section 5.4.3. The results of the comparison between the generated suggestions on three clinical vignettes are presented in Section 5.4.4. Finally, a discussion and conclusion is given in Section 5.5.

5.2 Related Work

VR has a proven track record. Contrary to common belief, it has effectively been used in clinical practice for over two decades [9–11]. The therapeutic approach relying on VR, known as VRET, was initially primarily offered in specialised settings, i.e. treatment centres for war veterans in the United States suffering from PTSD [12]. One of the main advantages of VRET, compared to conventional ET, is the possibility to immerse patients in Virtual Environments (VEs) that are highly controllable and customisable. This is particularly interesting for the treatment of anxiety disorders. Despite the common ground of anxiety disorders, each patient is still unique. Across patients, there may not only be subtle differences between feared stimuli but also in terms of the pace at which the patient progresses. Determining when a patient is ready for *the next step* is therefore individually determined. Optimising VE and the pace at which they evolve and tailoring that to individual patients is therefore necessary. Personalised VEs tend to increase the potential of creating a sense of presence, offering patients the idea of really being in a different place than where they physically are [13]. To some extent, the technology itself can facilitate this by creating a highly immersive experience, e.g. accommodating a wide field of view in the virtual world or offering highly realistic VE [14]. However, research indicates that creating a feeling of being a part of a VE is not only a characteristic of the technology itself. Tailoring the VE to the particular fears of individual patients can play an important role as well [15].

Although found to be clinically effective, the technical nature of VRET and the associated costs did not allow this treatment form to become widely available yet. In recent years, VR systems' ongoing commercialisation has opened up possibilities for more widespread use beyond these settings [16]. A lower hardware cost and increased accessibility of relevant software applications and platforms hold promise. Alongside established, extensive VRET platforms, e.g. Oxford VR[1] and Psious[2], a low-cost stand-alone VRET-app with demonstrated clinical effectiveness has also made its way to market [17]. Nevertheless, this does not imply that no challenges remain for psychotherapists to implement VRET. Psychotherapists are not necessarily tech-savvy or are insufficiently familiar with the wide range of possibilities and features that broadly available VR systems increasingly support [18]. The current solutions are either very static with predefined environments or are dynamic with an overload of manually configurable options. The static environments are easy to use but lack the possibility to personalise the therapy to the patient's needs completely. The dynamic environments allow this personalisation at the cost of increased complexity, hindering psychothera-

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[1] https://ovrhealth.com, accessed on 20/10/2021

[2] https://psious.com, accessed on 20/10/2021

pists from using these tools effectively. The latter can, in part, be overcome through vocational training, in which psychotherapists are informed and trained in interacting with VRET – and other – technological extensions to conventional practice [19]. As possibilities of VE are steadily increasing in number, so do the possibilities for tailoring these environments. The growing complexity implies that truly mastering a system will also require increasing and ongoing amounts of training, which introduces a novel threshold and limits the full potential for clinical practice. Furthermore, a VRET system should be easy to use, and the psychotherapist should possess the required knowledge to adopt a VR tool in therapy effortlessly. Otherwise, the VR system draws the psychotherapist's focus away from the patient, damaging the patient-therapist bond.

One way to deal with this challenge is through the development of supportive algorithms. Such algorithms could facilitate VR systems to consider clinical expertise without requiring psychotherapists to grasp the technical nuances fully. Nor do they need to know by heart the wide range of functionalities available in a system. More specifically, adaptation algorithms are needed to automatise this translation from expert observations and insights to environmental adaptations in VR. This will take away the burden of requiring psychotherapists to manually create the tailored environment they consider most suitable for each step of a VRET. At the same time, it can help them keep their focus during sessions to where it matters the most: on their patients.

A vast amount of lab research aims at uncovering the learning processes underlying ET. For this purpose, psychotherapists often use a Pavlovian fear condition paradigm to model the pathogenesis of anxiety disorders and ET [5, 20, 21]. This procedure consists of two parts, starting with the fear acquisition to mimic the development of an anxiety disorder and then followed by fear extinction as a model for ET. In the fear acquisition, a neutral stimulus (Conditioned Stimulus (CS)) is repeatedly presented to the subject, followed by an aversive stimulus (Unconditioned Stimulus (US)). As a result, the CS acquires a dangerous meaning and starts eliciting fear reactions in anticipation of the US (routinely measured as enhanced physiological arousal, US-expectancy and increased negative valence of the CS). This is commonly termed the Conditioned Response (CR). The current dominant view is that during conditioning, the person forms a mental association between representations of the CS and the US [22]. Novel confrontations with the CS will thereby activate the representation of the US as well, which produces fear reactions. Subsequently, in fear extinction, the subject is repeatedly exposed to this CS in the absence of the US, and the conditioned fear reactions decrease. This fear extinction procedure is similar to what happens in ET. However, what drives this fear reduction?

A rationale why fear declines during extinction is that the US is expected but not delivered whenever the CS appears. This violates a patient's expectancy, which drives new learning to update false expectations. Violations of these false expectations of danger are therefore vital in extinction learning. Researchers have formalised this notion in formulas that stipulate how expectations are updated after each violation. As in the influential theory of Rescorla and Wagner (1972) [23], the standard approach is to calculate the difference between what a patient expects and what has actually happened. This allows evaluating the amount of learning on any given extinction trial.

Furthermore, the Rescorla-Wagner (RW) model allows for an idiosyncratic formalisation per patient per exposure exercise. In theory, such an approach would allow to personalise and optimise VEs. A therapist, however, cannot perform the calculations of the RW model to determine the amount of learning in real-time during VRET. Therefore, this paper presents an algorithm that uses the RW model that will play an essential role in supporting a therapist to maximise potential learning during exposure exercises. The algorithm suggests VEs that are personalised and optimised for each individual patient at every step during the therapy process.

5.3 Methods

In this work, a prototype of an algorithm for adapting VR environments is presented, specifically for VRET. The adaptations aim to optimise the configuration of these VEs to match the patient's needs in each therapy exercise, as indicated by their psychotherapist. The adaptations are performed based on profile information of the patient, which describes characteristics of the phobia, and context information, which describes what happens during exposure exercises. The presented adaptation algorithm is to be integrated in a system for administering VRET. In this study the PATRONUS application is designed as a proof of concept in which the adaptation algorithm is implemented. This section describes this system and the proof of concept in detail.

5.3.1 System Overview

The adaptation system for VR content in ET consists of multiple software and hardware components. Figure 5.1 gives a high-level overview of the system. The personalised adaptations are calculated in the *Adaptor* component, which uses data about the patient and the exercises they performed. All the data is gathered and stored in a *Knowledge base* that combines that data with prior knowledge from domain experts, e.g. the knowledge introduced in the background section of this work. The *Knowledge base* offers an access point for the *Adaptor* to get the information needed to make adaptations. The output of the *Adaptor* is a set of suggestions for new environments. The psychotherapist then selects one of these suggestions. Before presenting the environment to the patient through the *VR system*, the psychotherapist can still manually change the configuration. By generating multiple suggestions, the psychotherapist can still decide how to advance the therapy as there often is not only one single solution in exposure therapy but multiple valid approaches.

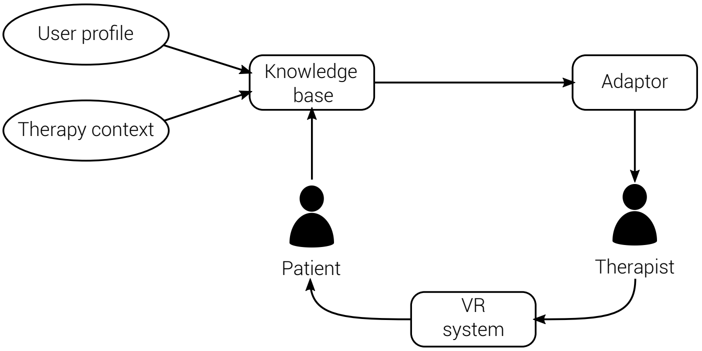

Figure 5.1: Overview of the adaption system for VRET

Because the psychotherapist has, at all times, complete control over what the patient sees, the adaptation system is a Decision Support System (DSS) [24]. It presents the information in an easy to digest format while leaving the final decision to a human expert. Before, during and after each exposure exercise, information is collected from the patient and stored in the *Knowledge base* for configuration of the next exercise.

5.3.2 Knowledge Base

The *Knowledge base* is a collection point for all information and knowledge. This section describes which data is used, how data is modelled and how knowledge is extracted from that data.

5.3.2.1 Data

Data is fed to the adaptation algorithm to generate new personalised adaptations for the VE. On the one hand, the user's profile information identifies the characteristics of their anxiety, e.g. the patient is uncomfortable in busy places and apprehensive of bright lights. On the other hand, the used context data is the level of anxiety during exposure which aids in understanding the effect of the performed exercises. The patients express their level of anxiety using the Subjective Units of Distress Scale (SUDS). It expresses the patient's perception of discomfort as a number between 0 and 10, which is widely used for ET [25]. The context data allows designing exercises tailored to the patient's phobia at each step throughout the therapy.

The profile information is collected by having the patient fill out a VR parameter questionnaire. This questionnaire is specifically constructed for this work and depends entirely on the specific environments supported by the system. The questionnaire inquires the patient about their expected reactions to the set of stimuli in the VR system. All these questions have the following format: "What effect do you expect [*parameter* *configuration of the VE*] has on you?". Each question is answered with "Anxious", "Not anxious", or "I don't know". Examples are:

- "What effect do you expect driving through a tunnel has on you?"
- "What effect do you expect standing in a crowded elevator has on you?"
- "What effect do you expect hearing your own heartbeat has on you?"

The context information about the progress during exercises is collected through exposure logs which are commonly used in ET [6]. In these exposure logs, the patient answers a few questions after each exercise:

- "How afraid are you immediately after the exposure exercise?" (SUDS)
- "What was your peak anxiety level during the exposure exercise?" (SUDS)
- "Did that what you feared the most actually happen during the exposure exercise?" [Yes/No]

These questions have been designed to precisely extract the information needed to evaluate the RW model used by the adaptation algorithm.

5.3.2.2 Ontology

Data in itself has little meaning. Only when adding context about the data, the information it holds becomes clear. Expert knowledge is required to add and interpret the context. The merger of these types of data and knowledge can ideally be performed through Semantic Web technologies [26], i.e. semantic ontologies, which provide formal descriptions of concepts, their properties and relationships between those concepts. These ontologies are built with domain experts through a co-design approach [27]. Instances of the defined concepts are created from raw data, thereby mapping the data on the ontology. These are called individuals.

For this research, a new ontology has been developed specifically for VRET. To the authors' knowledge, no ontologies yet exist that describe the domain of CBT in general and VRET in specific. The ontology is split up into three logical layers, each modelling a different level of specificity. The top layer contains a general upper ontology, which defines concepts relevant to ET in general. The layer below consists of a VRET-ontology, which extends the upper ontology with concepts specific for ET in VR. The bottom layer contains several ontologies, each corresponding to a specific VE. The presented ontologies in each layer are publicly accessible from our repository[3] and are discussed in more detail below.

The upper ontology is modelled around the concept of hypotheses about the patient's fear and is shown in Figure 5.2. These hypotheses model a relationship between

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[3] https://github.com/IBCNServices/PATRONUS-ontology, accessed on 20/10/2021

a set of fear stimuli and responses, e.g. a tiny elevator with no windows and no alarm button elicits high anxiety in the patient. A hypothesis is tested through an exposure exercise. Doing the exercise reveals the actual response of the user. One target hypothesis is defined. It is a translation of one of the patient's goals into a configuration for the system. The *Adaptor* will generate intermediate hypotheses based on this target hypothesis that is used for new exercises. The ontology models both internal and external stimuli. These are properties of the environment or events happening during the exercise. The patient's responses to the exercise can be modelled as either behaviour characteristics, e.g. avoidance, panic and freezing up, or a SUDS. Figure 5.2 shows some examples of individuals created for some of these classes in green. This represents instantiations of these concepts based on input data.

The VRET-ontology extends the upper ontology by providing VRET specific definitions for general concepts and introducing some new ones. The ontology is graphically presented in Figure 5.3. A *VRScenario* embodies the hypothesis in VR. Therefore, it is a subtype of *Hypothesis*. A scenario is an entire configuration of a VE with all its properties and events that can occur. *Exercise*, *Stimulus* and *EnvironmentProperty* from the upper ontology have a VRET equivalent prefixed by the acronym "*VR*". The equivalents of *InternalEvent* and *ExternalEvent* are *VRInteroceptiveStimulus* and *VREvent*, respectively. These sub-classes are needed and used in this system because potentially other ontologies on the same level as the VRET-ontology, e.g. an ontology for in vivo ET, could extend these super-classes as well. In addition, the VRET-ontology contains a classification for stimuli based on the datatype of the stimulus parameter. The *Adaptor* requires this classification to query the *Knowledge base* about the stimuli present in each VE and how they can be configured. The main two classes are *VRDiscreteStimulus* for stimuli with discrete values and *VRContinuousStimulus* for stimuli with an infinite range of values. Both have some subtypes as well.

The ontologies in the lower layer depend entirely on the design of the VEs. They classify the stimuli used in each VE based on the types defined in the VRET-ontology. In essence, each ontology in the lower layer describes one type of VE and corresponds to one specific phobia to be treated with the system. Through this approach, the system is agnostic to the specific phobias it can treat. Thus, to support more types of VE, only the *Knowledge base* needs to be extended with a description of those VEs, while the rest of the system remains untouched. The adaptation algorithm is build to work with the classes in the upper layers. Thus, through inheritance, the adaptation algorithm works with any VE ontology that extends the upper layers with sub-classes. Figure 5.4 shows an example of an ontology for a VE of a driving car. The concepts of the VRET-ontology, shown in grey, are extended to describe the specific attributes of the car VE.

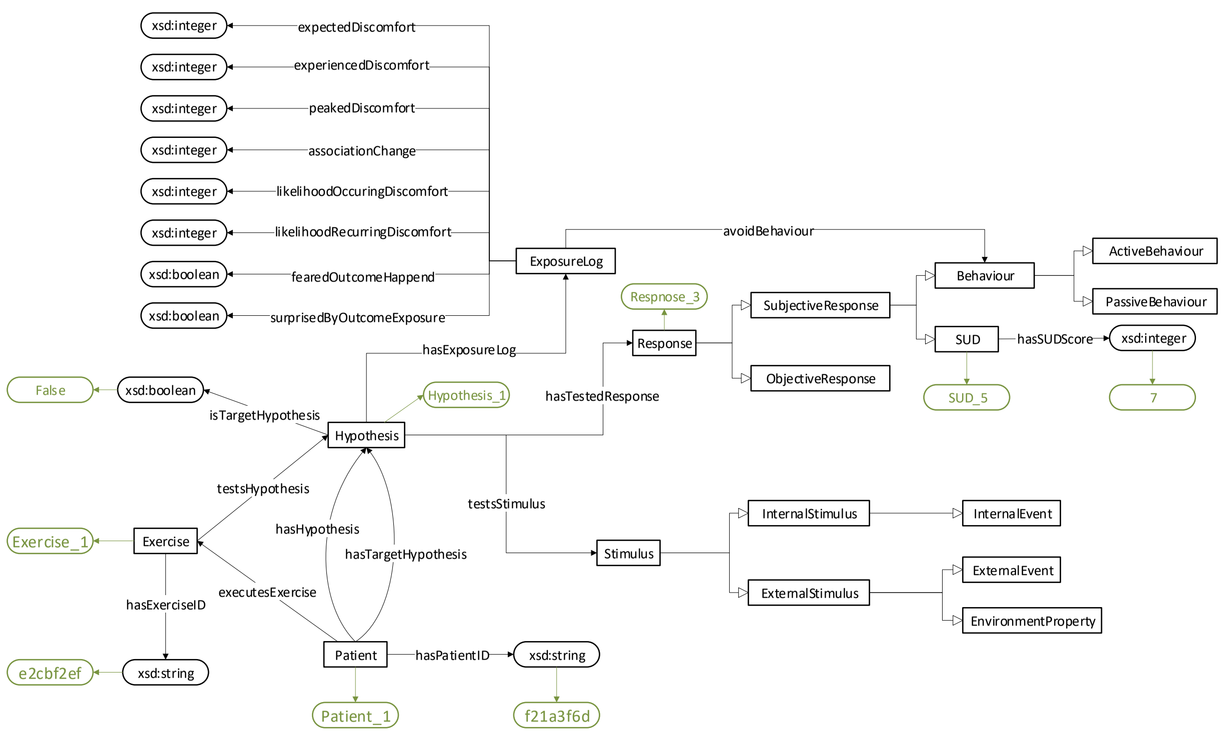

Figure 5.2: This graphical presentation of the upper ontology shows the concepts (black boxes) and the relations between them (black arrows). The green boxes represent examples of individuals created for the corresponding classes.

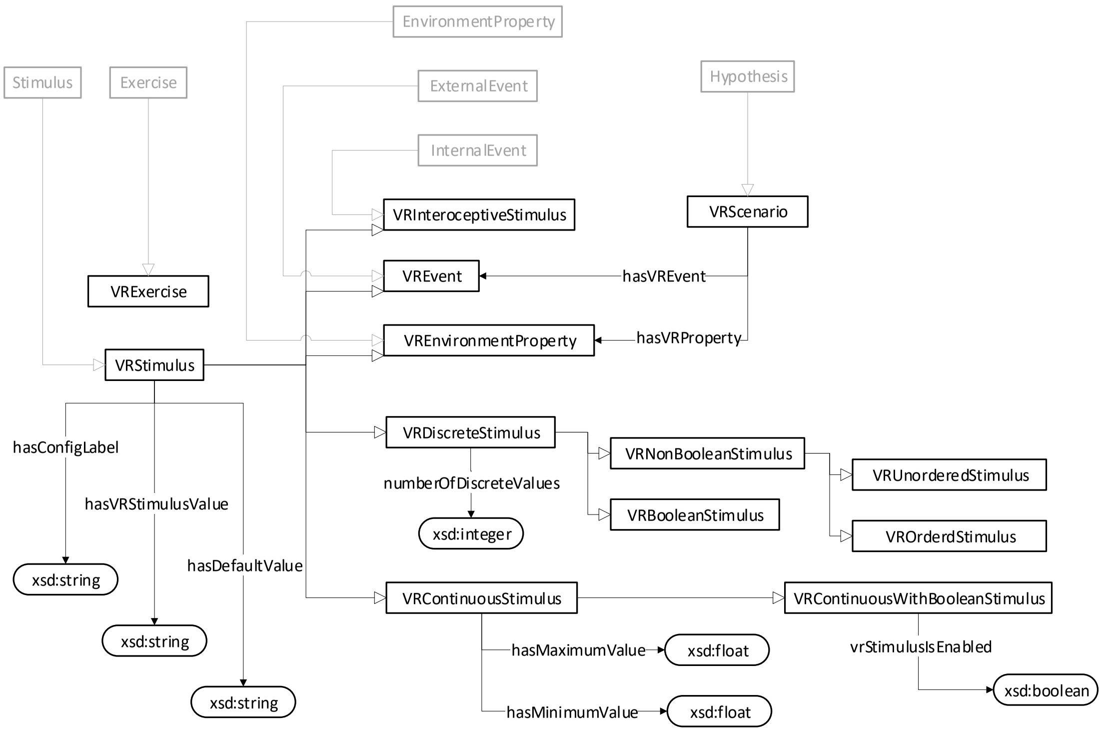

Figure 5.3: The concepts and relations of the VRET-ontology that extend the concepts of the upper ontology (grey)

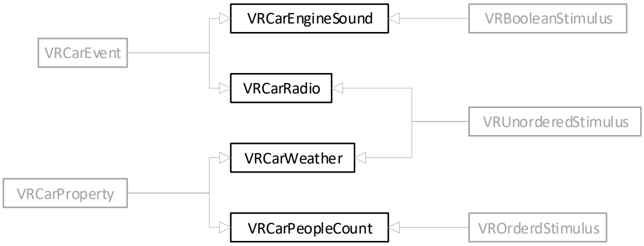

Figure 5.4: An example of a small ontology that describes a VE of a driving car. The environment has four parameters that can be configured (CS). They extend the VRET-ontology concepts (grey).

5.3.2.3 Semantic Reasoning

Semantic reasoning allows deriving logical consequences from the data and knowledge inside a *Knowledge base* [28, 29]. There are two types of information that can be derived. On the one hand, ontology reasoning is used to infer to which classes an individual belongs. On the other hand, user-defined reasoning extracts high-level insights from low-level data. This is called user-defined reasoning, as the rules which dictate the reasoner are formulated by the end-user. In other words, the domain experts' knowledge is translated into rules such that the computer system can replicate part of its thought process.

The *Knowledge base* contains two user-defined rules, but it can easily be extended with more rules or more complex rules. The first rule is a simple rule used to define the property *hasTargetHypothesis*. This relation holds when a patient has some hypothesis (*hasHypothesis*), and that hypothesis is marked as the target hypothesis (*isTargetHypothesis*). The second rule calculates the value of the association change defined by the RW model, which is needed in the *Adaptor* and is discussed in more detail in the next section. This value can be calculated from data collected through the exposure log. This is an excellent example of how the *Knowledge base* contains expert knowledge. The *Knowledge base* knows how to calculate the association change based on the available data.

5.3.3 Adaptor

The *Adaptor* is the component that contains the actual adaptation algorithm for personalising the environment. It collects the required data from the *Knowledge base* and provides four suggested configurations for the following exercises to the psychotherapist. The choice for four configurations is primarily pragmatic: it creates sufficiently distinct environments while keeping the choice for a specific environment manage-able for the psychotherapist. The *Adaptor* employs the theory and model proposed by Rescorla and Wagner [23] for calculating the explicit configurations. The mechanisms of the algorithm are discussed in detail in Section 5.4.1

5.3.4 Proof of Concept

The VE for which the adaptation algorithm is generating suggestions are part of the *VR system*. In this work, a proof of concept application for VRET has been developed which fulfils the role of the *VR system*. This proof on concept application is called PATRONUS[4] and is the product of an interdisciplinary collaboration between computer science engineers, user researchers, IT experts and psychotherapists. The proof of concept application with which the adaptation algorithm is interacting is further discussed in this subsection. Special attention is given to the virtual environments of the proof of concept.

5.3.4.1 PATRONUS System

The PATRONUS system aims to create a patient-centric blended healthcare solution for anxiety treatment through ET. The approach consists of therapy at the psychotherapist's office and longitudinal follow-ups through homework exercises on a mobile coaching app, as presented in Figure 5.5. During the face-to-face sessions, the patient receives ET through the use of VR. The VE are personalised to the specific needs of the patient. In between sessions, the patient can continue exposing themselves to anxiety-inducing environments through homework exercises on their mobile phone. The patient always plans the homework exercises in consultation with the psychotherapist. These homework exercises are instructions to experience real-life situations or VRET exercises similar to those performed during the face-to-face sessions.

At the centre of the PATRONUS system is a dashboard application, as shown in Figure 5.6. Through this dashboard, the psychotherapist can record information about the patient, configure and start VR exercises for ET and create homework exercises that synchronise with a mobile application on the patient's smartphone. The psychotherapist can also consult the progress of the patient from the dashboard. When configuring a VR exposure exercise, the psychotherapist can either manually configure a new environment or have the adaptation algorithm generate four suggestions for the patient.

5.3.4.2 The Virtual Environments

The VEs are designed to make them easily adaptable, either manually or through an algorithm. Each environment has some base elements and characteristics which cannot be changed. These define the overall purpose of the environment. For each

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[4] https://www.imec-int.com/en/what-we-offer/research-portfolio/patronus, accessed on 20/10/2021

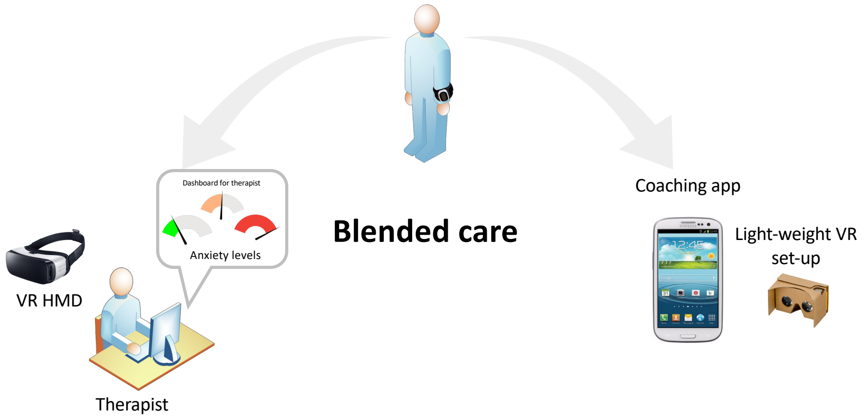
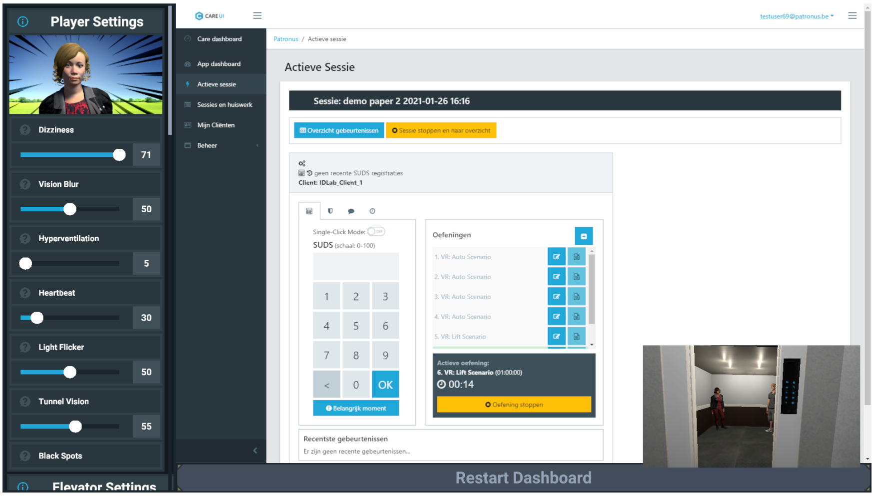


Figure 5.5: The PATRONUS system is a patient-centred blended care solution for anxiety treatment through VRET with the psychotherapist and at home.



Dizziness 71
Vision Blur 50
Hyperventilation 5
Heartbeat 30
Light Flicker 50
Tunnel Vision 55
Black Spots

Actieve Sessie

Sessie: demo paper 2 2021-01-26 16:16

geen recente SUDS registraties
Client: IDLab_Client_1

Single-Click Mode: OFF
SUDS (schaal: 0-100)

Oefeningen
1. VR: Auto Scenario
2. VR: Auto Scenario
3. VR: Auto Scenario
4. VR: Auto Scenario
5. VR: Lift Scenario

Actieve oefening:
6. VR: Lift Scenario (01:00:00)
00:14

Recentste gebeurtenissen
Er zijn geen recente gebeurtenissen...

Figure 5.6: The dashboard application is the interface for the psychotherapists to use the entire PATRONUS system.

environment, a set of parameters is defined, which further refines the elements and characteristics of the environment. These parameters are configurable and allow the environment to be adapted. In this implementation, each parameter is considered a potential stimulus that elicits fear, i.e. CS. The following sections discuss specific configurable parameters.

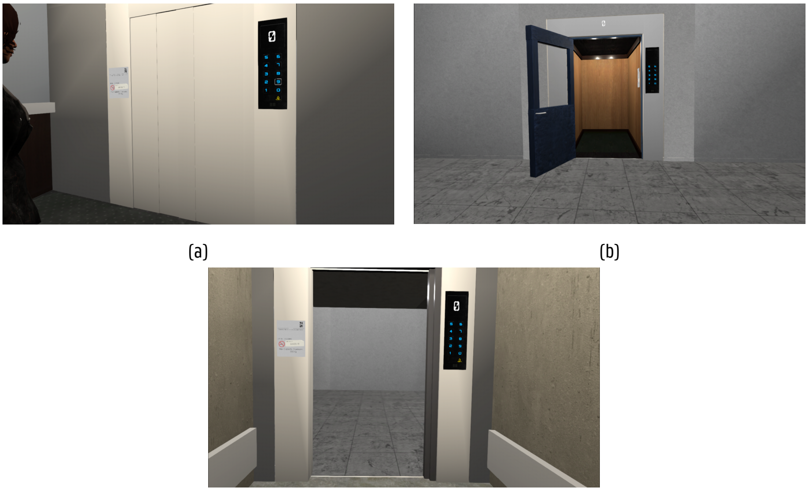
The PATRONUS system incorporates two distinct environments. There is an elevator environment and a car environment. Both environments can be used for people with panic disorder and claustrophobia. The car environment also focuses on fear of driving.

Apart from the environment-specific parameters, a small set of general adaptation parameters are provided. These are the so-called *interoceptive* parameters. These do not change anything about the environment itself. They are designed to elicit a specific interoceptive sensation in the patient by modifying the perception of the environment.

The *elevator* and *car* environments, and *interoceptive* parameters are discussed in more detail in the following sections.

Elevator environment The user can interact with the elevator environment by walking around freely and pressing the buttons in the elevator. In this scenario, the user controls what happens as they decide to enter the elevator or go to a specific floor. Interaction happens through hand-held controllers, which are represented by hands in the VE. The look and feel of the elevator are crucial because this can influence the patient's anxiety level. Therefore, three base types of elevators are supported, a modern-looking elevator (Fig. 5.7a), an old elevator (Fig. 5.7b) and a service elevator (Fig. 5.7c). They can then be further tailored by choosing a type of door from a one-sided sliding door (Fig. 5.7c), a two-sided sliding door (Fig. 5.7a), or a hinged door (Fig. 5.7b), adding windows (Fig. 5.7b), and changing the size of the elevator. Also, more subtle elements can be configured, such as whether the floor buttons are inside or outside the elevator, whether an alarm button is present or how much noise the elevator makes. The number of people in the elevator can be changed to simulate a crowded space. To further enhance the sense of presence, subtle visual cues are incorporated for the elevator's speed through moving light streaks around the doors and the sensation of the elevator starting and stopping through some camera shake. Lastly, three parameters simulate defects in the elevator as these are essential stimuli for some patients. Random shaking of the elevator is simulated through camera shaking, the lights in the cabin can dim at random moments, and the elevator could get stuck while moving between floors.

Car environment The patient is seated in a virtual car on the freeway. There is little interaction possible from the user with the VE. The user can only look around while being submitted to what is going on in the environment. To provide a better sense of presence in the environment, the patient holds two controllers matched to hands on



(a)

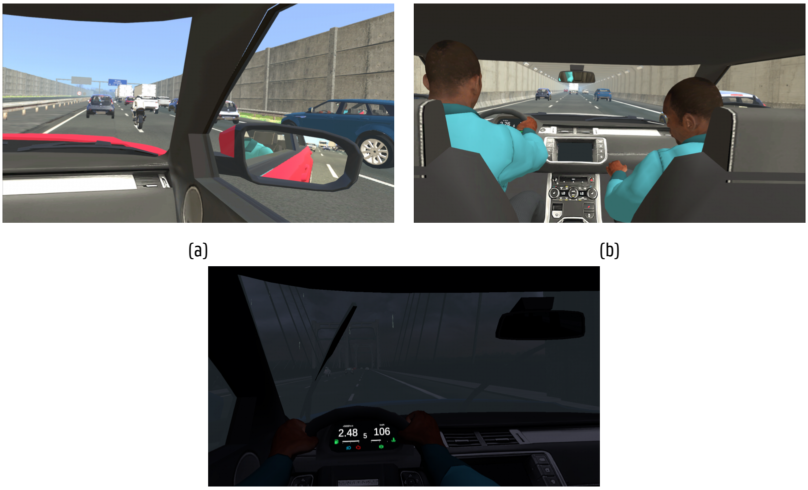
(b)

(c)

Figure 5.7: The look and feel of the elevator depends on the combination of many parameters such as the elevator interior, the door type, and the buttons' position. (a) Modern elevator with two-sided sliding doors, (b) Old elevator with a hinged door featuring a window, the buttons are located on the outside, (c) Service elevator with a one-sided sliding door.

the steering wheel. In this car environment, many parameters can be altered to increase or decrease the patient's level of anxiety. The first is the type of freeway: an open freeway (Fig. 5.8a), a tunnel (Fig. 5.8b) or a bridge (Fig. 5.8c). The traffic on the road is configurable as well: the amount of traffic, the speed level, the presence of motorcycles (Fig. 5.8a), and the lane in which the car is driving. Also, the time of day and the weather conditions can be altered. In this VE, it can be nighttime or daytime, and it can be sunny or rainy and clear or foggy. A set of parameters focuses on the situation in the car itself and discerns between visual and auditive stimuli. For the visual parameters, the patient can be seated behind the steering wheel or sit in the passenger's seat in the front or the back. Additionally, the number of passengers in the car can also be modified. There is also an option for enabling a blinking warning light on the dashboard to signal a defect. Finally, four more parameters provide acoustic stimuli to increase or decrease the patient's level of anxiety, as some patients are more susceptible to sounds. The patient can hear a car horn, wailing sirens and engine sounds. Also, the radio can be turned on and off, either broadcasting traffic information or instrumental music.

Interoceptive parameters Dizziness is achieved by applying motion on the camera view of the virtual environment, which causes a misalignment between the physical position of the user's head and the position in the virtual environment. A filter on the



(a) (b)

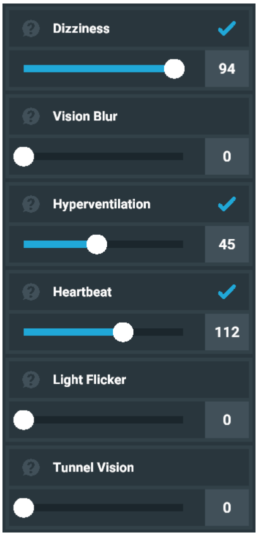
(c)

Figure 5.8: The combination of parameters such as the road type, the seating position and the time of day influence the representation of the car environment. (a) A busy freeway while a motorcycle overtakes the car, (b) A tunnel road while sitting in the backseat, (c) A road across a bridge by night.

visual feed applies a blur to simulate a sudden vision blur for the user. Tunnel vision is also a filter applied on the visual feed. This filter narrows down the field of vision resulting in a small area through which can be seen, while the rest is black. Another effect causes light flickers which create short bursts in which the view turns completely white. These flickers happen at random points in time. The last two are based on an acoustic cue. The sound of a heartbeat can be simulated. This creates the illusion that the patients hear their heartbeat. Lastly, intentionally causing hyperventilation is a common exercise in ET and elicits interoceptive sensations. Hyperventilation can be triggered by letting the patient breathe deeply in and out at a steady and fast pace. In the VE, a beeping sound indicates the pace. All interoceptive parameters can be set in the dashboard, see Figure 5.9, through a toggle button and a slider indicating the intensity.

5.4 Results

The primary result presented by this paper is the prototype of an adaptation algorithm for VRET. The algorithm creates four suggestions for possible new configurations of VE based on the needs of the patient by relying on the theoretical foundation provided by the RW model and data of the patient and prior exercises. This prototype is further described in this section. Furthermore, a scalability test on the execution time of the algorithm is performed in the next part of the section. Finally, the sug-



Dizziness ✓
94

Vision Blur
0

Hyperventilation ✓
45

Heartbeat ✓
112

Light Flicker
0

Tunnel Vision
0

Figure 5.9: The interoceptive stimuli are adjustable in the dashboard view during an exposure exercise.

gestions resulting from this algorithm are compared to prior manual configuration of two psychotherapists from three anonymised clinical vignettes.

5.4.1 Adaptation Algorithm

The adaptation algorithm relies on a plethora of heterogenous data of the patient, its history and the available VE for the VRET. This information is consolidated in a knowledge base as discussed in Section 5.3. This knowledge base is critical for the adaptation algorithm. Figure 5.10 presents the process of the adaptation algorithm to generated the four suggestions based on the information it has available.

The process starts by querying the knowledge base for the target hypothesis and a base hypothesis. The target hypothesis has been constructed from the VR parameter questionnaire. The base hypothesis corresponds to the hypothesis that was used in the last exercise. It is called the base hypothesis or configuration because it forms the starting point for the suggestions of the next exercise, i.e. for each new exercise, the configuration of the previous exercise is altered. If no target or base hypothesis exists, default suggestions will be provided to the psychotherapist as there is not enough data available to construct sensible suggestions. In this case, the process terminates early.

The next step is updating the RW model [23]. The following two formulas describe

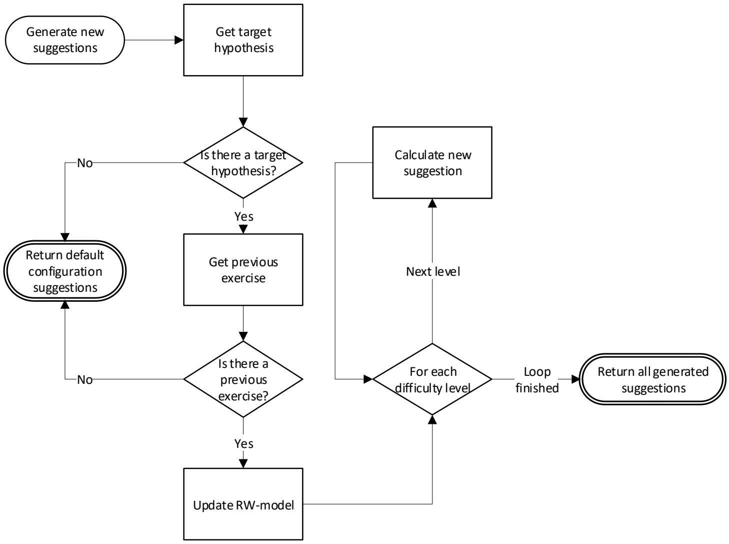


Figure 5.10: Flow diagram of the adaptive algorithm based on the Rescorla-Wagner model

the model.

$$V_X^{n+1} = \alpha_X \beta \left(\lambda - \sum_{s \in S} V_s \right), \tag{5.1}$$

$$V_X^{n+1} = V_X^n + V_X^{n+1}. \tag{5.2}$$

Equation 5.1 models the change in association, ΔV_X for trial $n+1$ between the CS X and the US whereas, Equation 5.2 expresses the total association strength between CS X and the US after $n+1$ trials. In Equation 5.1, α_X is the salience of X, β is the rate parameter for the US, λ is the maximum association possible for X, and S is the collection of all stimuli presented during the trial.

The knowledge base provides the information needed to perform the update step. Specifically, it provides estimations for the values of α_X, β, λ and V_{tot}. The theory of Rescorla and Wagner states that α_X and β need to remain the same for each exercise. The parameter β denotes the rate at which a patient forms new associations. Therefore, the value of β is associated with the number of exposure exercises needed before the patient shows a reduced SUDS for a particular stimulus. For the construction of this algorithm, we assume a value of 0.2 for the product of α_X and β in Equation 5.1. Finding the optimal values for α_X and β is outside the scope of this research. This work uses an estimated value as a default. The value for λ can be extracted from the exposure log directly. The answer to the question “Did that what you feared the most actually happen during the exposure exercise?" is either *yes* or *no*, which translates to a value of 1 or 0, respectively, for λ. Lastly, V_{tot} is the fear association of the patient for the combination of all stimuli in the current exercise. This value can also be directly obtained from the exposure log. The observed peak discomfort provides this value.

With the updated RW model, the four suggestions can be calculated. Each suggestion has an estimated difficulty as a number between 0 and 1 denoted *difficulty_level*. An even distribution of difficulties ranging from 0.5 to 0.95 is chosen, resulting in a diverse range of suggestions that are not too simple but still challenge the patient. Adjusting the difficulty level for each of the four suggestions can result in more diverse configurations if needed.

The difficulty value influences the number of stimuli for which a new value is chosen and the value of the new stimulus itself. As mentioned before, a new configuration is created by changing the configuration of the previous exercise, which was called the base hypothesis. Each stimulus from the base configuration changes with a probability p, as defined in Equation 5.3, and stays the same with a probability of $1 - p$. Therefore, a higher difficulty value leads to more stimuli with a new value, while a higher association with the previous exercise leads to fewer stimuli with a new value.

$$p = \mathit{difficulty\_level} * (1 - V_{tot}) \tag{5.3}$$

The new value of a stimulus is based on s, according to Equation 5.4. This value indicates the distance between the value of the stimulus and the target value of that stimulus. A value of 1 results in precisely the target value, while 0 results in the value furthest away from the target.

$$s = \mathit{difficulty\_level} / V_X \tag{5.4}$$

The target value t is the value given to a stimulus in the target hypothesis. The method for calculating the exact new value u of a stimulus depends on the datatype of its parameter and the target value of the stimulus. The four supported types are parameters with boolean values, parameters with an ordered set of possible values, parameters with an unordered set of possible values and parameters with continuous values.

For stimuli with boolean parameters, the value of u is calculated as Equation 5.5 formulates.

$$u = \begin{cases} \mathit{true} & s > 0.5 \\ \mathit{false} & s \leq 0.5 \end{cases} \tag{5.5}$$

If the parameter can take a value from a set of ordered options, s is first transformed to match the range between 0 and t, and then the value is rounded to the nearest integer number. This value then represents the selected option from the set as Equation 5.6 states.

$$u = \mathrm{round}(s \cdot t) \tag{5.6}$$

When the set of options is unordered, the value of s has little significance. Therefore, the algorithm always selects the exact target value.

Finally, for continuous values, the new setting is calculated by multiplying s by the target value and adjusting for the minimum value of the range as stated in Equation 5.7.

$$u = (s \cdot (t - \mathit{value}_{\mathit{min}})) + \mathit{value}_{\mathit{min}} \tag{5.7}$$

As mentioned before, the value of s indicates the relative difference between t and u. When $s = 0$, the difference should be maximal. In these formulas, the assumption was made that the target value is always close to 1, indicating a high intensity. Therefore, the opposite would be 0, indicating a low intensity. In practice, this assumption does not always hold as the target could also be exposed to a low-intensity stimulus because it elicits fear. If the target is close to 0, the new value of the stimulus can be calculated using the previous formulas as $1 - u$.

5.4.2 Implementation

The system in which the adaptation algorithm gets integrated is responsible for collecting data from different sources (e.g. manual input, questionnaires, previous exercises) and rendering the VE based on the configuration. Therefore, the algorithm and the knowledge base need to interact with the system to use the collected data and instruct it how to configure the VEs. The technical implementation details of the interaction with the system are discussed here.

Figure 5.11 illustrates the three components that enable the integration of the adaptation algorithm. These components communicate with any other part of the system through a message bus. A continuously running listener process written in Python monitors the bus for new incoming messages for the adaptions system. The message on the bus contains an identifier indicating for which patient the adaptations should be calculated. The message also contains the locations of the relevant data for that patient. For every incoming message, a new process is started which performs the calculations for the adaptions. The control flow is driven by the *Adaptor* component as depicted in Figure 5.1, which is also implemented in Python and interacts with a Java-based semantic reasoner called Pellet [30]. Once the suggestions are generated, these are pushed back on the message bus for the following components to handle them.

5.4.2.1 Ontology Representation and Reasoning

Ontologies need a formal description for a computer system to be able to interpret it. The ontology description uses OWL 2 [31], the most recent version of Web Ontology Language (OWL). OWL is a recommendation of the W3C. The *Adaptor* uses OWL API [32] for handling the OWL ontologies at runtime, while SPARQL is used to query the information from the ontologies. The Protégé [33] editor software was used to

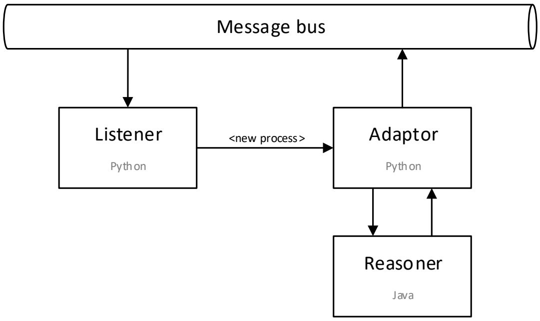


Figure 5.11: The implementation overview of the different components of the adaptation system and how the message bus is used for communication with any other part of the system.

create the OWL ontologies. Listing 5.1 presents a fragment of the VRET-ontology using OWL.

The user-defined rules also need a formal definition for the reasoner to interpret them. The Semantic Web Rule Language (SWRL) [34, 35] can be used for this. It makes it possible to describe logical rules for OWL ontologies. An example of a SWRL rule is as follows:

$$\begin{aligned} &\mathit{ExposureLog}(?e) \wedge \mathit{experiencedDiscomfort}(?e, ?x) \wedge \mathit{expectedDiscomfort}(?e, ?y) \\ &\qquad \wedge\ \mathit{swrlb} : \mathit{subtract}(?z, ?x, ?y) \longrightarrow \mathit{associationChange}(?e, ?z) \end{aligned}$$

5.4.2.2 Data Mapping

Raw incoming data is mapped onto the ontology. This means creating instances of the concepts defined in the ontology and assigning relationships between these instances based on the incoming data. Figure 5.12 depicts this data mapping process. The raw data enters the adaptation system in a semi-structured format, namely JSON. The result of this data mapping is a set of Resource Description Framework (RDF) triples. A triple consists of a subject, a predicate and an object, e.g. `patient` (subject) `hasHypothesis` (predicate) `hypothesis` (object). In this way, every relation of every instance can be defined. The data in semi-structured JSON format can be automatically mapped using a tool called *RMLmapper*, which uses the RDF Mapping Language (RML) [36] to define rules for mapping from one structure to another.

The RML syntax is rather complex. Therefore, an additional tool is used for generating these rules from a much simpler syntax. YARRRML [37] is an application that accepts mapping rules in YAML syntax and outputs the corresponding RML rules.

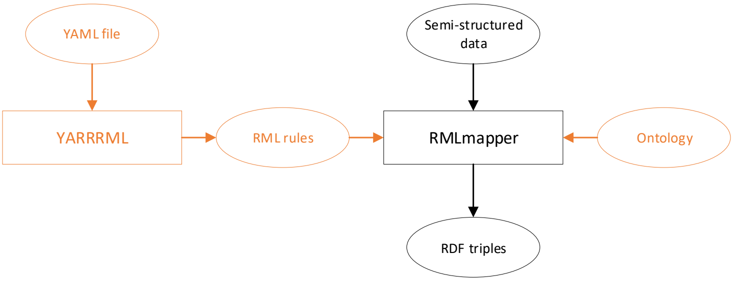


Figure 5.12: Overview of the data mapping process showing the two processor units (squares) and the data objects (ovals) that flow through it. The orange process is only executed once before execution time. Similarly, the orange data objects are created once at design time. The black process is executed repeatedly at runtime resulting in new data objects.

Constructing the RML rules using YARRRML is only performed once during implementation. The mapping into RDF triples using RMLmapper is performed for every new data entering the system. This is illustrated by the orange and black components, respectively, in Figure 5.12.

To illustrate this process, the following example is presented. The input is the JSON-file in Listing 5.1, which contains only an ID of the patient. The input data is mapped according to the mapping rules defined in Listing 5.2. These rules are in YAML syntax. Therefore, they are first translated into RML syntax, which results in the rules shown in Listing 5.3. The output of the process for this example is two triples shown in Listing 5.2. The first triple states that there is some entity which is of type *Patient*. The second triple indicates that this new entity has the property *hasPatientID*, which provides it with an ID.

```
{
    "ClientId": "f21a3f6d"
}
```

Listing 5.1: This is an example of a possible input JSON file. It only contains an ID of a patient.

```
base:patient_f21a3f6d a uet:Patient.
base:patient_f21a3f6d uet:hasPatientID "f21a3f6d"^^xsd:string.
```

Listing 5.2: The output of the mapping process are two triples.

5.4.3 Evaluation of the Execution Time

It is hardly feasible to collect large amounts of data from real-life experiments with actual patients for evaluating computational complexity and performance, nor would it be ethically appropriate to do so with a first protoype of the algorithm. Therefore,

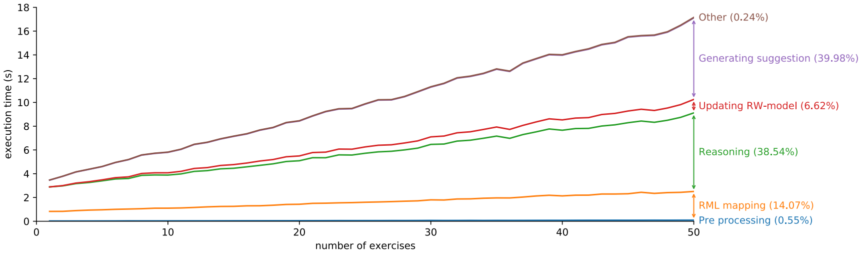


Figure 5.13: The majority of the total execution time of the algorithm, namely, 99%, is accounted for by four steps of the algorithm: RML-mapping step (14%), reasoning step (39%), updating step of the RW model (7%) and the suggestion generation step (40%) for 50 exercises. Pre-processing and the 'other processing' category are almost negligible, making up the final 1%.

these tests ran in a simulated environment with randomised data. Specifically, the execution time of the algorithm for an increasing amount of input data is evaluated. The amount of input data directly correlates to the number of previous exercises. Therefore, the tests are evaluated as a function of the number of previous exercises directly. The content of the processed data does not influence the execution time, thus, randomised data is used.

The number of input exercises for the simulation range from 1 to 50. The execution metrics presented are averaged over 50 repetitions. All simulations ran on a 2,4 GHz Dual-Core Intel Core i5 with 8GB of memory. The code is written in Python without any parallel computing.

The execution of the entire algorithm is divided into five steps, the *pre-processing* step, the *RML-mapping* step, the *reasoning* step, the *updating* step of the RW model and the *suggestion generation* step. The execution time for each step is reported individually. A category is added for *other* processing, including downloading data and querying the knowledge base to ensure the sum of all steps equals the overall execution time. Figure 5.13 shows the stack plot of the execution time as a function of the number of previous exercises. Table 5.1 presents the exact values of each step's average execution time and standard deviation for 1, 10, 20, 40 and 50 previous exercises.

Every step of the algorithm scales linearly with the number of previous exercises. The *pre-processing* step and the *other* processing take up the least amount of time and are almost negligible compared to the other four classes. For an input of 50 exercises, these four classes account for 99.2% of the total execution time. In total, 14.07% of the execution time is spent on data mapping, 38.54% is spent on reasoning, 6.62% is spent on updating the RW model, and 39.98% is spent on generating suggestions. All steps together scale at a rate of 0.27 seconds per additional previous exercise. The standard deviations are reasonably low for each step. The reasoning step does show the most deviation at max 953 ms.

Figure 5.14 compares the slope of each of these four dominating computation

Table 5.1: Each test condition is executed 50 times, the average execution time and standard deviations for each step are presented in seconds for 1, 10, 20, 30, 40 and 50 previous exercises.

number of exercises	Pre processing		RML mapping		Reasoning		Updating RW model		Generating suggestion		Other	
	avg	std	avg	std	avg	std	avg	std	avg	std	avg	std
1	0.023	0.003	0.806	0.104	2.060	0.245	0.023	0.003	0.568	0.047	0.012	0.004
10	0.035	0.005	1.066	0.052	2.785	0.126	0.191	0.036	1.720	0.143	0.021	0.001
20	0.050	0.009	1.380	0.081	3.661	0.499	0.405	0.073	2.934	0.285	0.027	0.008
30	0.071	0.048	1.730	0.265	4.666	0.499	0.633	0.103	4.186	0.335	0.033	0.016
40	0.080	0.004	2.054	0.098	5.525	0.685	0.870	0.137	5.441	0.468	0.038	0.018
50	0.095	0.006	2.412	0.133	6.610	0.953	1.135	0.171	6.857	0.553	0.041	0.016

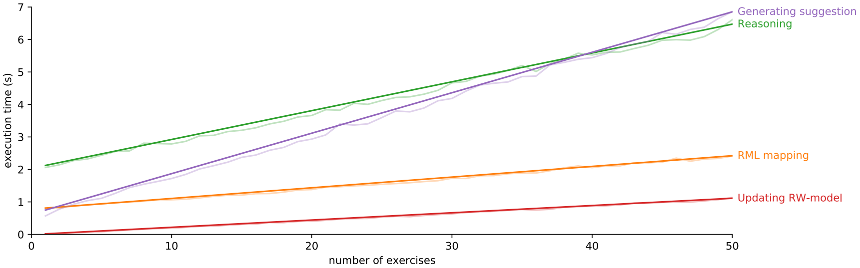


Figure 5.14: For each step, the average execution times (faded colours) are shown to which a linear function is fit (bright colours). Every step of the algorithm scales approximately linearly with the number of previous exercises. However, the reasoning and generation steps are the most affected by the amount of input data, as the execution time increases significantly more than the other two dominating computation steps with increased input data.

steps against each other. The *RW updating* step is the least affected by the amount of input data, while the *reasoning* and *suggestion generation* steps are affected the most. The *reasoning* step has a very high initial overhead. However, it has a relatively small slope. After approximately 39 exercises, the execution time of the *generation* step will dominate over that of the *reasoning* step. The high initial overhead of the reasoner is due to the slow startup time of the reasoning process, which is performed at the start of each simulation run. OWL-DL reasoning is a slow process that scales poorly for large amounts of data [38].

In the presented system, the *Adaptor* component lacks the capability of persistent storage. This has an impact on the data *mapping* step and the calculations for updating the RW model. Specifically, intermediate results of both steps cannot be stored. By introducing persistent storage and storing intermediate results, these two steps can be optimised. Since only new information from the last exercise needs processing, the *mapping* step would reduce to mapping the data of the last exercises. The execution time would be constant at approximately 800ms, as can be deduced from Figure 5.14. The same applies to the update step of the RW model. The time needed for this step would be constant at approximately 20ms, as shown in Figure 5.13. Assuming these optimisations are applied, the execution times can be estimated to be reduced by 15.8% for 50 previous exercises. This results in a scaling factor of 0.22 seconds per previous exercises. Additionally, the reasoning process would benefit from storing intermediate results. The reasoning would be limited to data from new exercises by storing the materialised ontology for each patient. Therefore, the gain in execution time is more challenging to estimate and is therefore not included in the presented time estimation above.

5.4.4 Clinical Vignettes

Through tests on data of clinical vignettes, the overall quality of the generated suggestions is evaluated. Specifically, VRET therapy sessions were held with clinical patients without the use of the adaptation algorithm. The data of these therapy sessions was collected as part of a study, for which the protocol was approved by the Medical Ethical Committee of Ghent University Hospital [EC/2019/0893]. During these sessions, three patients suffering from panic disorder or specific phobia – fear of driving diagnosed via a structured interview, Mini International Neuropsychiatric Interview (MINI) [39] – received ET with manually configured VR exposure exercises on the PATRONUS system. These patients had the following characteristics: Patient 1, male, 34 years, diagnosed with panic disorder; Patient 2, male, 68 years, diagnosed with specific phobia and fear of driving; Patient 3, female, 55 years, diagnosed with specific phobia. The two psychotherapists performing the therapy are experienced in their domain and well familiar with the PATRONUS system (psychotherapist 1, 38 year old, psychotherapist 2, 31 years, with experience between 10 and 15 years of professional experience). This experience provides them with good knowledge of how to create the best VE for the patients manually. During a post-therapy evaluation, the psychotherapists were presented with multiple sets of four suggestions for each exercise they actually performed with the patient during the therapy sessions. In other words, each set of suggestions was calculated with the data which would be available at that time to simulate the actual setting.

On the one hand, these suggestions are compared with the manual configurations of the psychotherapists from the actual exercise. On the other hand, the psychotherapists were asked to indicate the most appropriate suggestions. This approach was chosen to prevent the algorithm from influencing the psychotherapist, thereby introducing bias into the results. All tests from this evaluation are applied to the car environment because none of the participating patients required therapy using the elevator environment. However, environment design should not significantly impact the results as the algorithm is environment agnostic. In other words, the algorithm should adapt the values of any VR parameter or combination of parameters.

The similarity of the two configurations increases with the number of parameters with the same value between these two. For this evaluation, this similarity is expressed as a number between 0 and 1, where a value of 0 means two configurations are as dissimilar as possible while a value of 1 denotes two identical configurations. Table 5.2 presents the similarity of the four suggestions generated by the adaptation algorithm against the manual configuration of each exercise. For each row, the suggestion with the highest similarity is indicated in bold. In most cases, the highest similarity is between 0.6 and 0.8. This result indicates that the suggestions are indeed close to what the psychotherapist would do. For some configurations, the similarity is the same compared to two different suggestions. That is because the actual configuration was equally similar to both, not because both suggestions are identical. This occurs for

Table 5.2: The similarity of each generated suggestion compared to the used configurations. The bold cells indicate the highest similarity for each configuration. The grey cells indicate the choice of the psychotherapist during the post-study.

Exercise	Suggestions			
	1	2	3	4
1	0.53	**0.66**	0.53	0.50
2	0.81	**0.83**	0.62	0.82
3	0.77	0.78	0.77	**0.79**
4	**0.81**	0.79	0.78	0.77
5	0.58	**0.60**	0.55	0.49
6	**0.46**	**0.46**	0.44	0.38
7	**0.45**	**0.45**	0.40	0.34
8	**0.83**	0.79	0.75	0.81
9	**0.66**	0.65	0.60	0.62

exercises that have relatively low similarity to all suggestions. It suggests that the presented suggestions are not in line with the psychotherapists' approach during the therapy.

The results in Table 5.2 present the similarity scores of the environment parameters and interoceptive parameters combined for nine different exposure exercises covering three patients. Each exercise was assessed by one of the two psychotherapists. The tests show a significant difference in the average similarity for interoceptive parameters and environmental parameters. The similarity is 0.88 on average for the interoceptive parameters, while for the environmental parameters, it is 0.58. For specific suggested configurations, the similarity on the interoceptive parameters equals 1, meaning the configurations are identical. It is clear that appropriate personalised interoceptive parameter values are much easier to predict. However, if this increased accuracy is due to the smaller configuration space of these parameters compared to the environment parameters or better predictability of interoceptive parameters is unclear from the data.

The cells with a grey background in Table 5.2 indicate the suggestions the psychotherapist assessed as the most appropriate during the post-therapy evaluation. As can be seen, for some exercises, the psychotherapist decided that none of the suggestions was good enough (Ex. 3, 4 and 9). For other exercises (Ex. 1 and 2), the choice of the psychotherapist matched the suggestion with the highest similarity. In all other cases, the choice of the psychotherapist during the post-study did not match with the highest similarity suggestion of the actual therapy sessions. However, in those cases, the difference in similarity to the actual configuration between the psychotherapist's choice and the closes matching suggestion is minor. On average, a difference of 0.09 in similarity, with a minimum of 0.02 and a maximum of 0.21, was obtained.

5.5 Discussion and Conclusion

This work presents a prototype of an adaptation algorithm for personalised VE in VRET. A proof of concept application for VRET enabled the integration of the algorithm. Data from three clinical vignettes enabled the comparison of the manually configured environments and the generated suggestions. The results of this comparison indicate that the proposed system has merit, as therapists choose similar configurations to at least one generated suggestion. Indeed, the results suggest that the output of the adaptation algorithm is valuable to the experienced psychotherapists in this study. However, future studies are needed to discover if less experienced psychotherapists would benefit even more from the algorithm.

From a computational point of view, the tests showed that the system scales linearly with the number of previous exercises with a factor of 0.22 seconds per exercise. Although this is quite steep, the computation for 50 previous exercises is below 15 seconds. The domain experts estimate that the actual required number of VR exercises can vary but rarely exceed 50. Therefore, the execution time measured for 50 exercises can be considered an upper bound, which is acceptable for therapy application.

The relevance for potential application in clinical practice has also been a key focus throughout this work. Researching this relevance required a multidisciplinary mindset and resulted in continuous collaboration with psychotherapists. They provided a theoretically sound foundation for the resulting adaptation algorithm and implemented a proof of concept in practice. This helped to demonstrate the algorithm's potential better and pushed this research further than mere theoretical conceptualisation.

Nonetheless, further improvements are required to unlock the full potential. The application of the RW model should be further investigated. Specifically, research on the optimal values for α_x and β is needed. As α_x depends on the impact of stimulus x on each user, this value could potentially be calculated for each user/stimulus pair individually. Analogously, the parameter β models a property of the user itself, namely, the rate at which patients form new associations. Both parameters could be calculated from the personality treats of the patients.

Furthermore, no claims can be made concerning effectiveness or efficacy at this point. Future studies should be set up with large samples of participants, both psychotherapists and clients, and with a rigorous methodology. The development and evaluation methodology proposed by Birckhead et al. [40] can serve as an excellent framework to further iterate on the design of this algorithm and its VR application.

It is clear from the results that the therapist makes different decisions in some cases than those suggested by the adaptation algorithm. On the one hand, fully quantifying and automating the complex process of ET is probably not possible nor feasible. This is why the adaptation algorithm should primarily be considered as a decision support system to help guide psychotherapists. On the other hand, many solutions proposed by the system could have been proven to be relevant, as it is unlikely that only a single perfect configuration of the VR environment can be made at any given time. Nevertheless, the quality of the system can be further improved by learning from the decisions made by psychotherapists, especially as they also become increasingly familiar with VRET, the functionalities and the potential. Through self-learning technologies, the system would learn to adapt to the intentions of the therapist as well. Furthermore, with more qualitative input data for the algorithm, better suggestions become possible. Where a discrete expectancy violation metric is used in the current design of the algorithm, a continuous expectancy rating can provide a quantitative and qualitative improvement in future studies.

As immersive technology is becoming increasingly accessible, it is bound to spark the interest of psychotherapists as well. One particular technique that has already been proven valuable and effective in research is VRET. We expect that - with further research - adaptation algorithms like the one described in this paper will play a vital role in facilitating successful uptake in clinical practice. These algorithms have the potential to reduce the challenge for psychotherapists to master the operation of the systems fully and to make use of technology for its primary purpose: to facilitate offering high-quality and effective care to those in need of support.

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Statements of Ethical Approval

This study was approved by the Ghent University Hospital Ethical Committee [EC/2019/0893].

Code Repository

All source files of the ontology presented in this work are publicly available on our repository under the CC-BY-4.0 licence:
https://github.com/IBCNServices/PATRONUS-ontology.

Appendix

```
<?xml version="1.0"?>
<rdf:RDF
  xmlns="http://idlab.ugent.be/ontology/VRETPatronus.owl#"
```

```
  xml:base="http://idlab.ugent.be/ontology/VRETPatronus.owl"
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:owl="http://www.w3.org/2002/07/owl#"
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#">
  <owl:Ontology rdf:about="http://idlab.ugent.be/ontology/
      VRETPatronus.owl">
    <owl:imports rdf:resource="http://idlab.ugent.be/ontology/
        UpperET.owl"/>
  </owl:Ontology>

  <owl:ObjectProperty rdf:about="http://idlab.ugent.be/ontology/
      VRETPatronus.owl#hasVREvent">
    <rdfs:domain rdf:resource="http://idlab.ugent.be/ontology/
        VRETPatronus.owl#VRScenario"/>
    <rdfs:range rdf:resource="http://idlab.ugent.be/ontology/
        VRETPatronus.owl#VREvent"/>
    <rdfs:range rdf:resource="http://idlab.ugent.be/ontology/
        VRETPatronus.owl#VRInteroceptiveStimulus"/>
  </owl:ObjectProperty>

  <owl:Class rdf:about="http://idlab.ugent.be/ontology/VRETPatronus.
      owl#InternalEvent">
    <rdfs:subClassOf rdf:resource="http://idlab.ugent.be/ontology/
        UpperET.owl#InternalStimulus"/>
  </owl:Class>

  ...
</rdf:RDF>
```

Listing 5.1: Fragment of the VRET-ontology.

```
prefixes:
  base: "http://idlab.ugent.be/ontology/Patronus/individual/"
  uet: "http://idlab.ugent.be/ontology/UpperET.owl#"

mappings:
  patient:
    sources:
      - ['data.json~jsonpath', '$']
    s: base:patient_$(ClientId)
    po:
      - [a, uet:Patient]
      - [uet:hasPatientID, $(ClientId), xsd:string]
```

Listing 5.2: The mapping rules in YAML syntax instruct to create a new invidual of type Patient and give it an ID.

```
@prefix rr: <http://www.w3.org/ns/r2rml#>.
@prefix rml: <http://semweb.mmlab.be/ns/rml#>.
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>.
@prefix ql: <http:// semweb.mmlab.be/ns/ql#>.
@prefix map: <http://mapping.example.com/>.
@prefix uet: <http://idlab.ugent.be/ontology/UpperET.owl#>.
@prefix base: <http://idlab.ugent.be/ontology/Patronus/individual/>.
```

```
map:map_patient_0 rml:logicalSource map:source_0;
    a rr:TriplesMap;
    rdfs:label "patient";
    rr:subjectMap map:s_0;
    rr:predicateObjectMap map:pom_0, map:pom_1.
map:om_0 a rr:ObjectMap;
    rr:constant uet:Patient;
    rr:termType rr:IRI.
map:om_1 a rr:ObjectMap;
    rml:reference "ClientId";
    rr:termType rr:Literal;
    rr:datatype <http://www.w3.org/2001/XMLSchema#string>.
map:pm_0 a rr:PredicateMap;
    rr:constant rdf:type.
map:pm_1 a rr:PredicateMap;
    rr:constant uet:hasPatientID.
map:pom_0 a rr:PredicateObjectMap;
    rr:predicateMap map:pm_0;
    rr:objectMap map:om_0.
map:pom_1 a rr:PredicateObjectMap;
    rr:predicateMap map:pm_1;
    rr:objectMap map:om_1.
map:s_0 a rr:SubjectMap;
    rr:template base:patient_{ClientId}.
map:source_0 a rml:LogicalSource;
    rml:source "config_report.json";
    rml:iterator "$";
    rml:referenceFormulation ql:JSONPath.
```

Listing 5.3: These RML-mapping rules describe the same as the mapping rules in YAML syntax.

References

[1] J.-P. Lépine. *The epidemiology of anxiety disorders: prevalence and societal costs.* The Journal of Clinical Psychiatry, 63 Suppl 14:4–8, 2002.

[2] J. Alonso, M. C. Angermeyer, S. Bernert, R. Bruffaerts, T. S. Brugha, H. Bryson, G. Girolamo, R. Graaf, K. Demyttenaere, I. Gasquet, J. M. Haro, S. J. Katz, R. C. Kessler, V. Kovess, J. P. Lepine, J. Ormel, G. Polidori, L. J. Russo, G. Vilagut, J. Almansa, S. Arbabzadeh-Bouchez, J. Autonell, M. Bernal, M. A. Buist-Bouwman, M. Codony, A. Domingo-Salvany, M. Ferrer, S. S. Joo, M. Martinez-Alonso, H. Matschinger, F. Mazzi, Z. Morgan, P. Morosini, C. Palacin, B. Romera, N. Taub, and W. A. M. Vollebergh. *Prevalence of mental disorders in Europe: results from the European Study of the Epidemiology of Mental Disorders (ESEMeD) project.* Acta Psychiatrica Scandinavica, 109(s420):21–27, June 2004. doi:10.1111/j.1600-0047.2004.00327.x.

[3] D. H. Barlow, S. D. Raffa, and E. M. Cohen. *Psychosocial treatments for panic disorders, phobias, and generalized anxiety disorder.* In A guide to treatments that work, 2nd ed., pages 301–335. Oxford University Press, New York, NY, US, 2002.

[4] B. Depreeuw, L. A. Andrews, S. Eldar, and S. G. Hofmann. *The Treatment of Panic Disorder and Phobias.* In Evidence-Based Psychotherapy, pages 63–93. John Wiley & Sons, Inc., Hoboken, NJ, USA, December 2017. doi:10.1002/9781119462996.ch4.

[5] M. G. Craske, K. Kircanski, M. Zelikowsky, J. Mystkowski, N. Chowdhury, and A. Baker. *Optimizing inhibitory learning during exposure therapy.* Behaviour Research and Therapy, 46(1):5–27, January 2008. doi:10.1016/j.brat.2007.10.003.

[6] M. G. Craske, M. Treanor, C. Conway, T. Zbozinek, and B. Vervliet. *Maximizing Exposure Therapy: An Inhibitory Learning Approach.* Behaviour research and therapy, 58:10–23, July 2014. doi:10.1016/j.brat.2014.04.006.

[7] K. Meyerbröker and P. M. Emmelkamp. *Virtual reality exposure therapy in anxiety disorders: a systematic review of process-and-outcome studies.* Depression and Anxiety, 27(10):933–944, August 2010. doi:10.1002/da.20734.

[8] D. D. Ebert, T. Van Daele, T. Nordgreen, M. Karekla, A. Compare, C. Zarbo, A. Brugnera, S. Øverland, G. Trebbi, K. L. Jensen, F. Kaehlke, and H. Baumeister. *Internet- and Mobile-Based Psychological Interventions: Applications, Efficacy, and Potential for Improving Mental Health: A Report of the EFPA E-Health Taskforce.* European Psychologist, 23(2):167–187, May 2018. doi:10.1027/1016-9040/a000318.

[9] D. Freeman, S. Reeve, A. Robinson, A. Ehlers, D. Clark, B. Spanlang, and M. Slater. *Virtual reality in the assessment, understanding, and treatment of mental health disorders.* Psychological Medicine, 47(14):2393–2400, October 2017. doi:10.1017/S003329171700040X.

[10] P. Best, A. McKenna, P. Quinn, M. Duffy, and T. Van Daele. *Can Virtual Reality Ever Be Implemented in Routine Clinical Settings? A Systematic Narrative Review of Clinical Procedures Contained Within Case Reports for the Treatment of PTSD.* Frontiers in Virtual Reality, 1:563739, November 2020. doi:10.3389/frvir.2020.563739.

[11] S. Y. Park, S. M. Kim, S. Roh, M.-A. Soh, S. H. Lee, H. Kim, Y. S. Lee, and D. H. Han. *The effects of a virtual reality treatment program for online gaming addiction.* Computer Methods and Programs in Biomedicine, 129:99–108, June 2016. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0169260716000079, doi:10.1016/j.cmpb.2016.01.015.

[12] A. Rizzo, M. J. Roy, A. Hartholt, M. Costanzo, K. B. Highland, T. Jovanovic, S. D. Norrholm, C. Reist, B. Rothbaum, and J. Difede. *Virtual Reality Applications for the Assessment and Treatment of PTSD.* In S. V. Bowles and P. T. Bartone, editors, Handbook of Military Psychology, pages 453–471. Springer International Publishing, Cham, 2017. doi:10.1007/978-3-319-66192-6_27.

[13] R. Baños, C. Botella, M. Alcañiz, V. Liaño, B. Guerrero, and B. Rey. *Immersion and Emotion: Their Impact on the Sense of Presence.* CyberPsychology & Behavior, 7(6):734–741, December 2004. doi:10.1089/cpb.2004.7.734.

[14] M. Slater. *Immersion and the illusion of presence in virtual reality.* British Journal of Psychology, 109(3):431–433, August 2018. doi:10.1111/bjop.12305.

[15] P. Lindner, A. Miloff, W. Hamilton, L. Reuterskiöld, G. Andersson, M. B. Powers, and P. Carlbring. *Creating state of the art, next-generation Virtual Reality exposure therapies for anxiety disorders using consumer hardware platforms: design considerations and future directions.* Cognitive Behaviour Therapy, 46(5):404–420, September 2017. doi:10.1080/16506073.2017.1280843.

[16] P. Bun, F. Gorski, D. Grajewski, R. Wichniarek, and P. Zawadzki. *Low – Cost Devices Used in Virtual Reality Exposure Therapy.* Procedia Computer Science, 104:445–451, 2017. doi:10.1016/j.procs.2017.01.158.

[17] T. Donker, I. Cornelisz, C. van Klaveren, A. van Straten, P. Carlbring, P. Cuijpers, and J.-L. van Gelder. *Effectiveness of Self-guided App-Based Virtual Reality Cognitive Behavior Therapy for Acrophobia: A Randomized Clinical Trial.* JAMA Psychiatry, 76(7):682, July 2019. doi:10.1001/jamapsychiatry.2019.0219.

[18] P. Lindner, A. Miloff, E. Zetterlund, L. Reuterskiöld, G. Andersson, and P. Carlbring. *Attitudes Toward and Familiarity With Virtual Reality Therapy Among Practicing Cognitive Behavior Therapists: A Cross-Sectional Survey Study in the Era of Consumer VR Platforms.* Frontiers in Psychology, 10:176, February 2019. doi:10.3389/fpsyg.2019.00176.

[19] T. Van Daele, M. Karekla, A. P. Kassianos, A. Compare, L. Haddouk, J. Salgado, D. D. Ebert, G. Trebbi, S. Bernaerts, E. Van Assche, and N. A. J. De Witte. *Recommendations for policy and practice of telepsychotherapy and e-mental health in Europe and beyond.* Journal of Psychotherapy Integration, 30(2):160–173, June 2020. doi:10.1037/int0000218.

[20] S. Lissek, A. S. Powers, E. B. McClure, E. A. Phelps, G. Woldehawariat, C. Grillon, and D. S. Pine. *Classical fear conditioning in the anxiety disorders: a meta-analysis.* Behaviour Research and Therapy, 43(11):1391–1424, November 2005. doi:10.1016/j.brat.2004.10.007.

[21] P. Eelen and B. Vervliet. *Fear Conditioning and Clinical Implications: What Can We Learn From the Past?* In M. G. Craske, D. Hermans, and D. Vansteenwegen, editors, Fear and learning: From basic processes to clinical implications., pages 17–35. American Psychological Association, Washington, 2006. doi:10.1037/11474-001.

[22] B. Vervliet, M. G. Craske, and D. Hermans. *Fear Extinction and Relapse: State of the Art.* Annual Review of Clinical Psychology, 9(1):215–248, March 2013. doi:10.1146/annurev-clinpsy-050212-185542.

[23] R. Rescorla and A. R. Wagner. *A Theory of Pavlovian Conditioning : Variations in the Effectiveness of Reinforcement and Nonreinforcement.* Classical conditioning: current research and theory, 1972.

[24] R. A. Greenes. *Clinical Decision Support.* Elsevier, 2014. doi:10.1016/C2012-0-00304-3.

[25] R. E. McCabe. *Subjective Units of Distress Scale.* In Phobias: The Psychology of Irrational Fear, pages 361–362. ABC-CLIO, LLC, Santa Barbara, California, 2015.

[26] D. B. Yamada, V. T. Yoshiura, N. S. Brandão Miyoshi, I. B. de Lima, G. Y. Usumoto Shinoda, R. P. C. Lopes Rijo, J. M. de Azevedo Marques, M. M. Cruz-Cunha, and D. Alves. *Proposal of an ontology for Mental Health Management in Brazil.* Procedia Computer Science, 138:137–142, 2018. doi:10.1016/j.procs.2018.10.020.

[27] F. Ongenae, P. Duysburgh, N. Sulmon, M. Verstraete, L. Bleumers, S. De Zutter, S. Verstichel, A. Ackaert, A. Jacobs, and F. De Turck. *An ontology co-design method for the co-creation of a continuous care ontology.* Applied Ontology, 9(1):27–64, 2014. doi:10.3233/AO-140131.

[28] Xiao Hang Wang, Da Qing Zhang, Tao Gu, and Hung Keng Pung. *Ontology based context modeling and reasoning using OWL.* In IEEE Annual Conference on Pervasive Computing and Communications Workshops, 2004. Proceedings of the Second, pages 18–22, Orlando, FL, USA, 2004. IEEE. doi:10.1109/PERCOMW.2004.1276898.

[29] D. Isern, D. Sánchez, and A. Moreno. *Ontology-driven execution of clinical guidelines.* Computer Methods and Programs in Biomedicine, 107(2):122–139, August 2012. doi:10.1016/j.cmpb.2011.06.006.

[30] E. Sirin, B. Parsia, B. C. Grau, A. Kalyanpur, and Y. Katz. *Pellet: A practical OWL-DL reasoner.* Journal of Web Semantics, 5(2):51–53, June 2007. doi:10.1016/j.websem.2007.03.004.

[31] D. L. McGuinness and F. Van Harmelen. *OWL web ontology language overview.* W3C recommendation, 10(10), 2004.

[32] M. Horridge and S. Bechhofer. *The OWL API: A Java API for OWL ontologies.* Semantic Web, 2(1):11–21, 2011. doi:10.3233/SW-2011-0025.

[33] N. Noy, M. Sintek, S. Decker, M. Crubezy, R. Fergerson, and M. Musen. *Creating Semantic Web contents with Protege-2000.* IEEE Intelligent Systems, 16(2):60–71, March 2001. doi:10.1109/5254.920601.

[34] I. Horrocks, P. F. Patel-Schneider, H. Boley, S. Tabet, B. Grosof, and M. Dean. *SWRL: A semantic web rule language combining OWL and RuleML.* W3C Member submission, 21(79), 2004.

[35] X. Tang, M. Xiao, B. Hu, and D. Pan. *Exchanging knowledge for test-based diagnosis using OWL Ontologies and SWRL Rules.* Procedia Computer Science, 131:847–854, 2018. doi:10.1016/j.procs.2018.04.279.

[36] A. Dimou, M. Vander Sande, P. Colpaert, R. Verborgh, E. Mannens, and R. Van de Walle. *RML: a generic language for integrated RDF mappings of heterogeneous data.* In 7th Workshop on Linked Data on the Web, Proceedings, page 5, 2014. event-place: Seoul, Korea.

[37] P. Heyvaert, B. De Meester, A. Dimou, and R. Verborgh. *Declarative Rules for Linked Data Generation at Your Fingertips!* In The Semantic Web: ESWC 2018 Satellite Events, volume 11155, pages 213–217, Cham, 2018. Springer

International Publishing. Series Title: Lecture Notes in Computer Science. doi:10.1007/978-3-319-98192-5_40.

[38] R. Zgheib, S. Kristiansen, E. Conchon, T. Plageman, V. Goebel, and R. Bastide. *A scalable semantic framework for IoT healthcare applications.* Journal of Ambient Intelligence and Humanized Computing, June 2020. doi:10.1007/s12652-020-02136-2.

[39] T. Overbeek, K. Schruers, and E. Griez. *M.I.N.I., Mini International Neuropsychiatric Interview, Nederlandse Versie 5.0.0*, 1999.

[40] B. Birckhead, C. Khalil, X. Liu, S. Conovitz, A. Rizzo, I. Danovitch, K. Bullock, and B. Spiegel. *Recommendations for Methodology of Virtual Reality Clinical Trials in Health Care by an International Working Group: Iterative Study.* JMIR mental health, 6(1):e11973, January 2019. doi:10.2196/11973.

6

Conclusion

"He put on the glasses, and fell in love with a dream."

–Stanley G. Weinbaum (1902 - 1935)

Healthcare is an ever-changing domain because our health needs keep changing as well. The number of consultations increases while the healthcare capacity is reducing [1] and the number of people on waiting lists seeking medical help is significant [2]. The introduction of eHealth has been an attempt at making certain processes in healthcare more time and cost efficient. eHealth focusses on capturing and processing data and information through information and communication technology [1]. One of the technologies receiving increasingly more attention is Virtual Reality (VR). Through the use of VR, users feel as if they are in a completely different world, a virtual world in which every aspect can be designed to the liking of the creator. Immersive technology, such as Head Mounted Display (HMD), make it possible that users get a sense of presence in these virtual worlds by stimulating their senses with artificial input [3, 4]. Originally, VR hardware was extremely expensive and therefore research on the application of the technology was limited. However, the interest in VR technology was significantly boosted in 2013 with the introduction of cheaper, consumer-grade VR hardware. With the rise of eHealth and VR new challenges emerged in the areas of self-management and patient empowerment, patient-centred platforms, and personalised treatment [1].

This dissertation proposes several contributions to eHealth and VR for more effective treatment methods. First, VR applications were designed, developed and evaluated for three use cases as a tool to provide therapy: an application for treatment of Unilateral Spatial Neglect (USN) through Music Neglect Therapy (MNT), an application providing relaxation therapy in soothing environments, and a Virtual Reality Exposure Therapy (VRET) system for the treatment of anxiety disorders through gradual exposure. Second, two methods for personalising the Virtual Environment (VE) to the needs of the patient and the treatment were presented. In the relaxation therapy, personalisation is used to gradually adapt the VE to the preferences of the user in a home setting. The VRET application used personalisation as a support tool for therapists by providing suggestions for new exercises based on the input of the user during previous exercises. The therapist could choose a suggestion or create their own configuration. Third, an architecture for a patient-centred blended care platform is presented which supports the administering of VR-based therapy, the integration of a coaching app for the patient, and a dashboard application for the therapist through which they receive insights in the user's behaviour. The main advantages of this platform is how all tools are built to improve the treatment of the patient in face-to-face sessions and at home. By providing these supportive tools for the health care provider in which all information is centralised, they are better able to help the patient.

In the remainder of this section, the contributions to the open challenges from Section 1.5 are discussed in Section 6.1. Followed by a discussion of the remaining challenges and future directions in Section 6.2. Finally, this chapter and this dissertation will be concluded with some final closing words in Section 6.3.

6.1 Review of the Open Challenges

In Section 1.5, the open challenges in eHealth and VR were presented. In this section, the contributions to these challenges are reviewed.

Challenge 1: Assessment The first challenge states the need for automated assessment in VR. These assessments can support Health Care Professionals (HCPs) in making informed decisions as they are presented with recent information of the patient. But it can also be used to feed personalisation algorithms such that they can adapt to the needs of the patient. Furthermore, automated assessment can provide information on parameters that were previously left untouched. In Chapter 2, the VR application for the treatment of USN uses sensor data from HMD's internals sensors as a measure for assessment. This data was displayed on a dashboard application, which the HCP could monitor. During post-analysis, there was indeed evidence found that this measure provided insights in the behaviour of the patient that was linked to the severity of the USN. Furthermore, in Chapter 3, a mathematical model is presented for the prediction of the emotional state of the user. These predictions are used to drive a personalisation algorithm through heuristic optimisation. The approach in Chapter 3 is rather unique in the sense that it avoids the use of intrusive sensors for the assessment. Instead the model uses initial self-reports of the user and registers changes in the VE to make new predictions.

Challenge 2: Personalisation This challenge points out the need for additional techniques to provide personalisation in complex use cases. Personalisation improves the effectiveness of treatment in many cases because a one-size-fits-all approach is often not inclusive to all patients. However, personalising VEs is not straightforward. For HCP, on the one hand, it can be time consuming and infeasible when the amount of data and information is too large. Patients, on the other hand, often do not know exactly what they need. Therefore, personalisation algorithms can be a support tool for a HCP to make decisions more effectively, and a self-management tool for patients in between consultations with a HCP. Chapter 3 presents the personalisation algorithm as an example of self-management, where the algorithm provides changes to the VE with minimal input and minimal supervision. The algorithm is able to adapt the VE based on the emotional state of the user to maximise relaxation. The second application of personalisation in this dissertation is found in Chapter 5, were personalisation is used as a tool to support the therapist. The algorithm makes suggestions for new VE configurations that maximise the effectiveness of the Exposure Therapy (ET). It uses information from the patient's history to make new suggestions. The main contribution of this chapter is the integration of domain knowledge through semantic technology and the application of the Rescorla-Wagner (RW) model as foundation of an algorithm to maximise learning.

Challenge 3: Patient-centred platforms The need for large scale, patient-centred platforms, which incorporate the tools to provide treatment, and make information exchange and interpretation easier, is identified. For the design of these platforms the collaboration of all stakeholders is required to understand their needs. The purpose of such a platform is to provide better care for the patient in face-to-face sessions and at home. This is achieved by empowering the patient to continue practising outside of consultations, e.g. through a mobile app, and by providing the HCP with as much information as possible in an easy to comprehend format, e.g. on a dashboard application. One approach to collect additional information is by having the patient record events through the platform, that the HCP can use to improve the treatment. HCP also use the platform to manage the treatment itself, e.g. by creating new exercises that appear on the patients mobile app. In Chapter 4, a patient-centred, blended care platform is developed for VRET. It provides a good example of co-design in which the stakeholders are included in the design of the system. Furthermore, an architecture is presented that incorporates a VR system. The architecture makes it easy to develop intelligent algorithms, e.g. for personalisation, that require data from various sources.

Challenge 4: Expertise driven development Every contribution in this dissertation has kept the fourth challenge in mind. Research on the applications of VR in healthcare should be driven by the expertise of the health care domain experts and not by the VR technology. Indeed, the design of each VR application was driven by previous evidence or expertise from domain experts. The VR technology was mainly used as a tool to accomplish what was previously infeasible. However, innovation requires searching for new approaches and new solutions to existing problems that use new technologies. In that sense, the contributions in this dissertation have tried to use the latest finding in VR technology to improve on existing treatments.

Challenge 5: Co-design This challenge focusses on the need for co-design methodologies in the design of new VR applications. Specifically, the digital proficiency of patients and HCP needs to be considered. The aim of digital technology should be to help and support in complex tasks by removing that complexity. If new tools add additional complexity to use them, then the tool is rendered useless. To this end, the contributions in Chapters 2, 3, 4 and 5 have been designed to simplify the problem and support the user by requiring as little technical knowledge as possible. Specifically, this is accomplished through simple to use dashboard applications, and supportive systems for personalisation that operate autonomous with minimal input.

6.2 Remaining Challenges and Future Directions

This dissertation focussed on only a few of the challenges of VR in healthcare. There are of course still other challenges that remain to be researched. In this section the most prominent challenges for the adoption of VR in eHealth practice are listed.

6.2.1 Standardised Implementation

VR technology is still in full development. New innovations in hardware and software follow each other in quick succession. This has led to the situation in which studies and results of studies quickly become obsolete or comparison is made impossible. Even for studies only a few years apart, the availability of hardware and software will have changed completely [5]. In order to enable research to build further on existing applications in specific use cases, there is a need for standardised implementation guidelines. These should specify the characteristics of VR hardware and software ensuring that follow-up studies can use similar equipment. However, to make this possible, research is needed on the effects of hardware and software on the user. This will enable to account for changes in characteristics when interpreting test results.

6.2.2 Large Scale Effectiveness Studies

We still do not yet fully understand what the effect of VR is on patients and whether every form of personalisation is as effective. There is sometimes contradicting evidence found in literature. One of the most frequent shortcomings of current studies is the limited scope of user tests. These tests are fundamental to understand the circumstances in which VR technology is most effective in healthcare. Future studies need to focus on organising large scale randomised controlled trails. These should extend over large periods of time, with large populations to establish statistically significant results. Comparison against non-VR equivalents is also essential for comparative studies. Standardised implementation guidelines will help in this endeavour but do not suffice on their own. The lack of large scale studies is also a limitation of this research to be addressed in future projects.

6.2.3 Generalised Personalisation Framework

In literature, solutions for personalisation are designed only for very specific use cases, which makes it often infeasible to translate their findings to other use cases. There is a lack of frameworks that enable personalisation in a use case agnostic manner. Such a framework would be highly relevant as it will enable easier transfer of knowledge and techniques between use cases. One possibility to approach this problem is constructing an abstraction layer on top of use case specific personalisation requirements. With this abstracted definition, personalisation could be approached as an optimisation problem in which the objective is to maximise a combination of parameters, e.g. treatment progress, user enjoyment, or learning potential. Therefore, a thorough analysis of the requirements of personalisation in various use cases is first needed.

6.2.4 Gamification

VR technology already provides an intrinsic quality of enjoyment to otherwise bland treatment exercises. However, further investment on the enjoyment factor of eHealth applications, especially with VR, would not be in vain. Adopting gamification elements in the design of new VR therapy tools shows a lot of potential, especially in combination with personalisation of the gamification tactics. Furthermore, VR, with its background in the entertainment segment, is an ideal medium to apply this in. Increased enjoyment has shown to improve engagement, user retention and effectiveness.

6.2.5 Low Latency Deliver of Virtual Reality Content

To further reduce the cost of VR applications, more interest might go towards network delivered VR content, i.e. streaming of VR content. This would eliminate the need for high-end computer systems at the client side because content is created and processed on efficient large-scale servers. However, for this approach to be successful, additional research is needed on low latency delivery of this content over unstable networks such as the internet. There are multiple possible avenues in applications optimisation to further explore. Encoding strategies need further optimisation focused on tiled video, point clouds and light fields. Furthermore, techniques such as viewport prediction and content prefetching could be very beneficial for high quality and low latency delivery.

6.3 Closing Words

This dissertation presents the design and evaluation of 3 advanced VR-based applications for healthcare. Each presents an innovative contribution to the use of VR by tackling several challenges. I hope this dissertation will help in making VR technology become part of the everyday set of tools available to health care providers around the world. At the very least, may I inspire fellow researchers in pursuing VR and its applications in future studies. Because, I believe what we have seen so far, is just the tip of the iceberg.

References

[1] R. M. van der Kleij, M. J. Kasteleyn, E. Meijer, T. N. Bonten, E. J. Houwink, M. Teichert, S. van Luenen, R. Vedanthan, A. Evers, J. Car, H. Pinnock, and N. H. Chavannes. *SERIES: eHealth in primary care. Part 1: Concepts, conditions and challenges.* European Journal of General Practice, 25(4):179–189, October 2019. Available from: https://www.tandfonline.com/doi/full/10.1080/13814788.2019.1658190, doi:10.1080/13814788.2019.1658190.

[2] Eurostat. *Self-reported unmet needs for health care by sex, age, specific reasons and educational attainment level.* Technical report, 2019. Available from: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hlth_ehis_un1e&lang=en.

[3] L. Jensen and F. Konradsen. *A review of the use of virtual reality head-mounted displays in education and training.* Education and Information Technologies, 23(4):1515–1529, July 2018. Available from: http://link.springer.com/10.1007/s10639-017-9676-0, doi:10.1007/s10639-017-9676-0.

[4] G. Tieri, G. Morone, S. Paolucci, and M. Iosa. *Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies.* Expert Review of Medical Devices, 15(2):107–117, February 2018. Available from: https://www.tandfonline.com/doi/full/10.1080/17434440.2018.1425613, doi:10.1080/17434440.2018.1425613.

[5] B. Garrett, T. Taverner, D. Gromala, G. Tao, E. Cordingley, and C. Sun. *Virtual Reality Clinical Research: Promises and Challenges.* JMIR Serious Games, 6(4):e10839, October 2018. Available from: http://games.jmir.org/2018/4/e10839/, doi:10.2196/10839.

A

How do Users Interact with Mobile Health Apps? A Markov Chain Analysis

The mobile coaching app, introduced for the PATRONUS platform in Chapter 4, is a tool to support the patient in between therapy sessions. Through the app they can feel self-empowered because they have the means to perform their exercises at home, they can keep track of their personal goals and they can collect information which can, eventually, help their treatment. However, there is much more information about the patient's behaviour that could be relevant to improve the treatment. Obviously it is unfeasible for the patient to register all its behaviour manually. Therefore, it is most interesting to extract insights of the user by observing and analysing data that can be cheaply and autonomously collected. An example of this is the interactions of a patient with a mobile app, e.g. the coaching app in PATRONUS. Information such as the app pages they consult, the exercises they perform or the frequency at which they log new events can tell a lot. This research explored the use of Markov chains to analyse and detect patterns in the interaction of a patient with the app. These patterns could be used in future research to inform the psychotherapist, or to drive personalisation algorithms that can suggest appropriate content to the patient.

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Abstract Intelligent virtual coaches for healthcare require sufficient insights about the user. Data from interactions with a mobile health app have previously been overlooked as a source of valuable insights. In this paper, traces of interaction with a mobile app are analysed to identify the needs and goals of the user. The mobile app is part of a blended care solution for anxiety therapy. The paper illustrates how Markov Chain analysis proves to be a useful tool in classifying user interaction based on the user's goal.

A.1 Introduction

A virtual coach can only be as smart as the data it has available and the insights it can extract from that data. Fortunately, these days there is a lot of data easily accessible. There is a plethora of wearables that measure everything from heart rate, galvanic skin response and temperature, to activities, sleep quality and posture [1]. Due to the digitisation of files and tools, much more information than before is becoming available in digital form. One less obvious source of data is mobile app interaction, but because of their ease of access and wide applications in healthcare, they are certainly worth looking into [2–4]. How the user interacts with the app can provide useful insights into the needs and wellbeing of the user. Typically, these apps server multiple purposes. Observing which goal or purpose the user wants to server with this app could indicate the needs of that user.

In this paper, we explore which insights can be extracted in terms of goal identification from data which is collected from users interacting with a mobile application. The application is designed specifically as a complementary tool for anxiety Virtual Reality Exposure Therapy (VRET). We focus on searching techniques that are scalable to large amounts of data.

A.2 Mobile Application Data

The analysis in this paper is based on data collected from a mobile app designed as part of a blended care solution for exposure therapy.

A.2.1 Mobile Application Design

The mobile application is developed as part of a project called PATRONUS[1] in which a blended-care solution is created for VRET. Two of the goals of the project are to enable longitudinal follow-up of patients and provide homework exercises in between sessions for the patient to practice in real life and a virtual environment. The homework exercises are created by a therapist and become available to the user on its device

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[1] www.imec-int.com/en/what-we-offer/research-portfolio/patronus, accessed on 01/05/2020

after the therapy session. Physiological data was collected through one of two wearables, the Empatica E4[2] or the Chill+[3].

A selection of screenshot of different view in the mobile application are shown in Figure A.1. The start view of the application shows an overview of all the exercises of the user (Figure A.1a). This view lists all the exercises which are available to the patient. The list contains a combination of exercise in real life and exercises in Virtual Reality (VR) on the mobile device. When selecting an exercise the user gets forwarded to a detailed view of that exercise which in the case of VR exercises will forward them to the VR environment (Figure A.1b). The goals view (Figure A.1c) lists goals which have been defined in consultation with his/her therapist. These goals serve a motivational purpose as patients can reach intermediate goals that can help them towards coping with anxiety. Next, there is a screen which allows users to input information about their current state (Figure A.1d). Through this feature, the patient keeps a record of his/her emotional state in difficult situations. These records can later be reviewed with a therapist. Another screen provides an overview in the form of a timeline which lists all the exercises and goals in chronological order (Figure A.1e). This view has no other functionality otherwise. There is also a view with account settings and information which rarely needs to be accessed by the user. The account view is also used for connecting a wearable device. The application contains a few other screens which are not discussed in more detail as the name of the screen provides enough explanation about their purpose or the screen has no significance to this paper.

A.2.2 Data Collection

To analyse how the users are interacting with the app, data needs to be collected which represents this interaction. Specifically, the pages of the application the user is visiting, the order in which these are visited and for how long they are visited. All this information can be extracted when storing one data record each time the user sees a new view in the app together with a timestamp of when this view is shown. This kind of information can easily be recorded through the use of the Google Firebase platform[4].

In this study, data has been collected from 3 clients using the application to obtain a small dataset. For each user, the application was populated with some exercises, both VR and in vivo, and some goals were specifically set for those users. The activity in the app was recorded over a period of two weeks.

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[2] www.empatica.com/research/e4, accessed on 01/05/2020

[3] www.imec-int.com/nl/chill, accessed on 01/05/2020

[4] https://firebase.google.com, accessed on 01/05/2020

(a)

Sessie op: 19/06/2019 16:32

Hyperventileren
Ademen door een rietje - 2min - In Vivo
Oefening gepland op 26/06/2019

Vr: Auto Scenario
Auto VRE met suggesties volgens het algoritme
Oefening gepland op 26/06/2019

(b)

(c)

Openbaar vervoer
Voor mijn nieuwe job dien ik iedere dag de trein en bus te nemen. Tegen 1 mei wil ik dit zonder veel stress kunnen.
Doel nog niet voltooid.

Vliegtuig nemen
Tijdens de zomervakantie wil ik het vliegtuig kunnen nemen voor een reis met mijn familie naar Tenerife
Doel nog niet voltooid.

(d)

Log

Datum: vr 28/06/2019
Tijd: 08:46
0
0 100

Wat wilt u melden?
thuis

(e)

Doelen

Openbaar vervoer
Voor mijn nieuwe job dien ik iedere dag de trein en bus te nemen. Tegen 1 mei wil ik dit zonder
gepland op 01/05/2019

donderdag, 28 februari 2019

oefening: VR
gepland op 28/02/2019

Figure A.1: Screenshots of the different views in the PATRONUS mobile application. (a) List of all exercises with a short description, due date and image for each, (b) VR view rendered on screen (landscape mode) for a VR headset, (c) List of all goals with a short description for each, (d) Journal input page for a rating (0-100), additional text and a timestamp, (e) Timeline overview showing the planned exercises in the future and a list of goals.

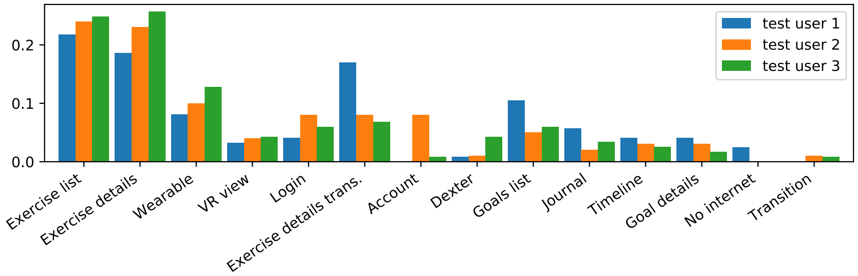

Figure A.2: Distribution plot of page visit frequency.

A.3 Data Analysis

The methodology of the data analysis is split up in two phases. First, the data is analysed from a static perspective in which only the visits to each page are considered. Second, the dynamic characteristics of the collected data are analysed. In other words, the transitions between pages are investigated. This section discusses the analysis and results in detail.

A.3.1 Static Analysis: Page Visit Analysis

The first and simplest analysis consists of looking at the distribution of the page visits for every user individually. In Figure A.2 the distributions of visits to each page are plotted per user. The plot is generated by summing the visits to each page and normalising it by the total of visits to each page per user. These results show slight differences between users, even though the instructions given to them were the same. This indicates that the user behaviour is different for each person, which hints at the different intentions of each user with the app which lead to different goals per user.

Some pages are less important than others. For example, transition pages which are visited only briefly to transition on to a next page typically have less importance. However, the visit distribution in Figure A.2 does not reflect this because it counts every visit to every page as equally important. This can be mitigated by taking the time on each page into account. Figure A.3 shows the same distribution when page visits are weighted by the time spend on that page. This plot shows a distribution of time spent on each page describing a more realistic view of which pages must be important to the user as they spent the most time on them. It can be seen that more than 10% of the time is spent on 5 of the screens: *Exercise list*, *Exercise details*, *Wearable*, *VR view* and *Login*. The two most interesting ones are the *Exercise details* and the *VR view* pages as they relate to performing exercises and the application. The challenge now is to try and understand why a person spends more time on one page than another.

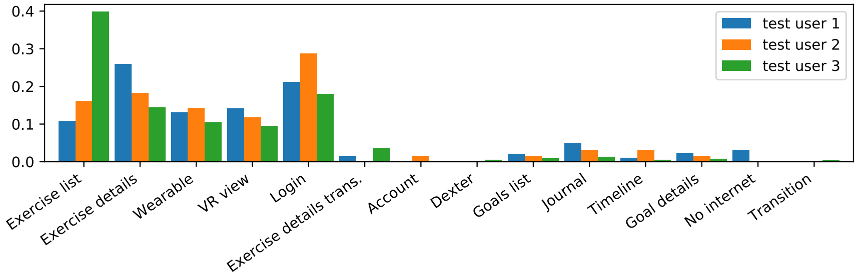

Figure A.3: Distibution plot of page visits weighted by time spend on page.

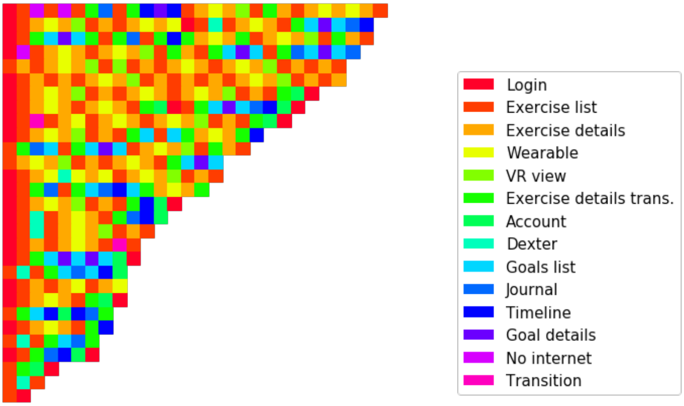

Figure A.4: Visualisation of the trace of the three users, each row represents a trace, each cell represents a page in that trace, the colour of the trace indicates which page it was.

A.3.2 Dynamic Analysis: Page Transition Analysis

The frequency of page visits only gives a few insights. In what follows, traces of page visits are considered as well. A trace is a sequence of consecutive page visits. It starts when the user opens the app and stops when he/she closes the app. These traces are visualised in Figure A.4 where each cell represents a page visit and its colour indicates which page it was. Every trace is different, they contain different colours and have different lengths. Some contain visits to pages which do not occur in other traces. This indicates that the colours/pages have specific goals that the users visit to complete a certain task. By tracking which traces contain which page visits, and in which order, more insights can be gathered about the needs and goals of the users. For example, frequent visits to the Journal page could indicate insecurity and frequent visits to the exercise page could indicate motivation to practice.

This initial visual inspection of the data is only possible for small amounts of data is in this case. However, typically the size of the dataset is too large to apply a visual analysis. Therefore, the focus is moved onto a scalable technique which could give similar insights. This is where Markov Chains come into play [5].

Markov Chains (MCs) are used for the analysis of many applications involving time series, they describe the stochastic behaviour of a sequence of events [6]. A page transition leads to a new state and the Markov property requires that the probability of the event leading to that state only depends on the previous state. An MC can be formalised by a state space S, a transition matrix P and an initial state distribution π_0. Applied on the app usage data, a sequence of events is interpreted as a sequence of transitions between the pages of the application. Specifically, this means that the state space S is given by the finite collection of all pages of the mobile app, $S = \{s_0, s_1, \ldots, s_n\}$. The probability of transitioning from page i to page j is given by p_{ij} and can be stored in a transition matrix P on row i and column j.

The aim is to be able to classify app sessions based on the traces created by interacting with the app. Having this classification could indicate the intention of the user navigating the app by linking page visits to a goal of the users. MCs can be used to classify these traces. Two approaches are discussed. In the first approach, domain knowledge is used to construct an MC manually based on what are known to be important pages to visit when trying to reach a goal. For every goal, and therefore corresponding class, an MC is created. One of the properties of a MC is that the likelihood for any trace to be generated by a certain MC can be calculated. This is done by multiplying the transition probabilities for all transition in the trace. In other words, the probability of a trace being generated by a MC which models a certain goal can be calculated, and therefore the probability of the goal of that trace as well. When calculating this probability for every hand-modelled MC, a probability for each goal is obtained that can be used for classifying the traces based on a threshold value. Equation A.1 formalises this classification function c, where trace t_j belongs to class i if the probability of that trace belonging to the MC with transition matrix P_i is strictly larger than α.

$$c(i, t_j) = \begin{cases} 1 & \text{if } Pr(t_j, P_i) \geq \alpha, \\ 0 & \text{otherwise.} \end{cases} \tag{A.1}$$

In fact, this allows for multi-label classification as a certain trace could contain multiple goals. This approach is feasible when the required domain knowledge is available to manually create MCs and when the correlation between goals and page visits is not too complex.

However, when this is not the case, a different technique is needed which could help in generating the MCs. This second approach will construct MCs and corresponding clusters of traces simultaneously in an iterative manner. The different steps of this procedure are as follows:

1. Evenly distribute all traces into n random clusters.

2. For each set, construct the MC.
3. Calculate for each trace the probability that this trace was generated by every MC of each cluster.
4. Assign each trace to the cluster for which it has the highest probability.
5. Repeat steps 2-4 until convergence is reached when no trace changes to a different cluster.

With this algorithm, n clusters with a corresponding MC are obtained for which n is selected manually. The algorithm is applied to our dataset with $n = 3$ because of the 3 main purposes of the app. To understand the classification, these MCs need to be analysed to identify which goals they detect in the traces. With this information, each new trace can be classified and labelled with a certain goal based on the probability of it being generated by each MC as in Equation A.1. The analysis of the MCs shows that one cluster reveals traces in which the wearable got connected to the app followed by exercises in VR. Another cluster reveals traces which interacted a lot with the journal page while the third cluster contains traces where the personal goals were consulted.

A.4 Conclusion

To make virtual coaches for healthcare more intelligent they need to have access to as many insights as possible from different sources of data. User interaction with a mobile health app produces valuable insights into the needs of the user. MCs have been proposed to cluster traces of interactions. By analysing the MC, the intentions and goals of each cluster of traces can be revealed. This showed how interaction with different parts of the application got identified and classified automatically. Thus, this paper illustrates how MC analysis can be used to extract insights about users which can be used by virtual coaches to support the user's needs. For example, repetitive consultation of health info in an app might trigger a virtual intervention. In another example, procrastination of exercises might be an incentive for the virtual coach to motivate the user.

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References

[1] B. Munos, P. C. Baker, B. M. Bot, M. Crouthamel, G. de Vries, I. Ferguson, J. D. Hixson, L. A. Malek, J. J. Mastrototaro, V. Misra, A. Ozcan, L. Sacks, and P. Wang. *Mobile health: the power of wearables, sensors, and apps to transform clinical trials.* Annals of the New York Academy of Sciences, 1375(1):3–18, 2016.

[2] D. R. Stukus, N. Farooqui, K. Strothman, K. Ryan, S. Zhao, J. H. Stevens, and D. M. Cohen. *Real-world evaluation of a mobile health application in children with asthma.* Annals of Allergy, Asthma & Immunology, 120(4):395–400, 2018.

[3] J. Helbostad, B. Vereijken, C. Becker, C. Todd, K. Taraldsen, M. Pijnappels, K. Aminian, and S. Mellone. *Mobile Health Applications to Promote Active and Healthy Ageing.* Sensors, 17(3):622, 2017.

[4] A. Drincic, P. Prahalad, D. Greenwood, and D. C. Klonoff. *Evidence-based Mobile Medical Applications in Diabetes.* Endocrinology and Metabolism Clinics of North America, 45(4):943–965, 2016.

[5] J. Stragier, G. Vandewiele, P. Coppens, F. Ongenae, W. Van den Broeck, F. De Turck, and L. De Marez. *Data Mining in the Development of Mobile Health Apps: Assessing In-App Navigation Through Markov Chain Analysis.* Journal of Medical Internet Research, 21(6):1–12, 2019.

[6] V. V. Mayil. *Web Navigation Path Pattern Prediction using First Order Markov Model and Depth first Evaluation.* International Journal of Computer Applications, 45(16):26–31, 2012.

B

Contextual Bandit Learning-Based Viewport Prediction for 360 Video

The sense of presence can easily be disturbed by bad quality of the Virtual Reality (VR), e.g. delays, low resolution, and other visual artefact. Especially in scenarios where VR content is delivered through the internet, this is a significant challenge. Streaming of 360 degree video to a head mounted display is an example of this. Because 360 degree video requires much more bandwidth than regular video, a technique for dynamic adaptive stream is used which can reduce the required bandwidth by encoding spatial video tiles at different qualities for a specified time segment. In an ideal scenario, only the video tiles in the centre of the user's field of view need to be encoded and transmitted in the highest quality. However, users keeps changing the direction they are watching, therefore, the encoding of the tiles need to change as well. In order to optimise the delivery of the 360 degree video, the user's view direction needs to be predicted in advance for the correct tiles to be encoded in the correct quality. This work presents an approach using self-learning contextual bandits, that make this prediction based on prior training data. This technique is not limited to 360 degree video but could also be extremely important for streaming computer generated virtual environments to low-cost VR hardware systems.

⋆ ⋆ ⋆

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Abstract Accurately predicting where the user of a Virtual Environment (VE) application will be looking at in the near future improves the perceive quality of services, such as adaptive tile-based streaming or personalised online training. However, because of the unpredictability and dissimilarity of user behaviour it is still a big challenge. In this work, we propose to use reinforcement learning, in particular contextual bandits, to solve this problem. The proposed solution tackles the prediction in two stages: (1) detection of movement; (2) prediction of direction. In order to prove its potential for VR services, the method was deployed on an adaptive tile-based VR streaming testbed, for benchmarking against a 3D trajectory extrapolation approach. Our results showed a significant improvement in terms of prediction error compared to the benchmark. This reduced prediction error also resulted in an enhancement on the perceived video quality.

B.1 Introduction

With the increase in cheap Head Mounted Display (HMD), the demand for immersive content and Virtual Reality (VR) applications is also rising. In such applications, accurate predictions of the behaviour of users within the omnidirectional environment allows to improve the perceived quality. One prominent example is adaptive tile-based 360° video streaming. Adaptive tile-based streaming exploits the fact that at any given moment the user can only observe a small portion of the entire panoramic video, *i.e.*, the viewport. It encodes the videos at different quality levels, splits the streams into temporal segments and divides these segments into spatial tiles. During streaming, tiles within the viewport are delivered in high quality while the others are in low quality [1]. In order to ensure a good experience, the system needs accurate predictions of the viewed viewport for the next segment. However, because of the unpredictability of head movement, this is currently a big challenge.

Existing solutions are either content-aware or content agnostic. Most content-aware approaches require preprocessing of the video content and thus, are too computationally intensive for real-time predictions and unfit for live VR video streaming (*e.g.*, Pano2vid [2]). Content agnostic solutions, in contrast, are much more lightweight as they only require the HMD sensor data. These approaches tend to assume linear motion for the viewing behaviour, such as the linear regression approach of Qian et al. [3]. Recently, Xie et al. [4] presented a Machine Learning (ML) approach based on pre-clustering users and multi-user regions of interest. However, their solution requires a lot of training data, while each video needs its individually trained model.

As many users do not move very often, existing general solutions are often biased towards predicting that the user never moves at all. However, other users, in contrast, might move very much and erratically, resulting in bad predictions for these users. An ML model, that first predicts the likelihood of the user moving significantly and next predicts how they move, could improve the performance, while avoiding per-video preprocessing. Furthermore, since each user produces a unique trajectory by watching a video, the model needs to adapt to new data and become more personalised over time.

Reinforcement Learning (RL) models can provide the required personalisation and per-stage learning. Their general principle is that the agents selects an action according to some trained policy based on some state that is presented to it (*i.e.* the context). In response to choosing an action, the agent receives a reward to reinforce good decisions and penalise bad ones. A well known subclass of RL are the Contextual Bandit (CB) agents, in which the chosen action has no influence on the next state. This characteristic makes CB agents the best fit for viewport prediction as the predicted location has no influence on where the user will actually look next.

In this paper, we present a novel CB learning-based viewport prediction approach for 360° video, which by only using the HMD sensor data, is able to accurately predict the trajectories of different types of users. The method has been evaluated on an adaptive tile-based streaming setup for 360° video, and has been benchmarked against a 3-dimensional extrapolation method [1].

B.2 Approach

In general, the system (Figure B.1) takes in a set of previous orientations of the HMD and feeds this to a 2D CB agent bank, which predicts, in two stages, if the user is bound to move and in which direction. The outcome of the agents results in the final prediction.

The 3D data $[x_t, y_t, z_t]$ from the HMD orientation is first processed and projected onto the 2D space, providing the longitudinal θ_t and the latitudinal ϕ_t coordinates on the 2D equirectangular projection of the sphere. Because of the wraparound of the projection in the longitudinal dimension, *i.e.* values pi and $-pi$ correspond to the same position on the sphere, ϕ_t is first converted to the unit vector (cosine and sine of the angle) before being put in the CB bank. A sliding window provides the last k samples to the CB bank. In order to simplify the prediction of the next position, the state space is discretised. Specifically, each position sample $[\theta_t, \phi_t]$ on the video is mapped to a cell $[\theta_t^i, \phi_t^j]$ of a grid with dimensions $n \times m$, where i and j are the row and column of the cell closest to the actual position. The CB bank consists of four Contextual bandits, one per dimension and decision (either motion or direction). The predicted actions of the four CB agents $[A_{t+1}^{mot^\theta}, A_{t+1}^{dir^\theta}, A_{t+1}^{mot^\phi}, A_{t+1}^{dir^\phi}]$ are subsequently used in the following algorithmic block to obtain the discretised predicted decisions $[\hat{\theta}_{t+1}^i, \hat{\phi}_{t+1}^i]$.

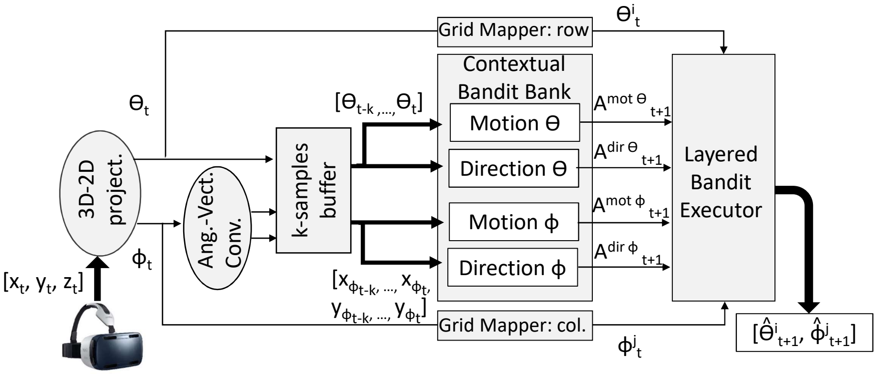

Figure B.1: Block diagram of the contextual bandit learning based viewport prediction algorithm.

B.3 Results on an Adaptive Tile-Based Virtual Reality Video Streaming System

A testbed was developed for the adaptive tile-based streaming use case of 360° video [5]. A mobile HMD is wirelessly connected to a VR content server that performs all predictions, stitching and encoding of the tiles before streaming the video to the HMD.

The study of the performance of the CB learning system was done with 5 users, while watching the Spotlight Stories Video: HELP, produced by Google[1]. The first three users were given no instructions except for watching the video as they normally would for the first time. The last two users were given instructions to move very erratic and to move continuously at a constant speed, respectively. The video was encoded with two qualities (full quality and low quality) and a 4×4 tiling scheme. Video segments were 1000 ms so predictions were also done over 1000 ms, while sensor samples were collected every 200 ms. Regarding the CB approach, the sliding window was set to hold 5 samples and the entire input space was discretised in 16×32 cells for the prediction. The system was trained on the data from users 1 and 3, and the evaluation was performed on all users. The proposed approach was compared with a 3-dimensional extrapolation method consisting of extrapolating the current sample based on the speed estimate obtained from the last two samples in the 3D Cartesian space [1]. Both prediction algorithms were evaluated according to two metrics, namely the prediction error and the relative quality. The error was defined as the angular difference between the prediction and the actual label sample for each time step. The quality was calculated as the percentage of the viewport that overlaps with the surface of the predicted tile. Since the predicted tile is streamed at the highest quality and the

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[1] https://www.youtube.com/watch?v=G-XZhKqQAHU, accessed on 01/03/2019

Table B.1: The average prediction error of the algorithms expressed in radians (lower is better).

	user 1	user 2	*user 3*	user 4	user 5
Bandit	***0.454***	**0.308**	***0.383***	**0.696**	**0.342**
3D-Extr.	*0.621*	0.393	*0.552*	0.992	0.568

Table B.2: The percentage of overlap between the viewport and the predicted tile, giving the quality of the viewport (higher is better).

	user 1	user 2	*user 3*	user 4	user 5
Bandit	***0.842***	**0.835**	***0.845***	**0.855**	**0.858**
3D-Extr.	*0.741*	0.781	*0.763*	0.647	0.804

rest at the lowest quality, this metric gives an indication of the relative quality of the perceived video.

Table B.1 shows the average prediction errors for all 5 users. The average error was calculated for both the bandit model predictions and the extrapolations. From this Table, it is clear that the bandit learning approach results in much better performance in terms of prediction error. As it could be expected, the extrapolation method performs worse for user 4, because the extrapolation is based on the heuristic that motion in one direction will continue in that direction at the same speed. However, the bandit approach, which was trained on users that did not show abnormal viewing behaviour, performs significantly better in this case. This suggests that the bandit agent is able to learn to anticipate certain motion.

Prediction error only gives half of the view on the performance and effectiveness of using a bandit agent to predict viewing behaviour for adaptive 360° video streaming. The quality of the video within the viewport is the most interesting outcome. Table B.2 shows the average relative quality within the viewport over the entire video for each user. The Table shows that the bandit agent approach performs better than the extrapolation method for all users. This means that even if there are errors in the prediction, due to the fact that the CB learning model is able to learn patterns, they are less noticeable for the quality.

To further illustrate, Figure B.2 plots out the prediction error and perceived quality of users 2 and 4 over a 10 seconds time window. These plots show that indeed, our approach does not only perform better on average, but persistently outperforms the extrapolation method. This is clear from the two rightmost plots, where the CB method avoids the quality to drop to 0%.

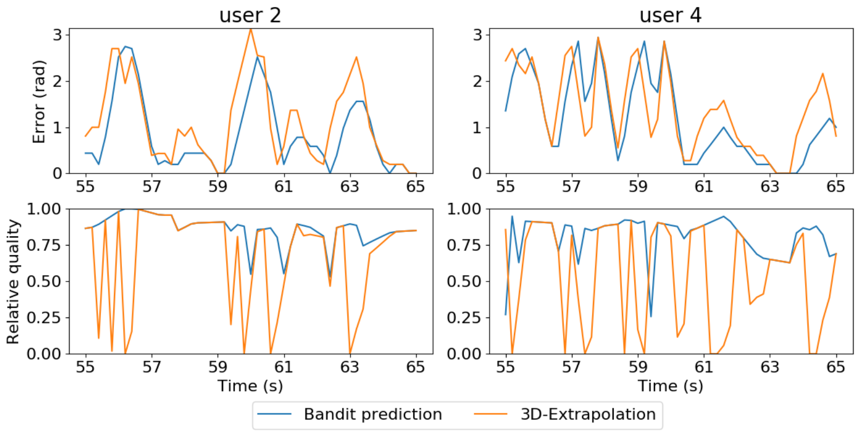

Figure B.2: Plots for the prediction error **(top)** and relative viewport quality **(bottom)** of users 2 **(left)** and 4 **(right)** over a time window of 10 seconds.

B.4 Conclusion

This paper presents a novel CB learning based approach to viewport prediction for 360° video. The proposed solution tackles the problem with layered self-learning components. The algorithm was applied on an adaptive tile-based streaming use case. The results have shown that our method results in better viewport prediction in comparison with a 3-dimensional extrapolation method. This reduced prediction error also results in improved, perceived video quality by the users. Future research will investigate the possibility of personalised and individual models for improved predictions, based on specific user behaviour.

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References

[1] J. van der Hooft, M. Torres Vega, S. Petrangeli, T. Wauters, and F. De Turck. *Optimizing Adaptive Tile-Based Virtual Reality Video Streaming.* In Proceedings of IFIP/IEEE IM 2019, 2019.

[2] Y.-C. Su, D. Jayaraman, and K. Grauman. *Pano2vid: Automatic cinematography for watching 360 videos.* In Eurographics Workshop on Intelligent Cinematography and Editing, pages 154–171. Springer, 2017.

[3] F. Qian, L. Ji, B. Han, and V. Gopalakrishnan. *Optimizing 360 Video Delivery over Cellular Networks.* In Proceedings of the 5th Workshop on All Things Cellular: Operations, Applications and Challenges, ATC '16, pages 1–6. ACM, 2016.

[4] L. Xie, X. Zhang, and Z. Guo. *CLS: A Cross-user Learning Based System for Improving QoE in 360-degree Video Adaptive Streaming.* In Proceedings of ACM MM 2018, pages 564–572. ACM, 2018.

[5] J. Heyse, M. Torres Vega, T. Wauters, F. De Backere, and F. De Turck. *Effects of Adaptive Streaming Optimizations on the Perception of 360 Virtual Reality Video.* In Proceedings of ITC 30, pages 89–92, 2018.